SpinTech VIII

8th International School & Conference on Spintronics and Quantum Information Technology

August 10–13, 2015
Basel, Switzerland
Congress Center

Chair: Daniel Loss, University of Basel
Co-Chair: Seigo Tarucha, University of Tokyo

Program & Abstract Book

https://spintech8.unibas.ch

We wish you a
successful and enjoyable time
at SpinTech VIII in Basel

The Local Organizing Committee

Daniel Loss
Seigo Tarucha
Christoph Kloeffel
Aicha Lang

Contents

8th International School and Conference on
Spintronics and Quantum Information Technology (SPINTECH VIII)
Aug 10-13, 2015; Basel, Switzerland

	Monday Aug 10	**Tuesday Aug 11**
8:00-	Registration	
8:45-9:00	Opening	
9:00-10:10	Awschalom	Marcus
10:10-10:40	Coffee break	Coffee break
10:40-11:50	Tarucha	Tserkovnyak
11:50-12:25	Marie	Zumbühl
12:25-14:30	Lunch break	Lunch break Posters A
14:30-15:05	Xue	
15:05-16:15	Klinovaja	Stano
		Ensslin
16:15-16:45	Coffee break	Coffee break
16:45-17:55	Nakamura	Jarillo-Herrero
		Ando
17:55-18:05	Short break	Short break
18:05-18:40	Majer	Gül
18:40-19:15	Brüne	Chesi; Henriques
19:15-19:50		Smejkal; Mook
	19:30 welcome reception	20:30 city tour

Wednesday Aug 12	**Thursday Aug 13**	
Heinz	Fujita; Broome	9:00-9:35
Demokritov	Morello	9:35-10:10
Coffee break	Coffee break	10:10-10:40
Brataas	Itoh	10:40-11:15
Tokura	De Franceschi	11:15-11:50
Poggio	Eriksson; Brauns	11:50-12:25
Lunch break Posters B	Lunch break	12:25-14:30
	Vignale; Botzem	14:30-15:05
Maletinsky	Oiwa	15:05-15:40
Christle	Samarth	15:40-16:15
Coffee break	Coffee break	16:15-16:45
Yazdani	Yeats; Cheng	16:45-17:20
Meyer; Csonka	Trif	17:20-17:55
Short break	Short break	17:55-18:05
Fabian	Kohda; Schäpers	18:05-18:40
Fuchs; Hennel	Aguado; Baumgartner	18:40-19:15
20:00 conference dinner		

school lecture: 60'+10'
conference talk: 30'+5'
contributed talk: 15'+2.5'

Monday, August 10

8:00 –	Registration
8:45 – 9:00	Opening
9:00 – 10:10	**David Awschalom**, University of Chicago “Quantum control of single spins in diamond and silicon carbide” (Lecture)
10:10 – 10:40	*Coffee Break*
10:40 – 11:50	**Seigo Tarucha**, University of Tokyo “Multiple spin qubits with improved gate fidelity” (Lecture)
11:50 – 12:25	**Xavier Marie**, Université de Toulouse “Spin and valley dynamics in MoS_2, $MoSe_2$ and WSe_2 monolayers”
12:25 – 14:30	*Lunch Break*
14:30 – 15:05	**Qi-Kun Xue**, Tsinghua University “Quantum anomalous Hall effect in magnetic topological insulator”
15:05 – 16:15	**Jelena Klinovaja**, University of Basel “Engineering topological quantum states: From 1D to 2D” (Lecture)
16:15 – 16:45	*Coffee Break*
16:45 – 17:55	**Yasunobu Nakamura**, University of Tokyo “Quantum magnonics with a macroscopic ferromagnetic sphere” (Lecture)
17:55 – 18:05	*Short Break*
18:05 – 18:40	**Johannes Majer**, Vienna University of Technology “Hybrid quantum systems: Coupling color centers to superconducting cavities”
18:40 – 19:15	**Christoph Brüne**, University of Würzburg “Transport and induced superconductivity in the topological surface and edge states of HgTe”
19:30 –	Welcome Reception

Tuesday, August 11

9:00 – 10:10	**Charles Marcus**, Niels Bohr Institute, Copenhagen “Noise suppression and filtering in spin qubits” (Lecture)
10:10 – 10:40	*Coffee Break*
10:40 – 11:50	**Yaroslav Tserkovnyak**, UCLA “Spin and orbital magnetic response on the surface of a topological insulator” (Lecture)
11:50 – 12:25	**Dominik Zumbühl**, University of Basel “Spin relaxation in GaAs spin qubits”
12:25 – 15:05	*Lunch Break* **POSTER SESSION A**
15:05 – 15:40	**Peter Stano**, RIKEN “Helical order in one dimensional semiconductors”
15:40 – 16:15	**Klaus Ensslin**, ETH Zürich “Non-local transport via edge-states in InAs/GaSb coupled quantum wells”
16:15 – 16:45	*Coffee Break*
16:45 – 17:20	**Pablo Jarillo-Herrero**, MIT, Cambridge “Quantum transport in van der Waals heterostructures”
17:20 – 17:55	**Kazuya Ando**, Keio University “Spin-current emission governed by nonlinear spin dynamics”
17:55 – 18:05	*Short Break*
18:05 – 18:40	**Önder Gül**, Delft University of Technology “Experimental progress on Majoranas in semiconductor nanowires”
18:40 – 18:57	**Stefano Chesi**, Beijing CSRC “Theory of box-model hyperfine couplings and transport signatures of long-range nuclear-spin coherence in a quantum-dot spin valve” (Contributed)
18:58 – 19:15	**Andre Henriques**, University of Sao Paulo “Model for the light-induced magnetization in singly charged quantum dots” (Contributed)
19:15 – 19:32	**Libor Smejkal**, ASCR, Prague “Magnetotransport in noncollinear antiferromagnets Ir_xMn_{1-x}” (Contributed)
19:33 – 19:50	**Alexander Mook**, MPI for Microstructure Physics, Halle “Topological magnon states – a way to nano-scale magnon waveguides” (Contributed)
20:30 –	City Tour

Wednesday, August 12

9:00 – 9:35	**Tony Heinz**, Stanford University “Probing and controlling the valley degree of freedom in two-dimensional transition metal dichalcogenide crystals”
9:35 – 10:10	**Sergej Demokritov**, University of Münster “BEC of magnons at room temperature and spatio-temporal properties of magnon condensate”
10:10 – 10:40	*Coffee Break*
10:40 – 11:15	**Arne Brataas**, NTNU, Trondheim “Spintronics with insulating antiferromagnets”
11:15 – 11:50	**Yoshinori Tokura**, RIKEN “Spin dependent quantum transport in Rashba semicondutors and topological insulators”
11:50 – 12:25	**Martino Poggio**, University of Basel “Measuring nanometer-scale spin systems by ultrasensitive cantilever magnetometry”
12:25 – 15:05	*Lunch Break* **POSTER SESSION B**
15:05 – 15:40	**Patrick Maletinsky**, University of Basel “Dynamics of a strongly strain-driven, hybrid spin-oscillator system”
15:40 – 16:15	**David Christle**, University of Chicago “Isolation and control of spins in silicon carbide”
16:15 – 16:45	*Coffee Break*
16:45 – 17:20	**Ali Yazdani**, Princeton University “Spotting the elusive Majorana under the microscope”
17:20 – 17:37	**Ernst Meyer**, University of Basel “Probing structure and majorana wave-function of mono-atomic Fe chains on superconducting lead” (Contributed)
17:38 – 17:55	**Szabolcs Csonka**, BME, Budapest “Quantum interference and local electrical tuning in InAs nanowire based Cooper pair splitter device” (Contributed)
17:55 – 18:05	*Short Break*
18:05 – 18:40	**Jaroslav Fabian**, University of Regensburg “Spintronics with novel 2d materials”
18:40 – 18:57	**Gregory Fuchs**, Cornell University “Time-resolved magneto-thermal microscopy of spin Hall effect driven dynamics” (Contributed)
	… next page …

18:58 – 19:15	**Szymon Hennel**, ETH Zürich “Generation and detection of spin currents in semiconductor nanostructures with strong spin-orbit interaction” (Contributed)
20:00 –	Conference Dinner

Thursday, August 13

9:00 – 9:17	**Takafumi Fujita**, Delft University of Technology “Triple quantum dot spin CCD” (Contributed)
9:18 – 9:35	**Matthew Broome**, University of New South Wales “Control of two-electron spin correlations on precision-placed donors in silicon” (Contributed)
9:35 – 10:10	**Andrea Morello**, University of New South Wales “Quantum information processing with single donors in silicon”
10:10 – 10:40	*Coffee Break*
10:40 – 11:15	**Kohei Itoh**, Keio Unversity “The role of isotope engineering in silicon and diamond quantum information processing”
11:15 – 11:50	**Silvano De Franceschi**, CEA Grenoble “CMOS bricks for silicon spin qubits”
11:50 – 12:07	**Mark Eriksson**, University of Wisconsin-Madison “Semiconductor quantum dot spin-charge hybrid qubits” (Contributed)
12:08 – 12:25	**Matthias Brauns**, University of Twente “G-factor anisotropy in Ge-Si core-shell nanowires” (Contributed)
12:25 – 14:30	*Lunch Break*
14:30 – 14:47	**Giovanni Vignale**, University of Missouri “Magneto-transport driven by spin-orbital scattering” (Contributed)
14:48 – 15:05	**Tim Botzem**, RWTH Aachen “Quadrupolar and anisotropy effects on dephasing in two-electron spin qubits in GaAs” (Contributed)
15:05 – 15:40	**Akira Oiwa**, Osaka University “Photon-electron spin coupling using gate-defined GaAs double quantum dots”
15:40 – 16:15	**Nitin Samarth**, Penn State University “Topological spintronics”
16:15 – 16:45	*Coffee Break*
16:45 – 17:02	**Andrew Yeats**, University of Chicago & UCSB “Persistent optical gating of a topological insulator” (Contributed)
17:03 – 17:20	**Guanglei Cheng**, University of Pittsburgh “Correlated nanoelectronics at $LaAlO_3/SrTiO_3$ interface” (Contributed)

… next page …

17:20 – 17:55	**Mircea Trif**, Université Paris Sud “Cavity quantum electrodynamics with mesoscopic topological superconductors”
17:55 – 18:05	*Short Break*
18:05 – 18:22	**Makoto Kohda**, Tohoku University “Spin-orbit induced electrical spin generation and detection in InGaAs quantum point contacts” (Contributed)
18:23 – 18:40	**Thomas Schäpers**, Research Center Jülich “Spin-transport in InAs nanowire quantum point contacts” (Contributed)
18:40 – 18:57	**Ramon Aguado**, CSIC, Madrid “Subgap spectrum of normal-superconductor nanowire junctions: helical regime and Majorana bound states from exceptional points” (Contributed)
18:58 – 19:15	**Andreas Baumgartner**, University of Basel “Giga-Hertz quantized charge pumping in bottom gate defined InAs nanowire quantum dots” (Contributed)

LECTURES
&
TALKS

Quantum control of single spins in diamond and silicon carbide

F.J. Heremans, C.G. Yale, D.J. Christle, A.L. Falk, P.V. Klimov, and D.D. Awschalom

Institute for Molecular Engineering, University of Chicago, Chicago, IL 60637 USA

Individual defects in diamond and other semiconductors have attracted interest as they possess an electronic spin state that can be employed as a solid state quantum bit at and above room temperature. The nitrogen-vacancy (NV) center in diamond is an optically addressable, solid-state spin that has enabled gigahertz coherent control, nanofabricated spin arrays, nuclear quantum memories, and nanometer-scale sensing for emerging applications in science and technology. We present an all-optical pump-probe technique to independently study the orbital and spin dynamics of a single NV center [1]. Using ultrafast optical pulses, we investigate the coherent orbital dynamics of the NV center excited state that occur on nanosecond to femtosecond timescales. We are able to demonstrate sub-nanosecond spin rotations, rotations about an arbitrary-axis, and controlled unitary evolution within the full spin-triplet manifold. These techniques also provide a time-domain probe to investigate Hamiltonian dynamics as well as a pathway toward integrating solid-state spin qubits with photonic networks.

Recent advances have also established silicon carbide as a promising host for a novel class of quantum technologies based on color center spins [2], with the potential for leveraging existing device platforms alongside solid-state quantum control. The family of divacancies stands out in particular because they are in many ways analogous to nitrogen-vacancy centers in diamond. These color centers emit near the optical telecom bands and have ground-state spin triplets that can be optically polarized, manipulated with microwaves, and have long spin coherence times that persist up to room temperature [3, 4]. We will present recent advances in this rapidly developing field including electrically driven spin resonance [5], coherent spin-strain coupling [6], the incorporation of silicon carbide defects into photonic crystal cavities, as well as the identification and manipulation of single spins [7]. In particular, the addressability of single spins in a material amenable to advanced growth and microfabrication techniques is an exciting route to technologies such as quantum repeaters, nuclear gyroscopes, and precision sensors inside of cells. This work is supported in part by the AFOSR and the NSF.

[1] L. C. Bassett*, F. J. Heremans*, et. al., Science **345**, 1333 (2014)
[2] J. R. Weber, W. F. Koehl, J. B. Varley, A. Janotti, B. B. Buckley, C. G. Van de Walle, and D. D. Awschalom. Proc. Natl. Acad. Sci. **107**, 8513 (2010)
[3] W. F. Koehl, B. B. Buckley, F. J. Heremans, G. Calusine, and D. D. Awschalom, Nature **479**, 84 (2011).
[4] A. L. Falk, B. B. Buckley, G. Calusine, W. F. Koehl, V. V. Dobrovitski, A. Politi, C. A. Zorman, P. X.-L. Feng, and D. D. Awschalom, Nature Comm. **4**, 1819 (2013)
[5] P.V. Klimov, A. L. Falk, B. B. Buckley, and D. D. Awschalom, Phys. Rev. Lett. **112**, 087601 (2014).
[6] A. L. Falk, P. V. Klimov, B. B. Buckley, V. Ivády, I. A. Abrikosov, G. Calusine, W. F. Koehl, Á. Gali, and D. D. Awschalom, Phys. Rev. Lett. **112**, 187601 (2014).
[7] D. J. Christle, A. L. Falk, P. Andrich, P. V. Klimov, J. Hassan, N. T. Son, E. Janzén, T. Ohshima, and D. D. Awschalom, Nature Materials **14**, 160 (2015).

Multiple spin qubits with improved gate fidelity

Seigo Tarucha
Graduate School of Engineering, The University of Tokyo
Riken Center for Emergent Matter Science

To date various techniques of implementing spin qubits have been developed with quantum dots including spin-1/2, singlet-triplet and exchange-only qubits. We have used a micro-magnet technique to make two spin-1/2 qubits and an entangling gate with GaAs-based double quantum dots (QDs). The necessary step for further scaling up the qubit system is to increase the number of QDs with a well-controlled charge state to prepare working qubits and improve the fidelity of the qubit gates as well.

I will first review spin-1/2 qubit gates with triple QDs including the charge state control, operation of three qubits, entangling gate and SWAP with accessible three spins. In addition I discuss a way to improve the gate fidelity with noise correlation dynamics taken into account. I show that by significantly decreasing the total data acquisition time, the coherence time of the spin qubit in a conventional GaAs architecture is enhanced by more than an order of magnitude, up to μsec, without any artificial manipulation of the nuclear spins. Secondly I explain necessary techniques to further increase the number of qubits with quadruple and quintuple QDs including detection and control of charge stability diagrams and qubit gates.

Spin and Valley Dynamics in MoS_2, $MoSe_2$ and WSe_2 monolayers

G. Wang[1], L. Bouet[1] , D. Lagarde[1], M. Glazov[2], A. Balocchi[1], T. Amand[1], B.L. Liu[3], B. Urbaszek[1] and X. Marie[1]

[1]*Université de Toulouse, INSA-CNRS-UPS, LPCNO, 135 Avenue de Rangueil,31077 Toulouse, France*

[2] *Ioffe Physical-Technical Institute of the RAS, 194021 St. Petersburg, Russia*

[3]*Institute of Physics, Chinese Academy of Sciences, P.O. Box 603, Beijing 100190, China*

The spectacular progress in controlling the electronic properties of graphene has triggered research in alternative atomically thin two-dimensional crystals. Monolayers (ML) of transition-metal dichalcogenides such as MoS_2 have emerged as very promising nanostructures for optical and electronic applications for mainly two reasons. First, the indirect bulk semiconductor MoS_2 becomes direct when thinned to 1ML, resulting in efficient optical absorption and emission. Second, inversion symmetry breaking (usually absent in graphene) together with the large spin-orbit interaction leads to a coupling of carrier spin and k-space valley physics, i.e., the circular polarization (σ+ or σ−) of the absorbed or emitted photon can be directly associated with selective carrier excitation in one of the two nonequivalent K valleys (K+ or K−, respectively).

We have investigated the optical and valley properties for both neutral and charged excitons in transition metal dichalcogenide monolayer MoS_2, $MoSe_2$ and WSe_2 with polarized photoluminescence spectroscopy [1,2,3]. The excitation energy dependence of both circular and linear polarization of excitons following one photon excitation will be discussed. Moreover we show that optical alignment of excitons (“exciton valley coherence”) can be achieved following two photon excitation.

The neutral and charged exciton spin/valley dynamics have been measured by time-resolved photoluminescence and pump-probe Kerr rotation dynamics [4,5]. The neutral exciton valley polarization decays within about 6 ps, as a result of strong electron-hole Coulomb exchange interaction in bright excitons. The temperature dependence is well explained by the developed theory, taking into account the long-range exchange interaction [6]. In contrast the valley polarization decay time for the charged exciton is much longer (~1ns) [7].

Finally recent results on magneto-photoluminescence spectroscopy on $MoSe_2$ and WSe_2 in Faraday configuration up to 9 T will be presented. Remarkably, we observe a reversal of the sign of the trion polarization between WSe_2 and $MoSe_2$. The extracted g-factors for both exciton complexes in both materials are of the order of g~4 ; these values will be discussed in the framework of a k.p theory [8].

[1] G. Sallen *et al*, PRB **86**, 081301(R) (2012)
[2] G. Wang et al, APL **106**, 112101 (2015)
[3] G. Wang *et al*, PRL **114**, 97403 (2015)
[4] D. Lagarde *et al*, PRL **112**, 047401 (2014)
[5] C.R. Zhu *et al*, PRB **90**, 161302(R) (2014)
[6] M. Glazov *et al*, PRB **89**, 201302(R) (2014)
[7] G. Wang *et al*, PRB **90**, 075413 (2014)
[8] G. Wang *et al*, 2D Semiconductors (2015, in press)

Quantum anomalous Hall effect in Magnetic Topological Insulator

Qi-Kun Xue
Department of Physics, Tsinghua University, Beijing 100084, China

Anomalous Hall effect (AHE) in magnetic materials was discovered by Edwin Hall in 1880. Since the late 1980's, theories have been proposed for realizing quantized version of AHE, quantum anomalous Hall (QAH) effect. By breaking time-reversal-symmetry with magnetic doping of Cr into three dimensional topological insulator $(Bi,Sb)_2Te_3$ thin films grown by molecular beam epitaxy, we have experimentally demonstrated the QAH effect at 30 mK. At zero magnetic field, the gate-tuned anomalous Hall resistance exhibits a quantized value of h/e^2 accompanied by a significant drop of the longitudinal resistance. The realization of the QAH effect paves a way for exploring exotic quantum phenomena in condensed matter and for developing lower-power-consumption electronics.

Engineering Topological Quantum States: From 1D to 2D

Jelena Klinovaja
Department of Physics, University of Basel, Klingelbergstrasse 82, Basel, CH-4056 Basel, Switzerland

I will present results on exotic bound states in one-dimensional (Majorana fermions and parafermions) and two-dimensional (edge states in topological insulators) condensed matter systems that have attracted wide attention due to their promise of non-Abelian statistics believed to be useful for topological quantum computing. I discuss systems in which topological properties could be engineered per demand. For example, Majorana fermions can emerge in hybrid systems with proximity pairing in which the usually weak Rashba spin-orbit interaction is replaced by magnetic textures. Here, I will discuss candidate materials such as semiconducting nanowires [1-2], graphene nanoribbons [3], atomic magnetic chains or magnetic semiconductors [4]. One further goal is to go beyond Majorana fermions and to identify systems that can host quasiparticles with more powerful non-Abelian statistics such as parafermions in double wires coupled by crossed Andreev reflections [5,6]. In the second part of my talk, I will focus on 'strip of stripes model' consisting of weakly coupled one-dimensional wires [6-8], where interaction effects in the wires can be treated non-perturbatively via bosonization. I will demonstrate that such systems can exhibit the integer or fractional quantum Hall effect [6], spin Hall effect [7], and anomalous Hall effect [8]. In the fractional regimes, the quasiparticles have fractional charges and non-trivial Abelian braid statistics.

[1] J. Klinovaja and D. Loss, Phys. Rev. B 86, 085408 (2012).
[2] D. Rainis, L. Trifunovic, J. Klinovaja, and D. Loss, Phys. Rev. B 87, 024515 (2013).
[3] J. Klinovaja and D. Loss, Phys. Rev. X 3, 011008 (2013); J. Klinovaja and D. Loss, Phys. Rev. B 88, 075404 (2013).
[4] J. Klinovaja, P. Stano, A. Yazdani, and D. Loss, Phys. Rev. Lett. 111, 186805 (2013).
[5] J. Klinovaja and D. Loss, Phys. Rev. B 90, 045118 (2014).
[6] J. Klinovaja, A. Yacoby, and D. Loss, Phys. Rev. B 90, 155447 (2014).
[7] J. Klinovaja and D. Loss, Phys. Rev. Lett. 111, 196401 (2013); J. Klinovaja and D. Loss, Eur. Phys. J. B 87, 171 (2014).
[8] J. Klinovaja and Y. Tserkovnyak, Phys. Rev. B 90, 115426 (2014).
[9] J. Klinovaja, Y. Tserkovnyak, and D. Loss, Phys. Rev. B 91, 085426 (2015).

Quantum magnonics with a macroscopic ferromagnetic sphere

Yasunobu Nakamura[1,2]

[1] Research Center for Advanced Science and Technology (RCAST), The University of Tokyo
4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
[2] Center for Emergent Matter Science (CEMS), RIKEN
2-1 Hirosawa, Wako, Saitama 351-0198, Japan
Email: yasunobu@ap.t.u-tokyo.ac.jp

We have investigated coherent properties of the spin system in a millimeter-scale ferromagnetic crystal. A magnon is a quantum of the collective spin excitations in such an ordered spin system. By using a circuit quantum electrodynamics approach, we develop a hybrid quantum system in which we can control and measure the quantum state of magnon excitations with a superconducting qubit.

We use a single-crystalline sphere of yttrium iron garnet (YIG) as a ferromagnet. It contains approximately 10^{18} electron spins ordered and aligned to an external magnetic field. One of the fundamental excitation modes is the uniform precession of the whole spins. The eigenfrequency is ~10 GHz under a static magnetic field of ~0.3 T. We control the excitation of a magnon in the mode in the quantum regime.

The sphere is embedded in a microwave cavity and cooled down to 10 mK. At the low temperature, the thermal excitations of the magnon and the microwave photon in the cavity are negligible. In the microwave spectroscopy, we observe magnon-polariton modes manifesting coherent coupling of the magnon and photon modes [1].

We also put a superconducting transmon qubit in the microwave cavity to introduce nonlinearity into the hybrid system. The cavity mode, now detuned from the magnon and the qubit frequencies, mediates the interaction between them via its virtual excitations. We observe a Rabi splitting of the qubit spectrum induced by the magnon vacuum [2]. In the time domain, pulsed microwave excitation allows us to control the magnon states via the corresponding Rabi oscillations.

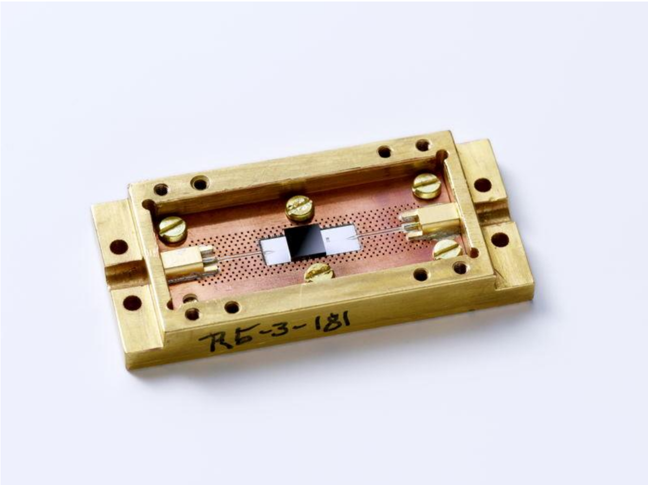
The results show that the macroscopic sphere of a ferromagnet can sustain a single coherent magnon and that we can manipulate its quantum state via superconducting circuits. Such hybrid quantum systems may open a path toward a quantum interface of superconducting qubits to other quantum degrees of freedom, e.g., via an interaction of the spins with light.

[1] Y. Tabuchi, S. Ishino, T. Ishikawa, R. Yamazaki, K. Usami, and Y. Nakamura, Phys. Rev. Lett. **113**, 083603 (2014).
[2] Y. Tabuchi, S. Ishino, T. Ishikawa, A. Noguchi, R. Yamazaki, K. Usami, and Y. Nakamura, arXiv:1410.3781.

Hybrid Quantum Systems
Coupling Color Centers to Superconducting Cavities

Johannes Majer
Vienna Center for Quantum Science and Technology, Atominstitut, Vienna University of Technology, Stadionallee 2, 1020 Vienna, Austria

Hybrid quantum systems based on spin-ensembles coupled to superconducting microwave cavities are promising candidates for robust experiments in cavity quantum electrodynamics (QED) and for future technologies employing quantum mechanical effects [1].



The main source of decoherence in this systems is inhomogeneous dipolar spin broadening and a full understanding of the complex dynamics is essential and has not been addressed in recent studies yet. We investigate the influence of a non-Lorentzian spectral spin distribution [2] in the strong coupling regime of cavity QED. We show for the first time experimentally how the so-called cavity protection effect influences the decay rate of coherent Rabi oscillation by varying the coupling strength in our experiment [3]. We then demonstrate how the Rabi oscillation amplitude can be enhanced by two orders of magnitude by pulsing the strongly coupled system matching a special resonance condition. Giving a way improving the coherent manipulation of the spin polarization helping to improve fidelity and performance in hybrid quantum systems.

[1] R. Amsüss, Ch. Koller, T. Nöbauer, S. Putz, S. Rotter, K. Sandner, S. Schneider, M. Schramböck, G. Steinhauser, H. Ritsch, J. Schmiedmayer, and J. Majer, *Cavity QED with Magnetically Coupled Collective Spin States*, Phys. Rev. Lett. **107**, 060502 (2011)
[2] K. Sandner, H. Ritsch, R. Amsüss, Ch. Koller, T. Nöbauer, S. Putz, J. Schmiedmayer, and J. Majer, *Strong magnetic coupling of an inhomogeneous nitrogen-vacancy ensemble to a cavity*, Phys. Rev. A **85**, 053806 (2012)
[3] S. Putz, D. O. Krimer, R. Amsuss, A. Valookaran, T. Nöbauer, J. Schmiedmayer, S. Rotter, and J. Majer, *Protecting a spin ensemble against decoherence in the strong-coupling regime of cavity QED*, Nat Phys **10**, 720-724 (2014)

Transport and induced superconductivity in the topological surface and edge states of HgTe

Christoph Brüne
Experimentelle Physik 3, Physikalisches Institut Universität Würzburg

Bulk HgTe is a semimetal with an inverted bandstructure in which the Gamma_8 band is located above the Gamma_6 band. To observe topological insulator behavior in HgTe a band gap has to be opened. This can be achieved by either applying tensile strain to a bulk HgTe layer [1] or by growing HgTe quantum well structures above the critical thickness [2]. The former, strained bulk HgTe, is a 3-dimensional topological insulator [3] while the latter is a 2 dimensional topological insulator [4].

This talk will focus on the transport properties of the topological surface and edge states in HgTe. We report on transport signatures related to the Dirac nature of these states. Furthermore the properties of induced superconductivity in the edge/surface states are investigated.

[1] L. Fu and C. Kane, Physical Review B **76**, 045302, (2007).
[2] Bernevig et al., Science **314**, 1757-1761, (2006).
[3] C. Brüne et al., Physical Review Letters **106**, 126803 (2011).
[4] M. König et al., Science **318**, 766-770 (2007).

Noise Suppression and Filtering in Spin Qubits

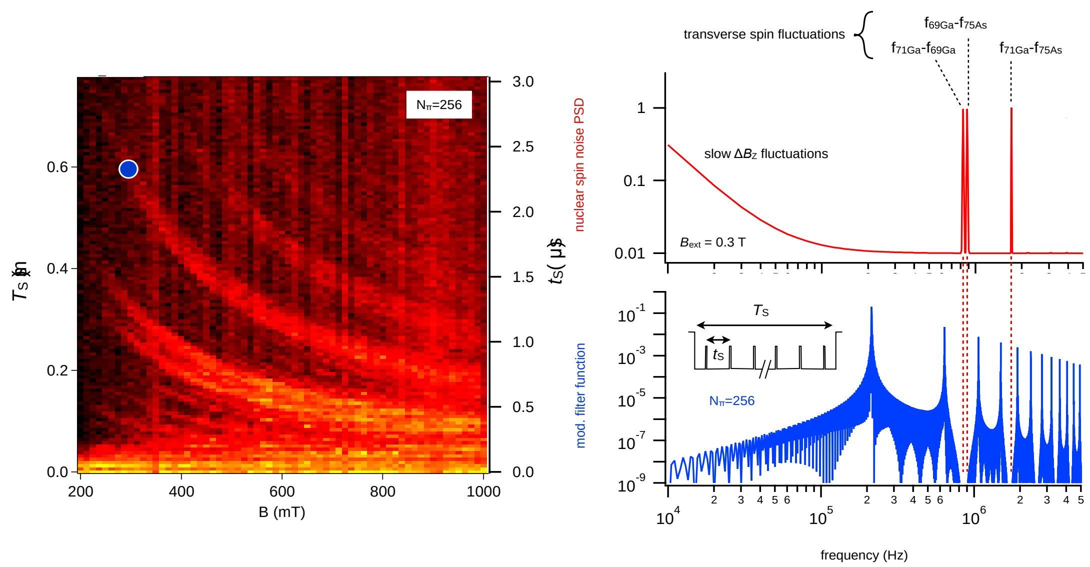
Frederico Martins[1], Filip K. Malinowski[1], Peter D. Nissen[1], Edwin Barnes[2], Mark S. Rudner[1]
Michael J. Manfra[3], Charles M. Marcus[1], Ferdinand Kuemmeth[1]
[1]*Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, Copenhagen Denmark*
[2]*Department of Physics, University of Maryland, College Park, MD 20742, USA*
[3]*Department of Physics, Purdue University, Purdue University, West Lafayette IN 47907, USA*

This talk presents recent results on how to mitigate electrical and hyperfine noise in a GaAs double quantum dot spin qubit. Exchange pulses can be realized by tilting the double well potential, the conventional method, or by symmetrically lowering the barrier, as originally suggested by Loss and DiVincenzo. The two methods are compared here. We find that lowering the barrier between dots has much less relative exchange noise compared to potential tilt. This yields significantly enhanced free induction decay times for barrier control compared to tilt control.

We then investigate nuclear noise, and show that appropriate CPMG pulse trains can filter not only low frequency noise but also narrow-band nuclear noise at the Larmor difference frequencies of the three nuclear species. This is illustrated in the figure below.

Optimizing these methods we show a T2 coherence times up to 870 microseconds.

Research is supported by IARPA MQCO Program, Army Research Office, Danish National Research Foundation, and the Villum Foundation.



Spin and orbital magnetic response on the surface of a topological insulator

Yaroslav Tserkovnyak

Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA

Coupling of the spin and orbital degrees of freedom on the surface of a strong three-dimensional insulator, on the one hand, and textured magnetic configuration in an adjacent ferromagnetic film, on the other, is discussed using a combination of transport and thermodynamic considerations. Expressing exchange coupling between the localized magnetic moments and Dirac electrons in terms of the electrons′ out-of-plane orbital and spin magnetizations, we relate the thermodynamic properties of a general ferromagnetic spin texture to the physics in the zeroth Landau level. Persistent currents carried by Dirac electrons endow the magnetic texture with a Dzyaloshinski-Moriya interaction, which exhibits a universal scaling form as a function of electron temperature, chemical potential, and the time-reversal symmetry breaking gap. In addition, the orbital motion of electrons establishes a direct magnetoelectric coupling between the unscreened electric field and local magnetic order, which furnishes complex long-ranged interactions within the magnetic film.

Spin Relaxation in GaAs Spin Qubits

D. M. Zumbühl[1], L. C. Camenzind,[1] L. Yu,[1] D. E. F. Biesinger,[1]
J. Zimmerman,[2] A. C. Gossard,[2]

[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2]*Materials Department, University of California, Santa Barbara, CA93106, USA*

Spins in quantum dots are promising candidates for the realization of qubits – the elementary units of a quantum computer – and hold the potential for scaling to a large number of qubits. Enormous computational power arises from quantum superposition and entanglement in a sequence of quantum gates – but only if the qubits remain coherent during these operations. Great progress in dynamical decoupling from nuclear spin noise has lead to spin coherence times approaching the millisecond range. To further improve coherence, it is becoming important to also understand and suppress spin relaxation, since relaxation – characterized by the T1 time – sets a fundamental limitation to coherence. In a magnetic field, relaxation occurs predominantly through spin-phonon coupling mediated by the spin-orbit interaction [1]. Since spin-orbit coupling is weak e.g. in GaAs or Si, very long T1 times exceeding 1 s have been measured [2].

In this talk, I present the experimental observation of a thermal electron exchange process via the reservoirs of a GaAs quantum dot [3], setting an intrinsic upper bound to T1 which can be orders of magnitude lower than the spin-phonon limit. The resulting metastable charge states – appearing in the double dot (DD) in absence of interdot tunneling – make the exchange process detectable with a charge sensor. Within a diamond shaped region, the DD switches its charge-state back and forth over time from an electron on the left dot to an electron on the right dot without direct interdot tunneling. After excluding unintentional charge traps and sensor back action, we present an extension of the orthodox DD transport theory accounting very well for the observations. The exchange process can be used for fast qubit initialization. Further, we outline ways to extend T1 up to the spin-phonon limit.

Further, I present measurements of the spin relaxation rate in a single-electron GaAs quantum dot as a function of the angle ϕ of the applied magnetic field $B_{\|}$ in the plane of the 2D electron gas. The spin relaxation rate W exhibits a sinusoidal dependence with a period of 180°, as similarly reported recently [4], and changes by a factor of about 20 from minimum to maximum. For the orientation with maximal spin relaxation times, T_1 reaches ~5 s at B = 1 T, extending the previous record [2] by a factor of five. Upon increasing the field to 12 T, the T_1 time is reduced by approximately five orders of magnitude, close to the expected B^5 dependence [1]. Taking into account the measured orbital excited-state energies, we obtain very good agreement with theory also for the angle dependence $W(\phi)$, indicating that Rashba and Dresselhaus SO strengths have the same relative sign and are within ~20% of each other.

In the future, we intend to manipulate the dot orbitals with gate voltages, implement electrical control of the Rashba SO interaction using top- and back gates [5], and also investigate the B-field angle dependence of the spin tunnelling asymmetry. Finally, we plan to study alternate spin relaxation mechanisms, e.g. 2-phonon processes in double dots.

[1] V.N.Golovach, A. Khaetskii, and D. Loss, Phys. Rev. Lett. **93**, 016601 (2004).
[2] S. Amasha, K. MacLean, I. Radu, D. M. Zumbuhl, M. A. Kastner, M. P. Hanson, and A. C. Gossard, Phys. Rev. Lett. **100**, 046803 (2008).
[3] D. E. F. Biesinger, C. P. Scheller, B. Braunecker, J. Zimmerman, A. C. Gossard, and D. M. Zumbuhl, arXiv:1505.03195 (2015).
[4] P. Scarlino, E. Kawakami, P. Stano, M. Shafiei, C. Reichl, W. Wegscheider, and L. M. K. Vandersypen, Phys. Rev. Lett. **113**, 256802 (2014).
[5] F. Dettwiler, J. Fu, S. Mack, P. J. Weigele, J. C. Egues, D. D. Awschalom, and D. M. Zumbuhl, arXiv:1403.3518 (2014).

Helical order in one dimensional semiconductors

Peter Stano[1,2]
[1]RIKEN Center for Emergent Matter Science, Wako-shi, Saitama 351-0198, Japan
[2]Institute of Physics, Slovak Academy of Sciences, 845 11 Bratislava, Slovakia

I will talk about a helical spin order arising in thermodynamical equilibrium in a one-dimensional conductor with localized spins (e.g., nuclear spins, or spins of magnetic impurities) [1]. The order is a consequence of the dimensionality, originating in a resonance peak of spin susceptibility [2], and is thus very general, arising in metals, semiconductors, and even gapped phases, such as superconductors [3]. An interesting locally antiferromagnetic variant is expected to occur in carbon nanotubes [4]. I will mention recent low temperature transport experiments with semiconducting GaAs wires which suggest that such helical order was established in nuclear spins of atoms of the wire [5]. I will introduce further detection methods, based on the peculiar response of this order expected in transport [6] and NMR [7] experiments. Finally, I will explain how such a helical order can be useful in the semi-super hybrid platform to stabilize Majorana fermions and to produce even more exotic many body excitations like fractionally charged fermions [8].

[1] B. Braunecker, P. Simon, and D. Loss, Phys. Rev. B 80, 165119 (2009).
[2] P. Stano, J. Klinovaja, A. Yacoby, and D. Loss, Phys. Rev. B 88, 045441 (2013).
[3] J. Klinovaja, P. Stano, A. Yazdani, and D. Loss, Phys. Rev. Lett. 111, 186805 (2013).
[4] Ch.-H. Hsu, P. Stano, and D. Loss, unpublished.
[5] C. P. Scheller, T.-M. Liu, G. Barak, A. Yacoby, L. N. Pfei_er, K. W. West, and D. M. Zumbueuhl, Phys. Rev. Lett. 112, 066801 (2014).
[6] V. Kornich, P. Stano, A. A. Zyuzin, and D. Loss, arxiv:1503.06950.
[7] P. Stano, and D. Loss, Phys. Rev. B 90, 195312 (2014).
[8] J. Klinovaja, P. Stano, and D. Loss, Phys. Rev. Lett. 109, 236801 (2012).

Non-local transport via edge-states in InAs/GaSb coupled quantum wells

Klaus Ensslin
ETH Zürich, Switzerland

This talk focuses experimental results on InAs/GaSb coupled quantum wells, a system which promises to be electrically tunable from a normal to a topological insulator. Hall bar structures of dimensions between 100 nm and a few micrometers gradually develop a pronounced resistance plateau near the charge neutrality point when reducing the device dimension, which comes along with distinct signatures of non-local transport along the sample edges. Plateau resistances are found to be above or below the quantized value expected for helical edge channels depending on device size. We present a discussion of these results based on the interplay between imperfect quantized edge conduction and a residual local bulk conductivity which suggests that occasionally reaching approximately the quantized edge-resistance in some devices may be an accidental coincidence.

This work was done in collaboration with Susanne Mueller, Atindra Pal, Matija Karalic, Thomas Ihn ,Thomas Tschirky, Christoph Charpentier, and Werner Wegscheider

Quantum transport in van der Waals heterostructures

Pablo Jarillo-Herrero
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Over the past decade, the physics of low dimensional electronic systems has been revolutionized by the discovery of materials with very unusual electronic properties where the behavior of the electrons is governed by the Dirac equation. Among these, graphene has taken center stage due to its ultrarelativistic-like electron dynamics and its potential applications in nanotechnology. Moreover, recent advances in the design and nanofabrication of heterostructures based on van der Waals materials have enabled a new generation of quantum electronic transport experiments in graphene. In this talk I will describe our recent experiments exploring electron-electron interaction driven quantum phenomena in ultra-high quality graphene-based van der Waals heterostructures. In particular I will show two novel realizations of a symmetry-protected topological insulator state, specifically a quantum spin Hall state, characterized by an insulating bulk and conducting counterpropagating spin-polarized states at the system edges. Our experiments establish graphene-based heterostructures as highly tunable systems to study topological properties of condensed matter systems in the regime of strong e-e interactions and I will end my talk with an outlook of some of the exciting directions in the field.

Spin-current emission governed by nonlinear spin dynamics

Kazuya Ando
Department of Applied Physics and Physico-Informatics, Keio University, Yokohama 223-8522, Japan

The collective excitation of localized spins coupled by the magnetic dipole and quantum exchange interactions is called spin waves or, in quantized form, magnons. This quasiparticle, associated with the elementary magnetic excitation, is responsible for a flow of spin angular momentum, a spin current, in magnetic insulators. The spin-carrier can be converted from magnons to conduction electrons at magnetic/nonmagnetic interfaces through dynamical spin exchange coupling between magnetization and conduction electron spins. This spin-carrier conversion enables dynamical generation of spin currents from magnetic insulators, enabling to explore the physics of spin current in condensed matter [1-3].

When a magnon is created in a magnet, this quasiparticle can split into two magnons, which triggers an angular momentum flow from the lattice to the spin subsystem. Recently it has been demonstrated that the dynamical spin-current generation is enhanced in the presence of magnon splitting [4]. However, the role of magnon interactions in the spin-current emission is still not well understood. Here, we show that the enhanced spin-current emission is enabled by spin-damping tuning triggered by the redistribution of magnons [5]. Our direct measurements of the spin damping demonstrate that the stabilized enhancement of the spin-current emission is enabled by the long lifetime of the dipole-exchange secondary magnons created at the inflection point of the dispersion curve, where the negative dipolar dispersion is compensated by the positive exchange dispersion. We demonstrate, furthermore, that the spin-current emission can be enhanced even in the absence of the magnon splitting; we found enhanced spin-current emission triggered by scattering processes that conserve the number of magnons. These findings demonstrate the crucial role of magnon lifetimes in spintronic devices, opening a way for controlling nonlinear spin-current emission through spin-damping tuning.

[1] K. Ando, S. Takahash, J. Ieda, H. Kurebayashi, T. Trypiniotis, C. H. W. Barnes, S. Maekawa, and E. Saitoh, Nature Materials **10**, 655 (2011).
[2] K. Ando, S. Watanabe, S. Mooser, E. Saitoh, and H. Sirringhaus, Nature Materials **12**, 622 (2013).
[3] S. Watanabe, K. Ando, K. Kang, S. Mooser, Y. Vaynzof, H. Kurebayashi, E. Saitoh, and H. Sirringhaus, Nature Physics **10**, 308 (2014).
[4] H. Kurebayashi, O. Dzyapko, V. E. Demidov, D. Fang, A. J. Ferguson, and S. O. Demokritov, Nature Materials **10**, 660 (2011).
[5] H. Sakimura, T. Tashiro, and K. Ando, Nature Communications **5**, 5730 (2014).

Experimental progress on Majoranas in semiconductor nanowires

Önder Gül

QuTech and Kavli Institute of Nanoscience, Delft University of Technology, The Netherlands

Majoranas in semiconductor nanowires can be probed via various electrical measurements. For example, tunnel spectroscopy reveals zero-bias peaks in the differential conductance. These zero-bias peaks have a particular dependence on magnetic field (magnitude and direction) and electron density. This dependence allows us to rule out various alternative theories for these observations. However, a direct demonstration of topological protection requires fixing the quasiparticle occupation in the system, the so-called parity conservation. We have demonstrated that the parity in a superconducting island can be stable over a minute timescale [1]. To achieve parity conservation for Majoranas, an essential prerequisite is a low density of quasiparticle states in the induced superconducting energy gap of a semiconductor nanowire. However, obtaining such hard induced gaps under Majorana conditions presents an outstanding challenge. We report on our progress in optimizing materials towards this goal.

The work is done in collaboration with the group of L.P. Kouwenhoven.

[1] van Woerkom, D. J. *et al. Nature Phys.* **11** (2015).

Theory of box-model hyperfine couplings and transport signatures of long-range nuclear-spin coherence in a quantum-dot spin valve

Stefano Chesi[1] and W. A. Coish[2,3]
[1]*Beijing Computational Science Research Center, Beijing 100084, China*
[2]*Department of Physics, McGill University, Montreal, Quebec H3A 2T8, Canada*
[3]*Quantum Information Science Program, CIFAR, Toronto, Ontario M5G 1Z8, Canada*

We have theoretically analyzed a quantum-dot spin valve in which coherent nuclear-spin dynamics is induced by charge transport of spin-polarized electron carriers, in combination with the hyperfine interaction in the quantum dot [1].

We first describe the spin-polarized nuclear state established in the long-time limit and then analyze the transient regime induced by reversing the voltage bias, which drives a reversal of nuclear polarization. Using a simple approach based on the Fermi Golden Rule, as well as a more general master equation, we show that long-range nuclear-spin coherence is established during the time evolution and leads to a strong enhancement of spin-flip transition rates (by an amount proportional to the number of nuclear spins). Through this mechanism, nuclear spin coherence is revealed by a short intense current burst, analogous to superradiant light emission. By including a local nuclear dephasing mechanism, we also describe the opposite regime of fully incoherent nuclear-spin dynamics, analogous to spontaneous light emission. The time scale characterizing the crossover to such incoherent evolution is on the order of the single-nuclear spin dephasing time, thus can be much longer than the time scale for the superradiant-like current burst.

Throughout this work we assume uniform hyperfine couplings, which yield the strongest coherent enhancement. We propose realistic strategies, based on isotopic modulation and wavefunction engineering in core-shell nanowires, to realize this analytically solvable “box-model” of hyperfine couplings [1].

[1] S. Chesi and W. A. Coish, arXiv:1503.03645 (2015).

Model for the light-induced magnetization in singly charged quantum dots

A. B. Henriques[1] and R. C. Cordeiro[1] and P. M. Koenraad[2]

[1] *Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*

[2] *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands*

Understanding the dynamics of spin orientation in charged quantum dots using light pulses is indispensable for their application in opto-spintronics and quantum information processing. In this contribution we investigate light-controlled spin dynamics in an ensemble of quantum dots each containing a single resident electron. We present a model that describes the time evolution of the magnetization, initiated by photons that selectively generate trions in which the electrons are either coupled into a singlet or triplet state.

Before photon arrival, the resident electron spins in the dots are uncorrelated, thus the net spin average is zero. However, circularly polarized photons resonant with the fundamental quantum dot energy gap can induce a magnetization [1]. Recently [2], we have shown that the time-dependent magnetic state of a single dot and of the ensemble can be obtained exactly, by resolving the time-dependent Schrödinger equation for the light-carrier interaction. The theory produces the amplitude and phase of the Larmor precession of the magnetization, which is found to be in excellent agreement with our experimental observations.

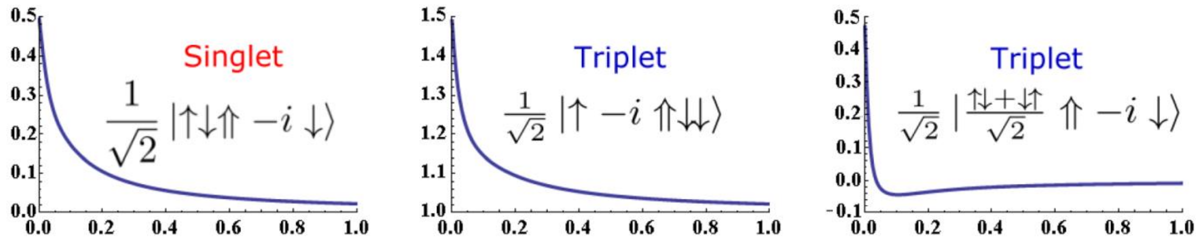


Fig. 1: Phase of the magnetization oscillations for all excitations as a function of B. The horizontal scale is the magnetic field in Teslas, applied in the [110] direction. The phase is given in units of π.

In Ref. [2], the excitation light was resonant with the fundamental energy gap of the QDs, whereby only singlet excitations are generated. In this work, we consider triplet excitations, generated when the excitation light is resonant with overtone QD states. In contrast to a singlet excitation, which is described a constant in time single-component spin wave function, the triplet excitation is described by a time-dependent three-component spin wave function, associated with a spin projection of +1, 0, or -1 along the magnetic field. Figure 1 shows our prediction of the magnetic field dependence of the phase of the magnetization oscillation after singlet and triplet allowed excitations, using right-hand circularly polarized photons. We shall present experimental results, obtained using the pump-and probe method, that support the predicted magnetic field dependence of the phase of the photoinduced magnetization precession as well as the phase difference between singlet and triplet excited magnetizations.

A.B.H. acknowledges financial support provided by CNPq (Projects 401694/2012-7 and 304685/2010-0), FAPESP (Project 2012/23406-0), and Laboratório de Microfabricação (LMF)/Laboratório Nacional de Nanotecnologia (LNNano).

[1] A. Greilich, D. R. Yakovlev, A. Shabaev, Al. L. Efros, I. A. Yugova, R. Oulton, V. Stavarache, D. Reuter, A.Wieck, and M. Bayer, Science **313**, 341-345 (2006).

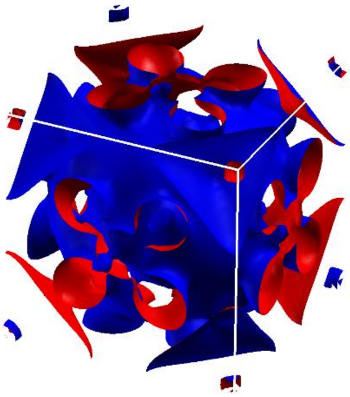
[2] A. B. Henriques, R. C. Cordeiro, P. M. Koenraad, F. W. M. Otten, M. Bayer, Phys. Rev. B (Rapid Communications), **91**, 081303 (2015).

Magnetotransport in Noncollinear Antiferromagnets Ir_xMn_{1-x}

Libor Šmejkal[1,2], Jakub Železný[1,2], Karel Carva[2], Ilja Turek[2,3] Tomáš Jungwirth[1,4]

[1]*Institute of Physics, ASCR, Cukrovarnická 10, CZ-16253 Praha 6, Czech Republic*
[2]*Department of Condensed Matter Physics, Charles University, Faculty of Mathematics and Physics, Ke Karlovu 5, CZ-12116 Prague 2, Czech Republic*
[3]*Institute of Physics of Materials, ASCR, Žižkova 22, CZ-616 62 Brno, Czech Republic*
[4]*School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom*

The magnetic structure of the thin films of IrMn has been probed experimentally quite recently.[1] These materials have a high Néel temperature (up to ~ 1000 K), are strongly spin-orbit coupled and can generate a large exchange-bias in adjacent ferromagnets, making them favorable as, e.g., pinning layers in spin valves. [2]



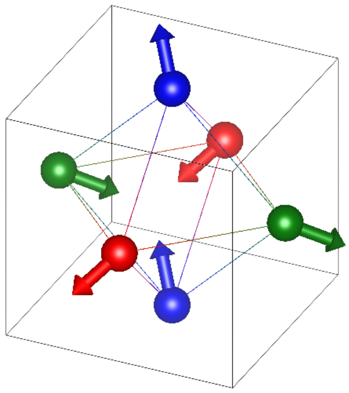


Figure 1 (a) Fermi surface of $IrMn_3$. (b) Magnetic structure of $IrMn_3$, manganese atoms are colored, iridium atoms located at the corners of the cube are not shown for the better reference.

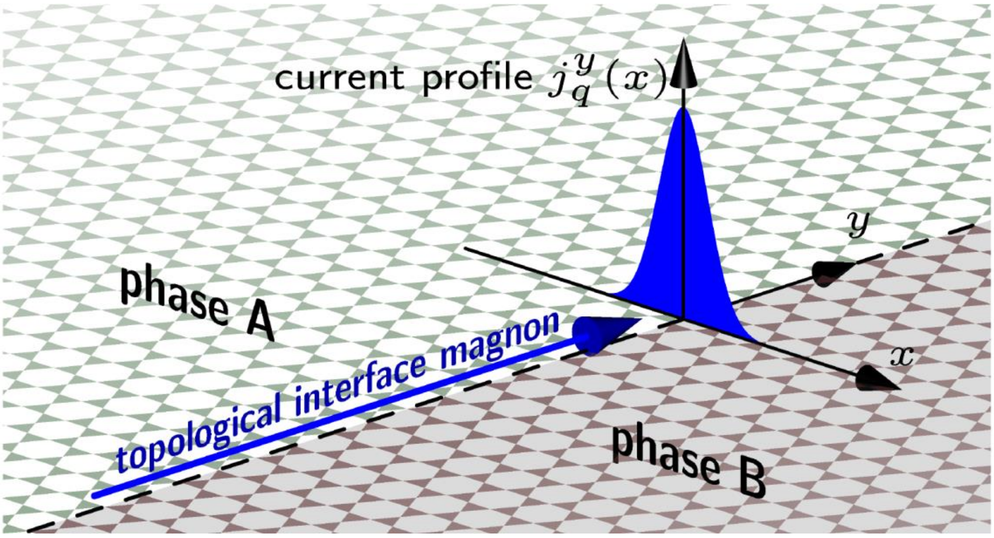
Very recently the current induces torques were measured in a variate of stacks comprising IrMn ultrathin layers.[3] This contribution will start with a brief discussion of general challenges in calculating antiferromagnets (AFM), e.g. complex Fermi surface in transition metals AFM on Fig.1(a). The rest will be focused on the understanding of $IrMn_3$ as a representative example of noncollinear AFM (Fig.(1b)). First we will present symmetry analysis and phenomenological predictions for the anisotropic magnetoresistance (AMR) and the anomalous Hall effect [4] in $IrMn_3$. This will be followed by fully relativistic first principles calculations of the AMR and of the AHE in the constant spectral broadening approximation, as well as, in the coherent potential approximation (CPA). We observe that the AMR is larger in $IrMn_3$ than in common collinear AFM. The AMR is mostly determined by spin-orbit coupling effects in the scattering captured by the CPA. A smaller AMR is obtained in the constant relaxation time approximation. The AHE is maximized in the clean limit and is suppressed by disorder in both the constant relaxation time approximation and the CPA.

[1] A. Kohn, A. Kovács, R. Fan, G. J. McIntyre, R. C. C. Ward, and J. P. Goff. The antiferromagnetic structures of $IrMn_3$ and their influence on exchange-bias. Scientific Reports, 3:2412, August 2013.
[2] L. Szunyogh, B. Lazarovits, L. Udvardi, J. Jackson, and U. Nowak. Giant magnetic anisotropy of the bulk antiferromagnets irmn and irmn 3 from first principles. Phys.Rev. B, 79:020403, Jan 2009.
[3] H. Reichlov8, D. Kriegner, V. Holý, K. Olejník, V. Novák, M. Yamada, K. Miura, S. Ogawa, H. Takahashi, T. Jungwirth, and J. Wunderlich. Current induced torques in structures with ultra-thin IrMn antiferromagnet. ArXiv e-prints, March 2015, also http://arxiv.org/abs/1502.04570 and references therein on spin torque studies in structures comprising IrMn
[4] Hua Chen, Qian Niu, and H. MacDonald, A.˙ Anomalous hall effect arising from noncollinear antiferromagnetism. Phys. Rev. Lett., 112:017205, Jan 2014.

Topological magnon states – a way to nano-scale magnon waveguides

Alexander Mook,[1] Jürgen Henk,[2] and Ingrid Mertig[1,2]
[1]*Max Planck Institute for Microstructure Physics, D-06120 Halle (Saale), Germany*
[2]*Institute of Physics, Martin Luther University Halle-Wittenberg, D-06099 Halle (Saale), Germany*

Topological magnon insulators exhibit a nontrivial topology due to the Dzyaloshinskii-Moriya interaction which opens up band gaps in the magnon dispersion relation; it causes a nonzero Berry curvature and nonzero Chern numbers. Obeying the bulk-boundary correspondence, topological magnon insulators host topologically nontrivial edge magnons and, consequently, energy as well as spin currents along their edges [1,2].



Bringing two topological magnon insulators into contact (*figure:* phase **A** and **B**) results in topologically protected unidirectional interface magnons (*figure:* blue arrow). As these interface modes decay toward both bulk regions, their currents are confined to a few nanometer wide strip around the interface (*figure:* blue current profile), which is considered a waveguide for magnons. Owing to the topological nature of the interface states, the interface currents follow any geometry.

We study theoretically interfaces of semi-infinite kagome ferromagnets in various topological phases, with a focus on the formation and the confinement of nontrivial interface magnons [3]. We analyze generic magnon dispersions with respect to the number of band gaps and the respective winding numbers. An investigation of the heat current profiles about the interface is followed by proposals of composing magnon waveguides with nano-scale confinement, one from topologically different phases, another from identical phases. On top of this, we identify material classes for the construction of these magnon waveguides.

[1] L. Zhang, J. Ren, J.-S. Wang, and B. Li, Phys. Rev. B **87**, 144101 (2013).
[2] A. Mook, J. Henk, and I. Mertig, Phys. Rev. B **89**, 134409 (2014).
[3] A. Mook, J. Henk, and I. Mertig, Phys. Rev. B, accepted (2015).

Probing and Controlling the Valley Degree of Freedom in Two-Dimensional Transition Metal Dichalcogenide Crystals

Tony F. Heinz
Department of Applied Physics, Stanford University, Stanford, CA 94305, USA and
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

The transition metal dichalcogenide (TMDC) crystals in the family of MoS_2, $MoSe_2$, WS_2, and WSe_2 are direct-gap semiconductors in the limit of monolayer thickness. Like graphene, these layered van-der-Waals materials are environmentally stable and can be prepared both by exfoliation and chemical synthesis. The electronic and optical properties of these 2D semiconductors have attracted much recent attention as a counterpart to the semi-metallic graphene system.

One of the intriguing properties of the monolayer TMDC materials lies in the existence of two degenerate, but quantum mechanically distinct valleys in momentum space: The K and K' (or –K) valleys that define their direct gap. Because of the broken inversion symmetry of the crystal, these states are characterized by different angular momentum. As we discuss, they can be selectively accessed by circularly polarized light of different handedness. Because of the spin-polarized nature of the valence bands, there is also an association between the creation of valley polarization and spin polarization in these materials.

In addition to reviewing our evolving understanding of the use of the helicity of light to access the valley degree of freedom optically, we will describe recent measurements in which the valley degeneracy is lifted by the application of a perpendicular magnetic field. Such tuning of the relative valley energy levels can be observed directly by optical spectroscopy. We will further discuss the creation of a static valley polarization in doped samples under a magnetic field. This effect can be identified by the spectroscopic signature of the emission from the charged exciton (trion) states.

BEC of magnons at room temperature and spatio-temporal properties of magnon condensate

S. O. Demokritov
Institute for Applied Physics, University of Münster, Germany

Magnons are the quanta of magnetic excitations in a magnetically ordered media. In thermal equilibrium, they can be considered as a gas of quasiparticles obeying the Bose-Einstein statistics with zero chemical potential and a temperature dependent density. We will discuss the room-temperature kinetics and thermodynamics of the magnons gas in yttrium iron garnet films driven by a microwave pumping and investigated by means of the Brillouin light scattering spectroscopy. We show that the thermalization of the driven gas results in a quasi-equilibrium state described the Bose-Einstein statistics with a non-zero chemical potential, the latter being dependent on the pumping power. For high enough pumping powers Bose-Einstein condensation (BEC) of magnons can be experimentally achieved at room temperature. Spatio-temporal kinetics of the BEC-condensate will be discussed in detail. Among others interference of two condensates, vortices, and propagating waves of the condensate density will be addressed.

Spintronics with Insulating Antiferromagnets

Arne Brataas
Norwegian University of Science and Technology, Department of Physics, NO-7491 Trondheim, Norway

Usually, antiferromagnets only function as passive spintronics components. However, antiferromagnets' markedly different properties as compared to ferromagnets make them interesting and attractive in a more dynamic role. Antiferromagnets can operate in the THz frequency regime, and since there are no magnetic stray fields their usage enables the creation of smaller structures than with ferromagnets. Furthermore, in insulators, there are no moving charges involved so that the power reduction can be significant.

We will demonstrate that antiferromagnetic insulators couple strongly to electric currents and thermal temperature differences in adjacent normal metals. Therefore, antiferromagnets can remarkably fulfil the role as active components in spintronics devices despite their lack of a macroscopic magnetic moment, and even when they are insulating.

First, we will demonstrate that spin pumping is as operative from insulating antiferromagnets as from ferromagnets [1], in apparent contradiction to naïve intuition. Via Onsager reciprocity relations, this implies there is a considerable spin-transfer torque on antiferromagnetic insulators via spin accumulation in adjacent normal metals. Second, we will demonstrate that a temperature gradient drives a large heat flow from magnons in antiferromagnetic insulators to electrons in neighboring normal metals [2]. The same coefficients as in the spin-transfer and spin-pumping processes also determine the thermal conductance. However, in contrast to ferromagnets, the heat is not transferred via a spin Seebeck effect. Instead, the heat is transferred via a large staggered spin Seebeck effect.

[1] R. Cheng, J. Xiao, Q. Niu, and A. Brataas, Phys. Rev. Lett. 113, 147204 (2014).
[2] A. Brataas, H. Skarsvåg, E. G. Tveten, and E. Løhaugen (unpublished).

Spin dependent quantum transport in Rashba semicondutors and topological insulators

Yoshinori Tokura[1,2]
[1]*RIKEN Center for Emergent Matter Science (CEMS)*
[2]*Department of Applied Physics, University of Tokyo*

Polar semiconductors with large Rashba effect as well as topological insulators have characteristic Dirac like band dispersions with spin-momentum locking. Introduction of magnetic moments coupled with the Dirac electrons can further bring about abundant spintronic functions. The relevant topics to be presented include

・Polar semiconductors BiTeX(X=Te, Br, Cl) with gigantic Rahsba effects and dynamics of the Driac electrons therein

・Photogalvanic effects of bulk Rashba semiconductors

・Quantum Hall effects in top and bottom surface states of BST film

・Dirac-fermion mediated ferromagnetism and quantum anomalous Hall effect

・Quantum Hall effect and skymion formation of semimagnetic heterostcuture TI

・Photogalvanic effects of TI and ferromagnetic TI

Measuring nanometer-scale spin systems by ultrasensitive cantilever magnetometry

Martino Poggio
Department of Physics, University of Basel, Switzerland

The study of nanometer-scale magnetism is a vibrant sub-field of condensed matter physics concerned principally with magnetic phenomena in low-dimensional systems – phenomena that are often not observable in macroscopic systems. Its relevance to a variety of applications including precision sensing, high-density information storage and processing, and sensitive scanning probe techniques make the subject of particular technological interest. I will discuss our recent efforts to use ultrasensitive force sensors in measurements of spin-physics on the nanometer-scale, in particular: 1) nuclear magnetic resonance (NMR) measurements of nuclear spins in nanostructures and 2) magnetization measurements of individual nanomagnets.

Magnetic resonance force microscopy (MRFM) measurements of small nuclear spin ensembles reveal the transition between regimes dominated by thermal and statistical nuclear polarization. The ratio between the two types of polarization provides a measure of the number of spins in the detected ensemble [1]. I will demonstrate a method for measuring, manipulating and controlling the spin polarization of nanometer-scale spin ensembles [2]. These capabilities will be discussed in light of a recent proposal by Loss and colleagues predicting that the spin-orbit interaction (SOI) in semiconductor nanowires (NW) can be quantified through measurements of the relaxation rate of the constituent nuclear spins [3]. Specifically, their theory predicts that the nuclear T_1 in a ballistic NW with Rashba and SOI has pronounced signatures, which depend on the strength of the SOI. Semiconductor NWs with strong SOI have attracted a great deal of recent interest due to the various topologically non-trivial electronic states that they are predicted to support. Given our demonstrated ability to do nanometer-scale NMR on semiconductor NWs, I will discuss ongoing measurements in this direction.

I will conclude by presenting cantilever magnetometry measurements of the magnetization of individual nanometer-scale magnets. We are interested in studying the magnetism of low-dimensional systems and in coming to a greater understanding of their magnetic configurations. Measurements on ferromagnetic nanotubes [4], single-crystal magnetic nanoparticles, and of nanostructures hosting magnetic skyrmions will be highlighted.

1. Herzog et al., *Appl. Phys. Lett.* **105**, 043112 (2014)
2. Peddibhotla et al., *Nature Phys.* **9**, 631 (2013)
3. Zyuzin et al., *Phys. Rev. B* **90**, 195125 (2014).
4. Weber et al., *Nano Lett.* **12**, 6139 (2012); Buchter et al. *Phys. Rev. Lett.* **111**, 067202 (2013).

Dynamics of a strongly strain-driven, hybrid spin-oscillator system

Patrick Maletinsky
Department of Physics, University of Basel, Switzerland

A single spin coupled to a mechanical oscillator forms a prototypical hybrid quantum system. With a strong and robust coupling mechanism, such devices could yield high-performance nanoscale sensors, be applied for quantum information processing tasks or ultimately be used to study macroscopic objects in the quantum regime. In this talk, I will present our recent experiments where we established a novel type of such a hybrid spin-oscillator system. Specifically, we implemented for the first time diamond nanomechanical resonators, which are coupled to embedded Nitrogen-Vacancy (NV) centre electronic spins through crystalline strain. This strain coupling mechanism is highly robust, potentially strong and leads to interesting dynamics due to the nontrivial strain coupling Hamiltonian. I will illustrate these aspects though our recent experimental results, which include the first quantitative determination of the relevant strain coupling constants and the demonstration of resolved sideband operation in our devices. I will also discuss recent experiments in which we demonstrated strong, coherent driving of NV spins through time-varying strain fields and studied the resulting intriguing dynamics of the strain-driven NV spin system. Our results constitute first essential steps towards future experiments of our hybrid system in the quantum regime. Examples for these include spin-based oscillator sideband cooling or the recently proposed generation of spin-squeezing in nanomechanical oscillators.

Isolation and control of spins in silicon carbide

David J. Christle, Paul V. Klimov, Abram L. Falk, and David D. Awschalom

Institute for Molecular Engineering, University of Chicago, Chicago, IL 60637 USA

Over the past several decades, silicon carbide (SiC) has evolved from being a simple abrasive to a versatile material platform for high-power electronics, optoelectronics, and nanomechanical devices. These technologies have been driven by advanced growth, doping, and processing capabilities, and the ready availability of large-area, single-crystal SiC wafers. Motivated by the nitrogen-vacancy center in diamond's success in quantum information processing and photonics, recent efforts have sought to find point defects with analogous functionality in a more technologically mature and versatile material host. In particular, families of divacancies and related defects [1,2] in SiC have now been shown to have ground-state electronic-spin triplets, optical addressability near telecom wavelengths [3], and sensitivity to magnetic, electric [4], and strain fields [5].

We will focus on our recent isolation of single divacancy defects in wafers of 4H-SiC [6]. The electronic spin states associated with these defects exhibit exceptionally long ensemble spin coherence times, exceeding 1 millisecond, despite the presence of a relatively dense nuclear spin bath. Moreover, we will present recent efforts to merge robust electronic spins in this material with highly coherent ^{29}Si nuclear spins. In particular, we demonstrate both the near-unity initialization of an ensemble of electron-nuclear spin registers and their high-fidelity Bell-state entanglement. Ensembles of entangled spins show promise for high-precision metrology and long-lived quantum memories. Our results motivate SiC color-centers as attractive platforms for wafer-scale quantum technologies.

[1] W. F. Koehl, B. B. Buckley, F. J. Heremans, G. Calusine, and D. D. Awschalom, Nature **479**, 84 (2011)
[2] A. L. Falk, B. B. Buckley, G. Calusine, W. F. Koehl, V. V. Dobrovitski, A. Politi, C. A. Zorman, P. X.-L. Feng, and D. D. Awschalom, Nat. Comm. **4**, 1819 (2013)
[3] G. Calusine, A. Politi, and D. D. Awschalom, Appl. Phys. Lett. **105**, 011123 (2014)
[4] P.V. Klimov, A. L. Falk, B. B. Buckley, and D. D. Awschalom, Phys. Rev. Lett. **112**, 087601 (2014)
[5] A. L. Falk, P. V. Klimov, B. B. Buckley, V. Ivády, I. A. Abrikosov, G. Calusine, W. F. Koehl, Á. Gali, and D. D. Awschalom, Phys. Rev. Lett. **112**, 187601 (2014)
[6] D. J. Christle, A. L. Falk, P. Andrich, P. V. Klimov, J. Hassan, N. T. Son, E. Janzén, T. Ohshima, and D. D. Awschalom, Nat. Mater. **14**, 160 (2015)

Spotting the elusive Majorana under the microscope

Ali Yazdani
Princeton University

Topological superconductors are a distinct form of matter that is predicted to host boundary Majorana fermions. The search for Majorana quasi-particles in condensed matter systems is motivated in part by their potential use as topological qubits to perform fault-tolerant computation aided by their non-Abelian characteristics. Recently, we have proposed a new platform for the realization of Majorana fermions in condensed matter, based on chains of magnetic atoms on the surface of a superconductor. This platform lends itself to measurements with the scanning tunneling microscope (STM) that can be used to directly visualize the Majorana edge modes with both high energy and spatial resolution. Using rather unique STM instrumentation, we have succeeded in creating this platform and have observed the predicted signatures of localized Majorana edge modes. I will describe our Majorana platform, the experiments to date, and the outlook for further experiments on Majorana fermions in our platform.

[1] S. Nadj-Perge, I. Drosdov, A. Bernevig, A. Yazdani, Physical Review B, Rapid Communication, 88, 020407 (2013).
[2] S. Nadj-Perge, I. K. Drozdov, J. Li, H. Chen, S. Jeon, J. Seo, A. H. MacDonald, B. A. Bernevig, A. Yazdani, Science 346, 6209 (2014).
[3] J. Li, H. Chen, I. K. Drozdov, A. Yazdani, B. A. Bernevig, A. H. MacDonald, Physical Review B 90, 235433 (2014).

Probing structure and majorana wave-function of mono-atomic Fe chains on superconducting lead

Rémy Pawlak[1], Marcin Kisiel[1], Jelena Klinovaja[1], Tobias Meier[1], Shigeki Kawai[1], Thilo Glatzel[1], Daniel Loss[1] and Ernst Meyer[1]

[1]*Department of Physics, University of Basel, Klingelbergstr. 82, 4056, Basel Switzerland*

Majorana fermions (MF), predicted in 1937 by E. Majorana [1], are fermionic particles which are their own anti-particles. In analogy with electrons, MFs are half-spin integer particles and satisfy the Dirac equation. However, the MF wave-function is purely real in contrast to the electron (complex with positron as anti-particle) which has fundamental consequences on the intrinsic properties of the particle. In particular, its emergence in well designed condensed-matter systems opens new perspectives for quantum computation [2]. After more than 80 years search, this elusive particle has been recently observed by Scanning Tunneling Microscopy as zero-energy state at the end of Fe chains deposited on superconducting lead [3-4].

In this contribution, we will show our recent experiments combining scanning tunneling microscopy (STM) and atomic force microscopy (AFM) at low temperature. By revealing the atomic structure and electronic properties of such self-assembled chains on Pb(110), we confirmed the MF presence at the wire ends and extracted the decay length of its wave-function. Our results, in good agreement with previous theory [5], show a short decay length (<25 nm) which supports its future use as *qbits*. Interestingly, AFM imaging also reveals an additional force signature at the MF location [6].

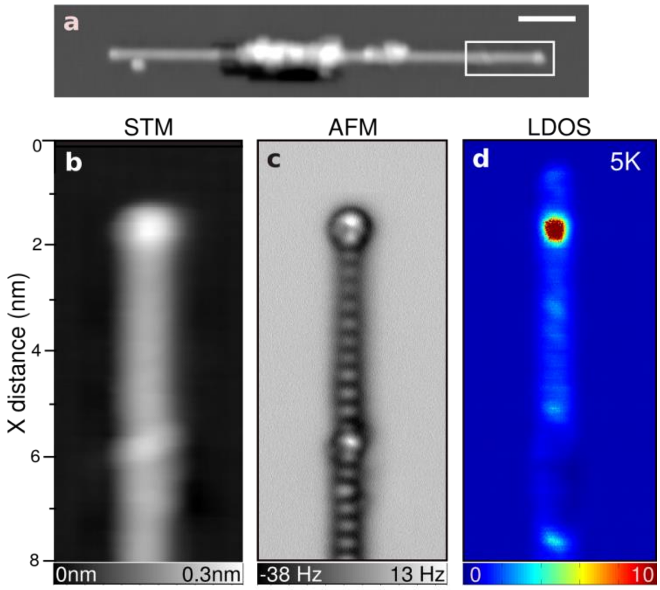


Figure 1: a, STM topographic image of a Fe wire self-assembled on Pb(110). **b,** Close-up STM image of the wire end. **c,** Constant-height AFM image of the wire revealing its atomic structure. **d,** Corresponding constant-height and zero-bias normalized dI/dV map (LDOS) showing the presence of a conductance peak located at the wire end that is attributed to the Majorana bound state.

[1] E. Majorana, *Nuovo Cimento* **14**, 171 (1937).
[2] A. Kitaev, *Ann. Phys.* **303**, 2 (2003).
[3] V. Mourik *et al.*, *Science* **336**, 1003 (2012).
[4] S. Nadj-Perge *et al. Science* **346**, 602 (2014).
[5] J. Klinovaja, D. Loss, *Phys. Rev. B* **86**, 085408 (2012).
[6] R. Pawlak, M. Kisiel, J. Klinovaja, T. Meier, S. Kawai, T. Glatzel, D. Loss, E. Meyer. Submitted.

Quantum interference and local electrical tuning in InAs Nanowire based Cooper Pair Splitter device

G. Fulop,[1] F. Dominguez,[2] S. d'Hollosy,[3] A. Baumgartner,[3] P. Makk,[1, 3] M.H. Madsen,[4] V.A. Guzenko,[5] J. Nygard,[4] C. Schonenberger,[3] A. Levy Yeyati,[2] and S. Csonka[1]

[1]*Department of Physics, Budapest University of Technology and Economics, Budafoki ut 6, 1111 Budapest, Hungary*

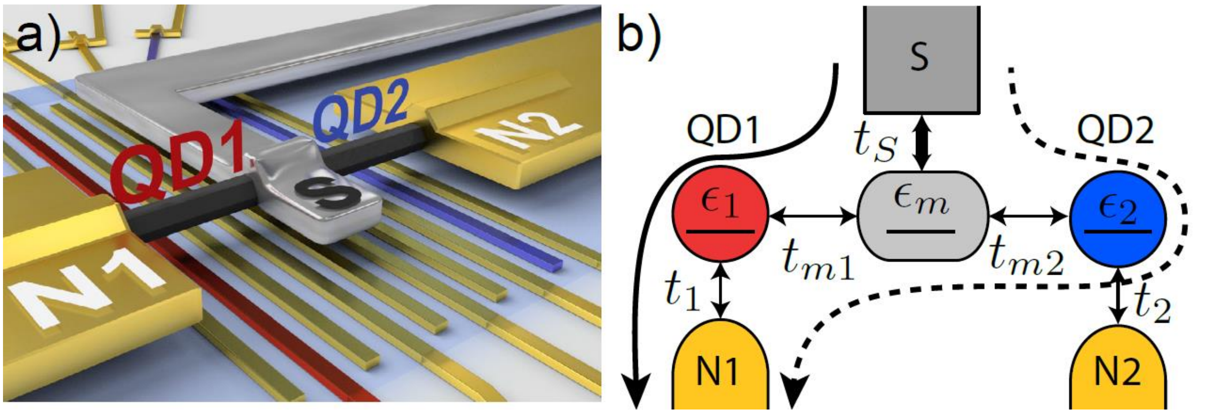
[2]*Departamento de Fisica Teorica de la Materia Condensada, Condensed Matter Physics Center (IFIMAC) , and Instituto Nicolas Cabrera, Universidad Autonoma de Madrid, E-28049 Madrid,*

[3]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*

[4]*Nano-Science Center, Niels Bohr Institute, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen, Denmark*

[5] *Laboratory for Micro- and Nanotechnology, Paul Scherrer Institute, CH-5232 Villigen PSI,*

A Cooper pair splitter consists of a central superconducting contact, S, from which electrons are injected into two parallel, spatially separated quantum dots (QDs) [1-3]. This geometry and electron interactions can lead to correlated electrical currents due to the spatial separation of spin-singlet Cooper pairs from S. We present experiments on such InAs Nanowire based devices with a series of bottom gates (see Figure), which allows for spatially resolved tuning of the tunnel couplings between the QDs and the electrical contacts and between the QDs. We show that the positive conductance correlation of the quantum dots could turn to negative by changing the tunnel couplings [4]. Furthermore, the non-local conductance resonances could evolve from a symmetric Lorentzian at low magnetic fields to a Fano-like (asymmetric) shape at higher magnetic field. Using simple model calculations we show that competition of Cooper pair splitting with other processes generate these experimental findings. E.g. the asymmetric shape of the signal is resulted by quantum interferences of local Andreev reflections and quasi particle processes. The influence of these effects on Cooper pair splitting efficiency is also discussed.



Panel a) Structure of an InAs NW based Cooper Pair Splitter (CPS). NW is shown with dark gray, superconductor/normal contacts is with light gray/gold. Fine gate structure is placed bellow the NW. Panel b) Simple model representing the CPS system, with an additional quantum dot bellow the superconductor lead. Arrows represent two paths which interfere and give Fano-like shape of non-local resonance in local Andreev reflection processes.

[1] P. Recher, E.V. Sukhorukov, and D. Loss, Phys. Rev. B **63**, 165314 (2001).
[2] L. Hofstetter, S. Csonka, J. Nygard, and C. Schonenberger, Nature **461**, 960 (2009).
[3] L.G. Herrmann, F. Portier, P. Roche, A. Levy Yeyati, T. Kontos, and C. Strunk, Phys. Rev. Lett. **104**, 026801 (2010).
[4] G. Fülöp, S. d'Hollosy, A. Baumgartner, P. Makk, V.A. Guzenko, M.H. Madsen, J. Nygård, C. Schönenberger, S. Csonka, Phys. Rev. B **90**, 235412 (2014).

Spintronics with novel 2d materials

Jaroslav Fabian
Institute for Theoretical Physics, University of Regensburg, 93040 Regensburg

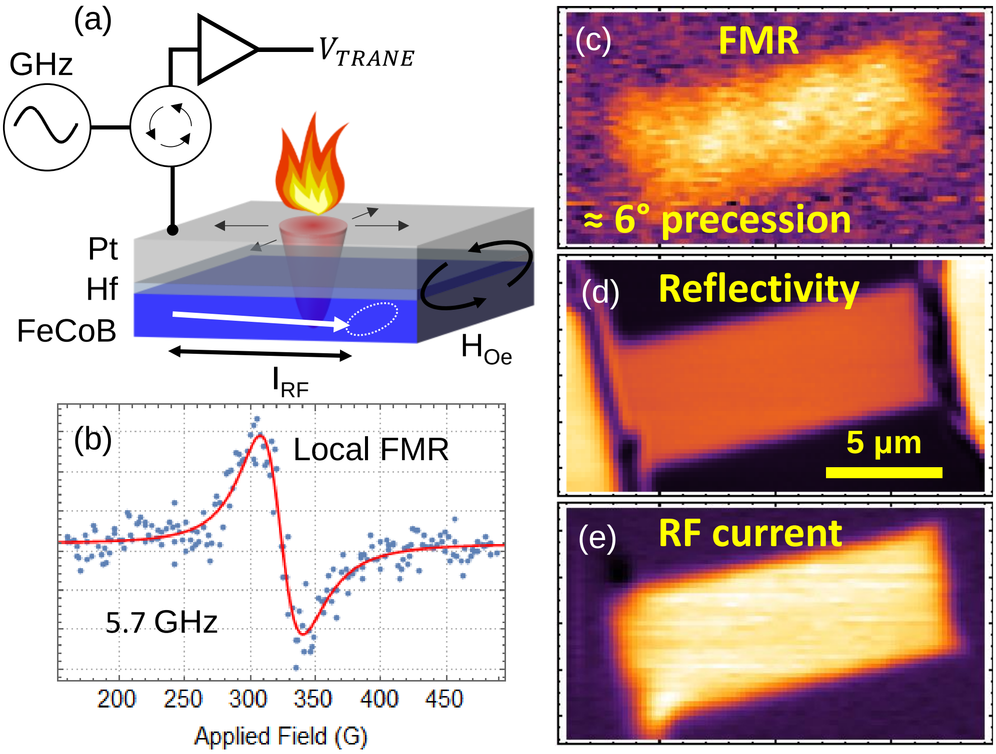
Two dimensional materials, such as graphene, transition metal dichalcogenides, or black phosphorous, offer immense opportunities for electronics, spintronics [1], and optospintronics. Being ultimately thin these materials could make the thinnest diodes and transistors, or the thinnest magnetic sensors and read heads. Being essentially a surface, they are also susceptible to adatoms and admolecules which can induce magnetic moments and giant spin-orbit coupling [2]. This is in fact a great opportunity, allowing us to decorate (functionalize) graphene and like materials with specific defects to make desired properties. I will review the essential spin physics of novel two dimensional materials, including spin-orbit coupling and magnetic moments, and discuss ramifications of the functionalization for spin transport experiments. Most of the results are obtained by performing computationally demanding density functional calculations on large atomic supercells, necessary to study the physics in the dilute defect limit. These calculations [2, 3] show a nice agreement with spin Hall effect and spin relaxation experiments, but also make authoritative predictions for potential charge and spin based devices based on graphene and 2d semiconductors and their hybrid structures. I acknowledge support from DFG SFB 689, GRK 1570, and European Union Seventh Framework Programme under Grant Agreement No. 604391 Graphene Flagship.

[1] W. Han, R. Kawakami, M. Gmitra, and J. Fabian, Nature Nanotechnology 9, 794 (2014).
[2] M. Gmitra, D. Kochan, and J. Fabian, Phys. Rev. Lett. 110, 246602 (2013).
[3] D. Kochan, M. Gmitra, and J. Fabian, Phys. Rev. Lett. 112, 116602 (2014).

Time-Resolved Magneto-Thermal Microscopy of Spin Hall Effect Driven Dynamics

F. Guo,[1] J. M. Bartell,[1] D. H. Ngai,[1] and G.D. Fuchs[1]
[1]*Cornell University, Ithaca, NY USA*

The spin Hall effect has emerged as a powerful tool to electrically excite and manipulate magnetization. We have recently developed the time-resolved anomalous Nernst effect (TRANE) microscope [1] as a tool to study the spatial profile of spin Hall driven dynamics in magnetic devices. Here we experimentally demonstrate quantitative and phase sensitive imaging of ferromagnetic resonance excited by the spin Hall effect in Pt/Hf/FeCoB multilayers. Using our TRANE microscope, we quantify the local response of magnetization to spin-transfer torque and Oersted field torque in spin Hall multilayers by analyzing precessional phase with picosecond resolution. We show that spatial variations and proximity to the sample edge influences the local phase of spin-torque driven ferromagnetic resonance. In turn, this impacts the spatially averaged spin hall angle extracted from conventional spin-transfer torque FMR experiments. Moreover, because our technique also measures the amplitude and phase of the microwave current density as a function of position, we directly probe the phase relationship between the current drive and the magnetic response. This quantitative imaging with a hybrid electrical/optical/thermal probe brings a new perspective to the growing understanding of spin Hall effect driven dynamics in magnetic multilayer devices.



(a) Schematic of device and measurement. In TRANE microscopy, a localized picosecond thermal gradient transduces the magnetic moment into an electrical voltage. (b) Local FMR measured using TRANE on a spin Hall Effect multi-layer. The FMR lineshape depends on phase of RF current at the time of picosecond thermal probe. (c) TRANE image of FMR at 5.7 GHz corresponding with a mean 6° precessional angle. Concurrently imaged sample reflection signal (d) and RF current density (e).

[1] J. M. Bartell*, D. H. Ngai*, Z. Leng, G. D. Fuchs, "Table-top Measurement of Local Magnetization Dynamics Using Picosecond Thermal Gradients: Toward Nanoscale Magnetic Imaging." arXiv:1502.06505 (2015).

Generation and Detection of Spin Currents in Semiconductor Nanostructures with Strong Spin-Orbit Interaction

Fabrizio Nichele,[1,*] Szymon Hennel,[1] Patrick Pietsch,[1] Werner Wegscheider,[1] Peter Stano,[2,3] Philippe Jacquod,[4] Thomas Ihn,[1] and Klaus Ensslin[1]

[1]Solid State Physics Laboratory, ETH Zürich, 8093 Zürich, Switzerland
[2]RIKEN Center for Emergent Matter Science, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[3]Institute of Physics, Slovak Academy of Sciences, Dubravska cesta 9, 84511 Bratislava, Slovakia
[4]HES-SO, Haute Ecole d'Ingénierie, 1950 Sion, Switzerland
**Present Address: Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen*

Storing, transmitting, and manipulating information using the electron spin resides at the heart of spintronics. Fundamental for future spintronics applications is the ability to control spin currents in solid state systems. Among the different platforms proposed so far, semiconductors with strong spin-orbit interaction are especially attractive as they promise fast and scalable spin control with all-electrical protocols. Here we demonstrate both the generation and measurement of pure spin currents in semiconductor nanostructures. Generation is purely electrical and mediated by the spin dynamics in materials with a strong spin-orbit field. Measurement is accomplished using a spin-to-charge conversion technique, based on the magnetic field symmetry of easily measurable electrical quantities. Calibrating the spin-to-charge conversion via the conductance of a quantum point contact, we quantitatively measure the mesoscopic spin Hall effect in a multiterminal GaAs dot. We report spin currents of 174 pA, corresponding to a spin Hall angle of 34%.

[1] Phys. Rev. Lett. 114, 206601 (2015).

Triple quantum dot spin CCD

T.A. Baart,[1] M. Shafiei,[1] T. Fujita,[1] F.R. Braakman,[1] C. Reichl,[2] W. Wegscheider,[2] and L.M.K. Vandersypen [1]
[1]*Kavli Institute of Nanoscience Delft, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*
[2]*Solid State Physics Laboratory, ETH Zurich, Schafmattstrasse 16, 8093 Zurich, Switzerland*

Nanofabricated arrays of quantum dots are promising platforms for the control of individual electron spins. Recent advances have allowed us to create linear arrays of increasing numbers of quantum dots, which poses new challenges for single-shot spin read-out, and calls for shuttling electrons along the array. In this talk we demonstrate single-shot read-out of three individual electron spins in a linear triple dot array (Fig. 1) with a method that resembles the operation of a charge-coupled-device (CCD). Our results show a perspective in which spin shuttling across larger quantum dot arrays is feasible.

The spin CCD read-out protocol starts with reading out the rightmost spin using standard spin-to-charge conversion [1]. Next we shuttle the centre electron to the right dot and read out its spin state. In the end we shuttle the left spin through the centre dot to the right, and complete the three-spin read-out in CCD-style. Single-shot read-out fidelities are in the range of 94-98%, with the highest fidelity for the spin that is read out first. We also selectively flip each of the three spins using electric dipole spin resonance (EDSR) [2] (Fig. 2) exploiting the small difference in g-factors between the dots. This corresponds to writing the bits of the Single-Spin CCD.

Finally, we study the scalability of this approach by shuttling a single electron up to 500 times between the dots in the array, and find no sign of spin flipping mechanisms during shuttling other than through spontaneous relaxation when residing in one of the dots between shuttling events. The high fidelity of the spin shuttle is made possible by optimal orientation of the magnetic field, the triple dot axis, and the crystal axis. The next fundamental question is whether the quantum coherence is preserved during the shuttling.

.

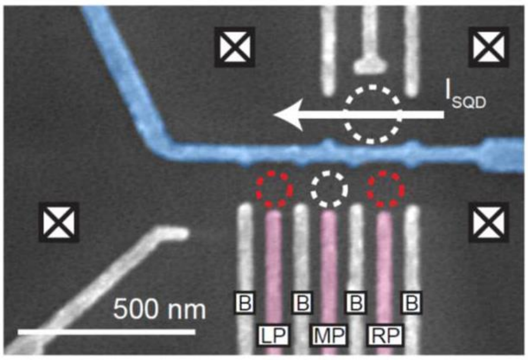


Fig. 1   Linear array of three quantum dots forming a three qubit device in GaAs. The spin state of the qubits is read out sequentially by monitoring the current I_{SQD} through the neighbouring sensing dot.

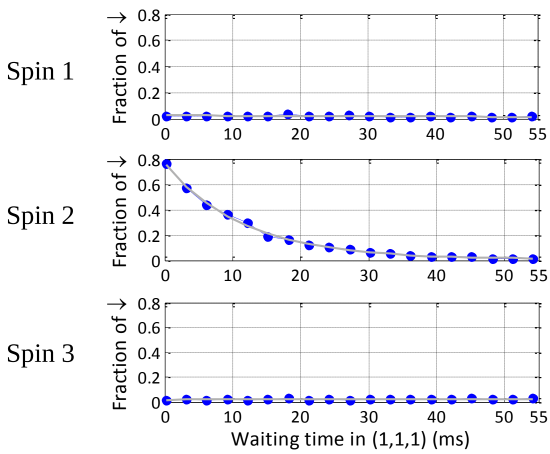


Fig. 2   After loading the spin state up-up-up in the CCD array, we selectively flip spin 2 using EDSR. We then vary the waiting time before reading out the spin states and observed the expected T_1 relaxation process using CCD-style single-shot read-out.

[1] J.M. Elzerman *et al*., Nature **430,** 431-435 (2004).
[2] M. Shafiei *et al*., Phys. Rev. Lett, **110,** 107601 (2013).

Control of two-electron spin correlations on precision-placed donors in Si

Matthew A. Broome,[1] Matthew G. House,[1] Sam Hile,[1] Sam K. Gorman,[1] Joris Keizer, [1] Will J. Baker,[1] and Michelle Y. Simmons[1]

[1] *Centre of Excellence for Quantum Computation and Communication Technology, School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia*

This work demonstrates the first important step toward controllable spin-spin interactions between single electrons confined to phosphorus donors in silicon. We use precision placed few donor quantum dots made with STM lithography, where each dot is tunnel coupled to an in plane single electron transistor. Figure 1a shows the lithographic pattern identifying two donor quantum dots with V_L and V_R gates to measure the charge stability map shown in Fig. 1b. We operate around the (2,0)-(1,1) charge region where electron exchange interactions are expected as a result of the coherent tunnel coupling between the two dots. Using a sequence of pulses we can read the spin state of an electron on each dot in the (1,1) charge state [1,2]. From T_1 measurements (17s and 60s for left and right dot extrapolated at 1.5T) the donor numbers are predicted to be 1P and 2P on the left and right dot respectively.

We start by initializing the electrons in the (1,1) region, after which we pulse along a detuning axis towards the (2,0) charge region (green line in Fig. 1b). As a function of this detuning we observe the impact of correlations between the spins [3].

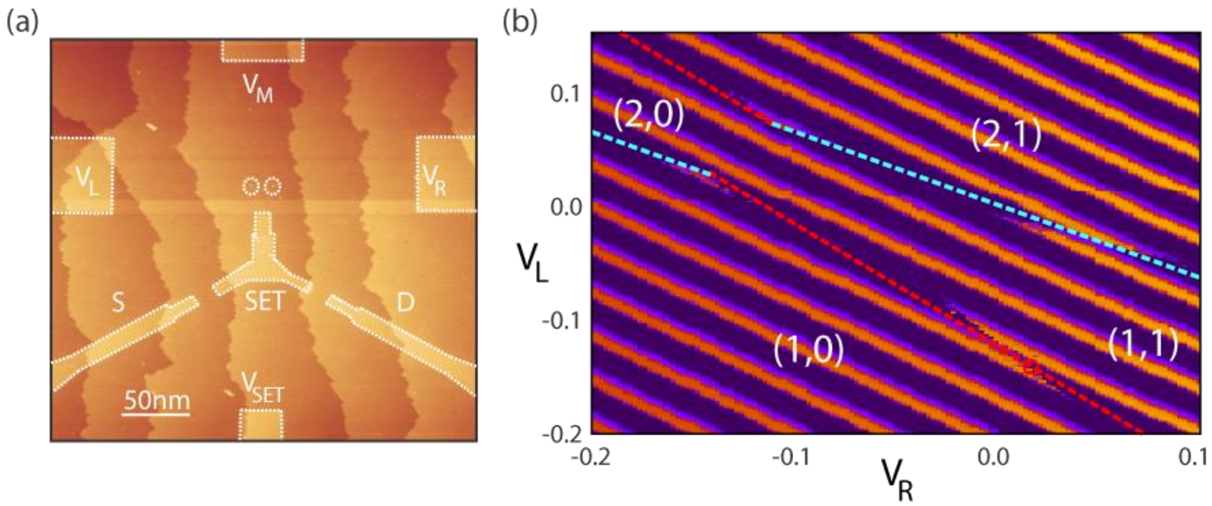


Figure 1: (a) Few donor double-dot patterened by STM lithography. Around the patterned dots are in-plane gates and a SET charge sensor used for spin readout. (b) Charge stability map showing charge regions of the two donor dots.

The probability of measuring anti-correlated spins was observed to be higher than those predicted from the individual spin statistics alone. Ongoing experiments are focused on the coherent manipulation of two spin states.

[1] Elzerman, J. M. et al. Single-shot read-out of an individual electron spin in a quantum dot, *Nature* 430, 431–435 (2004).
[2] Buch, H. et al. Spin readout and addressability of phosphorus-donor clusters in Silicon, *Nature Communications* 4, 2017 (2013)
[3] KC Nowack, et al. Single-shot correlations and two-qubit gate of solid-state spins, *Science* 333 (6047), 1269-1272 (2011).

Quantum Information Processing with Single Donors in Silicon

Andrea Morello
Centre for Quantum Computation & Communication Technology,
School of Electrical Engineering & Telecommunications,
UNSW Australia, Sydney NSW 2052, Australia

A phosphorus (^{31}P) donor in silicon is, almost literally, the equivalent of a hydrogen atom in vacuum. It possesses electron and nuclear spins 1/2 which act as natural qubits, and the host material can be isotopically purified to be almost perfectly free of other spin species, ensuring extraordinary coherence times.

I will present the current state-of-the-art in silicon quantum information technologies. Both the electron [1] and the nuclear [2] spin of a single ^{31}P atom can be read out in single-shot [3] with high fidelity, through a nanoelectronic device compatible with standard semiconductor fabrication. High-frequency microwave [4] pulses can be used to prepare arbitrary quantum states of the spin qubits, with fidelity in excess of 99%. Our latest experiment on the ^{31}P nucleus has established the record coherence time (35 seconds) for any single qubit in solid state [5], by making use of an isotopically enriched ^{28}Si epilayer.

Finally, I will discuss current efforts to scale up the system to multi-qubit quantum logic operations. We have demonstrated on a single-atom device the long-sought "*A*-gate" electrical control of a spin in a continuous microwave field [6], which greatly facilitates addressing multiple qubits. We have observed the singlet/triplet states of a strongly-coupled donor pair [7], proposed a new scheme for entangling two-qubit logic gates [8] that does not require atomically precise placement of the ^{31}P donors, and we are exploring cavity-mediated long-distance spin coupling.

These results show that silicon – the material underpinning the whole modern computing era – can be successfully adapted to host quantum information hardware.

[1] J. Pla et al., *Nature* **489**, 541 (2012)
[2] J. Pla et al., *Nature* **496**, 334 (2013)
[3] A. Morello et al., *Nature* **467**, 687 (2010)
[4] J. Dehollain et al., *Nanotechnology* **24**, 015202 (2013)
[5] J.T. Muhonen et al., *Nature Nanotechnology* **9**, 986 (2014)
[6] A. Laucht et al., *Science Advances* **1**, e1500022 (2015)
[7] J.P. Dehollain et al., *Phys. Rev. Lett.* **112**, 236801 (2014)
[8] R. Kalra et al., *Phys. Rev. X* **4**, 021044 (2014)

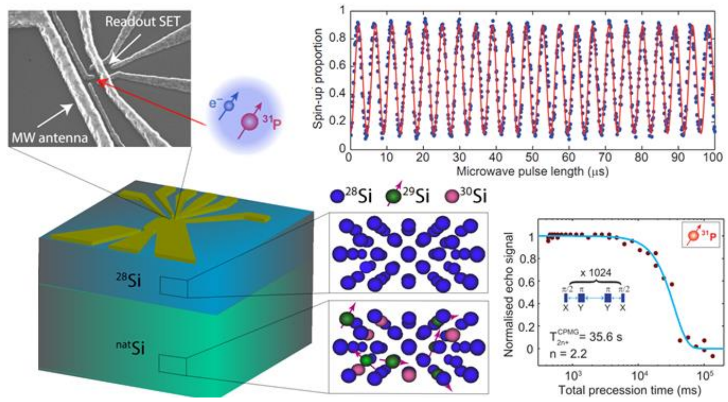


Fig. 1: Device structure, electron Rabi oscillations and nuclear coherence time of a single-atom spin qubit in silicon.

The Role of isotope engineering in silicon and diamond quantum information processing

Kohei M. Itoh

School of Fundamental Science and Engineering, Keio University, Yokohama 223-8522 Japan

The role of isotope engineering in silicon quantum computing and diamond quantum sensing is discussed [1]. While elimination of the ^{29}Si nuclear spins from the host silicon matrix has been proven crucial to ensure long enough coherence time [2, 3], removal of the ^{28}Si and ^{30}Si mass fluctuation is also important, for example, to define the NMR frequencies of donor nuclear spins like ^{31}P [4]. Effects of elimination of ^{13}C nuclear spins from the diamond matrix are similar [5]. This talk aims to present a variety of isotope effects that are relevant to quantum information processing using silicon and diamond.

This work has been supported in part by the Grants-in-Aid for Scientific Research (S) by MEXT, in part by the Core-to-Core Program by JSPS, in part by Project for Developing Innovation Systems by MEXT, and Cooperative Research Project Program of the RIEC, Tohoku University.

[1] K. M. Itoh and H. Watanabe, *"Isotope engineering of silicon and diamond for quantum computing and sensing applications,"* MRS Communications **4**, 143-157 (2014). [Open access perspective article]

[2] A. Laucht, J. T. Muhonen, F. A. Mohiyaddin, R. Kalra, J. P. Dehollain, S. Freer, F. E. Hudson, M. Veldhorst, R. Rahman, G. Klimeck, K. M. Itoh, D. N. Jamieson, J. C. McCallum, A. S. Dzurak, A. Morello, *"Electrically Controlling Single-Spin Qubits in a Continuous Microwave Field,"* Sci. Adv. **1**, e1500022 (2015)

[3]J. T. Muhonen, J. P. Dehollain, A. Laucht, F. E. Hudson, R. Kalra, T. Sekiguchi, K. M. Itoh, D. N. Jamieson, J. C. McCallum, A. S. Dzurak, and A. Morello, *"Storing Quantum Information for 30 Seconds in a Nanoelectronic Device,"* Nature Nanotechnology **9**, 986–991 (2014).

[4] M. Veldhorst, J. C. C. Hwang, C. H. Yang, A. W. Leenstra, B. de Ronde, J. P. Dehollain, J. T. Muhonen, F. E. Hudson, K. M. Itoh, A. Morello, and A. S. Dzurak, *"An Addressable Quantum Dot Qubit with Fault-Tolerant Control-Fidelity,"* Nature Nanotechnology **9**, 981–985 (2014).

[5] T. Sekiguchi, A. M. Tyryshkin, S. Tojo, E. Abe, R. Mori, H. Riemann, N. V. Abrosimov, P. Becker, H.-J. Pohl, J. W. Ager, E. E. Haller, M. L. W. Thewalt, J. J. L. Morton, S. A. Lyon, and K. M. Itoh, *"Host Isotope Mass Effects on the Hyperfine Interaction of Group-V Donors in Silicon,"* Phys. Rev. B **90**, 121203(R) (2014).

[6] Y. Romach, C. Müller, T. Unden, L. J. Rogers, T. Isoda, K. M. Itoh, M. Markham, A. Stacey, J. Meijer, S. Pezzagna, B. Naydenov, L. P. McGuinness, N. Bar-Gill, and F. Jelezko, *"Spectroscopy of Surface-Induced Noise Using Shallow Spins in Diamond,"* Phys. Rev. Lett. **114**, 017601 (2015).

[7] T. Rosskopf, A. Dussaux, K. Ohashi, M. Loretz, R. Schirhagl, H. Watanabe, S. Shikata, K. M. Itoh, and C. L. Degen, *"Investigation of Surface Magnetic Noise by Shallow Spins in Diamond,"* Phys. Rev. Lett. **112**, 147602 (2014).

[8] K. Ohashi, T. Rosskopf, H. Watanabe, M. Loretz, Y. Tao, R. Hauert, S. Tomizawa, T. Ishikawa, J. Ishi-Hayase, S. Shikata, C. L. Degen, and K. M. Itoh, *"Negatively Charged Nitrogen-Vacancy Centers in a 5 nm Thin ^{12}C Diamond Films,"* Nano Lett. **13**, 4733-4738 (2013).

CMOS bricks for silicon spin qubits

S. De Franceschi
CEA, INAC and Université Grenoble Alpes, 17 Rue des Martyrs, F-38000 Grenoble, France

The implementation of silicon spin qubits onto an industrial CMOS platform may largely facilitate their development into large-scale integrated quantum circuits. Along this line, we have recently shown that both few-electron and few-hole quantum dots can be formed in silicon nanowire transistors based on 300-mm silicon-on-insulator technology. In the case of holes, g-factors are found to be anisotropic and gate dependent providing a pathway to electrically driven spin manipulation via the g-tensor modulation resonance mechanism. Here I will report further progress towards the first truly CMOS spin qubits. In particular I will present the first realizations of double quantum dots in dual-gate nanowire transistors. We have observed the spin-blockade effect (useful for spin readout) and obtained the first experimental signatures of hole-spin resonance. In addition to transport measurements I will present data obtained with a dual-gate reflectometry setup. This alternative approach, besides enabling sensitive and faster readout of the quantum dot states, is better suited for future multi-qubit integration.

Semiconductor quantum dot spin-charge hybrid qubits

Dohun Kim[1,2], D. R. Ward[1,3], C. B. Simmons[1], D. E. Savage[4], M. G. Lagally[4], Mark Friesen[1], S. N. Coppersmith[1], and Mark A. Eriksson[1]

[1]Department of Physics, University of Wisconsin-Madison, Madison, WI 53706, USA

[2]Department of Materials Science and Engineering, Yonsei University, Seoul 120-749, South Korea

[3]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

[4]Department of Materials Science and Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA

Isolated spin and charge in semiconductors provide a promising platform to explore quantum mechanical coherence and develop engineered quantum systems. The quantum dot charge qubit offers a simple architecture and high-speed operation, but generally suffers from fast dephasing due to strong coupling of the environment to the electron’s charge. On the other hand, quantum dot spin qubits have demonstrated long coherence times, but their manipulation is often slower than desired for important future applications. This talk will present experimental progress of a ‘hybrid’ qubit, formed by three electrons in a Si/SiGe double quantum dot, which combines desirable characteristics (speed and coherence) in the past found separately in qubits based on either charge or spin degrees of freedom. By resonantly modulating the double dot energy detuning and employing electron tunneling-based readout, we achieve fast (> 100 MHz) Rabi oscillations and purely electrical manipulations of the three-electron spin states. We demonstrate universal single qubit gates using a Ramsey pulse sequence as well as microwave phase control, the latter of which shows control of an arbitrary rotation axis on the XY plane of the Bloch sphere. Quantum process tomography yields π rotation gate fidelities higher than 93 (96) % around the X(Z) axis of the Bloch sphere. We further show that the implementation of dynamic decoupling sequences on the hybrid qubit enables coherence times longer than 150 ns. We discuss a path forward to fidelities better than the threshold for quantum error correction using surface codes.

Acknowledgement : This work was supported in part by ARO (W911NF-12-0607), NSF(PHY-1104660), and by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000. Development and maintenance of the growth facilities used for fabricating samples is supported by the DOE (DE-FG02-03ER46028). This research utilized NSF-supported shared facilities at the University of Wisconsin-Madison.

G-factor anisotropy in Ge-Si core-shell nanowires

M. Brauns[1], J. Ridderbos[1], A. Li[2], E.Bakkers[2], and F.A. Zwanenburg[1]
[1] *NanoElectronics Group, MESA+ Institute for Nanotechnology, University of Twente, Drienerlolaan 5, 7522 NB Enschede, The Netherlands*
[2] *Photonics & Semiconductor Nanophysics Group, Department of Applied Physics, TU Eindhoven, Den Dolech 2, 5612 AZ Eindhoven, The Netherlands*

We grow monocrystalline and nearly defect-free Ge-Si core-shell nanowires, which we use to fabricate devices with ohmic contacts to the nanowire and local gates. The low defect density allows us to electrostatically define quantum dots of various lengths in the wires. We can control quantum dot lengths from ~50 to ~400 nm and the longer dots can be split into a double dot in a controlled way from strong to very weak interdot tunnel coupling indicating a very clean system.

In literature, reported g-factors for Ge-Si core-shell nanowires are relatively small, ranging from 1.0 to 2.2 [1, 2], although theoretical calculations predict g-factors that significantly exceed the free-particle g-factor of 2 [3]. We observe g-factors up to 8 in magnetospectroscopy measurements on quantum dots of several sizes. In agreement with theoretical calculations in literature [3], we also find the g-factor to be highly anisotropic reaching the maximum value when the magnetic field is perpendicular to the wire axis. These high g-factors would be useful for quantum computation applications using spin-orbit states as well as Majorana bound states.

[1] Roddaro S, Fuhrer A, Brusheim P, Fasth C, Xu HQ Samuelson L (2008) Phys. Rev. Lett. 101 186802.
[2] Hu Y, Kuemmeth F, Lieber CM, Marcus CM (2011) Nature Nanotech 7 47-50.
[3] Maier F, Kloeffel C, Loss D (2013) Phys. Rev. B 87 161305.

Magneto-transport driven by spin-orbital scattering*

Steven S.-L. Zhang,[1] Shufeng Zhang,[2] and G. Vignale[1]
[1]*Department of Physics, University of Missouri, Columbia, MO 65211, USA*
[2]*Department of Physics, University of Arizona, Tucson, AZ 85721, USA*

Layered structures of materials with different magnetic and/or spin orbital properties are rapidly emerging as most promising candidates for spintronic applications. A slew of new effects are under study, which have no analogue in bulk materials or differ subtly from their three-dimensional counterparts. Spin polarization and spin transfer torque (STT), can be generated by passing an in-plane electric current near the interface between the two materials. Novel types of anisotropic magneto-resistance (AMR) are possible near interfaces. Spin polarized currents may produce a nonlocal form of the anomalous Hall effect (AHE). In this work, we apply quantum kinetic theory to analyze these phenomena. A key ingredient of the theory is the application of generalized Fuchs-Sondheimer boundary conditions [1] to include spin precession of electrons scattering at interfaces. Our main findings are presented below.

For a bilayer consisting of a ferromagnetic metal (FM) and a non-magnetic-insulator (NI) (such as Py/Bi2Se3), we show that an unconventional AMR arises from the concerted actions of the surface spin orbit scattering and the spin asymmetry in the conductivity of the FM layer [1]. In brief, interfacial spin orbit scattering causes spin mixing of the two conducting channels of the FM, which results in an increase of the overall resistivity. Furthermore, we found this new AMR exhibits an angular dependence that is distinct from that of the conventional bulk effect: the resistance changes when the magnetization is rotated around the current, *even if the angle between these two vectors does not change*. Our work also leads to a reinterpretation of recent experiments on spin current and STT generation [2] in bilayer systems. In our interpretation, the spin current is injected into the FM layers as a result of spin rotation of electrons during the surface scattering. We emphasize that this alternative interpretation of the STT effect in bilayers has nothing to do with the conventional explanation in terms of surface states [2], and allows us to connect the STT to the bulk transport properties of the FM layer.

Lastly, we predict a novel non-local AHE in heavy-metal/ferromagnetic-insulator bilayers: the Hall current in the heavy metal depends on the magnetization of a spatially separated insulating layer. The essential physical picture of this AH effect can be described as follows: first, when an in-plane current is applied, the non-equilibrium distribution function becomes spin-polarized due to scattering at the magnetic interface; second, the spin polarized electron flux near the interface generates a charge Hall current due to the bulk spin orbit scattering. The resulting AHE thus appears at the *first order* in the spin Hall angle (or spin orbit coupling), in contrast to the spin Hall Anomalous Hall effect, which is found to be of *second order* in the spin Hall angle [3]. We believe that this AH effect can be easily demonstrated experimentally since it will have opposite signs for heavy metals whose spin Hall angles are of opposites signs (e.g., Pt and Ta).

*Work supported by NSF Grants DMR-1406568 and ECCS-1404542.

[1] S. S.-L. Zhang, G. Vignale, S. Zhang, arXiv:1504.03310.
[2] A. R. Mellnik *et al.*, Nature, **511**, 449 (2014).
[3] Y.-T. Chen *et al.,* Phys. Rev. B, **87**, 144411 (2013).

Quadrupolar and anisotropy effects on dephasing in two-electron spin qubits in GaAs

Tim Botzem,[1] Dominique Bougeard,[2] and Hendrik Bluhm[1]
[1]*JARA-Institute for Quantum Information, RWTH Aachen University, D-52074 Aachen, Germany*
[2]*Department of Physics, University of Regensburg, D-93040 Regensburg, Germany*

Understanding the decoherence of electron spins in semiconductors due to their interaction with nuclear spins is of fundamental interest as they realize the central spin model and of practical importance for using electron spins as qubits [1].

A dephasing channel of current interest is the quadrupolar interaction of nuclear spins with electric field gradients, which is often thought of to enhance electron spin coherence by suppressing spin diffusion. Here we show experimentally that for gate-defined GaAs quantum dots, quadrupolar couplings can also be a limiting factor for coherence, but can be eliminated by choosing an appropriate field orientation (see Fig. 1). This effect arises from a faster decorrelation of transverse nuclear fields due to quadrupolar broadening of the nuclear Larmor precession. Furthermore, we observe an additional envelope modulation of spin coherence that can be attributed to an anisotropic electronic g-tensor.

These results complete our understanding of dephasing in gated quantum dots and point to mitigation strategies. They may also help to unravel unexplained behavior in related systems such as self-assembled quantum dots [2] and III-V-nanowires [3].

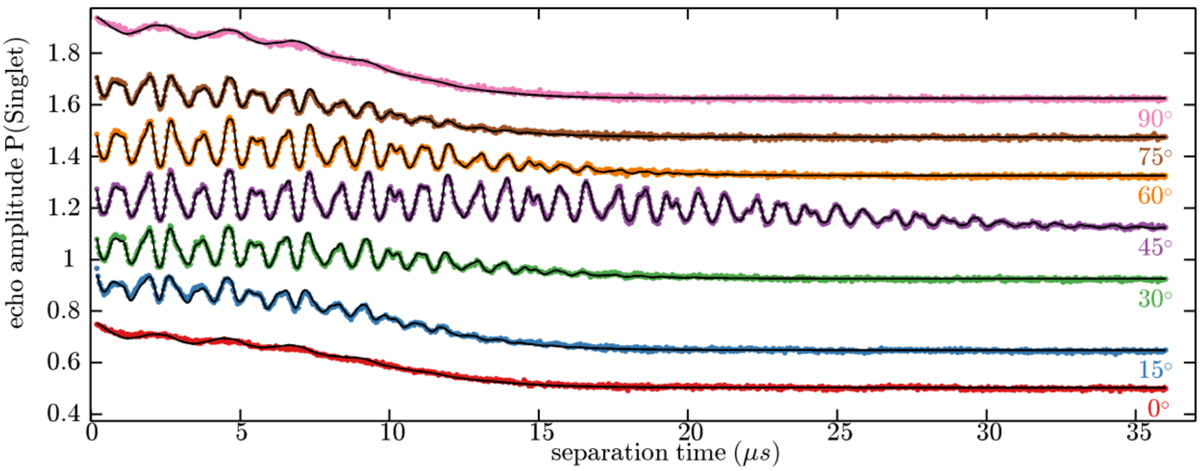


Fig. 1: Echo amplitude at 300 mT as a function of separation time for different in-plane magnetic field directions, with 0° corresponding to either the [1 1 0] or [1 $\bar{1}$ 0] direction. Curves are offset for clarity and normalized using simultaneously recorded single-shot histograms. At 45°, parallel to the crystallographic [1 1 0]-axis, coherence time is enhanced as quadrupolar couplings are suppressed. When rotating the field a g-factor anisotropy arises, leading to oscillations, built up from three slightly different nuclear Larmor frequencies, in the envelope decay. Data are fitted to a semi-classical model.

[1] Bluhm et al., Nature Physics 7 (2010).
[2] Munsch et al., Nature Nanotechnology 9 (2014).
[3] Nadj-Perge et al, Nature 468 (2010).

Photon-electron spin coupling using gate-defined GaAs double quantum dots

Akira Oiwa,[1] Takafumi Fujita,[2,3] and Seigo Tarucha[2,4]
[1] *The Institute of Scientific and Industrial Science, Osaka University, Japan*
[2] *Department of Physics, The University of Tokyo, Japan*
[3] *Kavli Institute of Nanoscience Delft, Quantum Transport, Delft University of Technology, The Netherlands*
[4] *Center for Emergent Matter Science (CEMS), RIKEN, Japan*

Electrically controlled quantum dots(QDs) with potentially long spin coherence time have been extensively developped as suitable candidates for scalable solid-state qubits. Recently, the conversion of quantum states between single photons, which can transmit the quantum information for long distance, and single electron spins in QDs has become very attractive for realizing the global quantum information network and distributed quantum computation. The quantum state conversion from photons to electron spins has been proposed and has been experimentally verified by ensemble magneto-optical measurements in quantum well (QW) structures [1,2]. Here we report the angular momentum conversion from single photons to single electron spins in QDs formed in a QW designed for the coherent conversion.

We have established the detection of single photoelectrons using single-shot charge sensing techniques in GaAs-based QDs [3-5]. In this work, using the spin dependent inter-dot tunneling due to Pauli spin blockade in a double QD (DQD) the detection of single photoelectron spins with high distinguishability can be realized [6]. We use DQDs fabricated in an AlGaAs/GaAs QW with 7.3 nm well width [5,7]. Single photoelectrons were excited from the heavy hole states. We show the angular momentum conversion from single photons to single electron spins in the double QD from the dependence of the detected spin orientation on the incident photon polarization [6]. This is a promissing result to realize the coherent quantum state conversion and moreover to generate an entanglement between distant spins.

Authors acknowledge the collaborations with K. Kuroyama, H. Kiyama, G. Allison, M. Larsson, P. Stano, K. Morimoto, S. Teraoka, S. Haffouz, D. G. Austing, A. Ludwig, and A. D. Wieck. This work was supported by Grants-in-Aid for Scientific Research A (No. 25246005), S (No.26220710), and Innovative Area "Nano Spin Conversion Science" (No. 26103004), ImPACT Program of Council for Science, Technology and Innovation and SCOPE of MIC, the Asahi Glass Foundation.

[1] R. Vrijen and E. Yablonovitch, Phys. E **10**, 569 (2001).
[2] H. Kosaka *et al.*, Phys. Rev. Lett. **100** 096602 (2008).
[3] A. Pioda *et al.*, Phys. Rev. Lett. **106**, 146804 (2011).
[4] T. Fujita *et al.*, Phys. Rev. Lett. **110**, 266803 (2013).
[5] K. Morimoto *et al.*, Phys. Rev. B **90**, 085306 (2014).
[6] T. Fujita *et al.*, submitted.
[7] G. Allion *et al.*, Phys. Rev. B **90**, 235310 (2014).

Topological Spintronics

Nitin Samarth, Anthony Richardella, Abhinav Kandala and Joon Sue Lee
Department of Physics, Penn State University, University Park PA 16802

We provide a perspective on the emergence of “topological spintronics,” which exploits the helical spin texture of two-dimensional surface states in three-dimensional topological insulators. Spin- and angle-resolved photoemission spectroscopy shows how this spin texture can be engineered using either quantum tunneling between surfaces [1] or by breaking time-reversal symmetry [2]. In bilayers of a topological insulator and a ferromagnetic metal, we find evidence for a highly efficient charge-to-spin conversion at room temperature, measured through spin torque ferromagnetic resonance [3]. When time-reversal symmetry is broken in a ferromagnetic topological insulator, the presence of a magnetic gap leads to the emergence of a quantum anomalous Hall insulator at cryogenic temperatures, characterized by a precisely quantized Hall resistance and vanishing longitudinal resistance. We find that the “giant“ anisotropic magnetoresistance of quantum anomalous Hall insulators provides quantitative insights into the interplay between dissipationless edge state transport and co-existing dissipative channels in regimes away from perfect quantization [4].

This work was supported by DARPA, ONR, ARO MURI and by C-SPIN, one of six centers of STARnet, a Semiconductor Research Corporation program, sponsored by MARCO and DARPA. The work was carried out in collaboration with Alex Mellnik, Madhab Neupane, Su-Yang Xu, Duming Zhang, Susan Kempinger, Eun-ah Kim, Chao-xing Liu, Zahid Hasan and Dan Ralph.

[1] M. Neupane, A. Richardella *et al.*, *Nature Communications* **5**, 3841 (2014).

[2] S.-Y. Xu *et al., Nature Physics* **8**, 616 (2012).

[3] A. Mellnik, J. S. Lee, A. Richardella *et al.*, *Nature* **511**, 449 (2014).

[4] A. Kandala, A. Richardella, *et al., Nature Communications* (in press).

Persistent optical gating of a topological insulator

Andrew L. Yeats,[1,2] Yu Pan,[3] Anthony Richardella,[3] Peter J. Mintun,[1]
Nitin Samarth,[3] and David D. Awschalom[1,2]

[1]Institute for Molecular Engineering, University of Chicago, Chicago, IL 60637, USA.
[2]Department of Physics, University of California, Santa Barbara, CA 93106, USA.
[3]Department of Physics, Penn. State University, University Park, PA 16802, USA.

The spin-polarized surface states of topological insulators (TIs) are attractive for applications in spintronics and quantum computing. A central challenge with these materials is to reliably tune the chemical potential with respect to the Dirac point and the bulk bands. Here, we demonstrate persistent, bidirectional control of the chemical potential of $(Bi,Sb)_2Te_3$ thin films grown by molecular beam epitaxy on (111) $SrTiO_3$ [1]. By optically manipulating the distribution of space charge in $SrTiO_3$ substrates using two colors of light, we induce a persistent field effect in the TI films comparable to electrostatic gating techniques but without additional materials or processing. This enables us to optically pattern arbitrarily shaped *p*- and *n*-type regions in a TI, which we subsequently image with scanning photocurrent microscopy. The ability to optically write and erase mesoscopic electronic structures in a TI may aid in the investigation of the unique properties of the topological insulating phase. The gating effect also generalizes to other thin film materials on $SrTiO_3$, suggesting that these phenomena could provide optical control of chemical potential in a wide range of ultra-thin electronic systems.

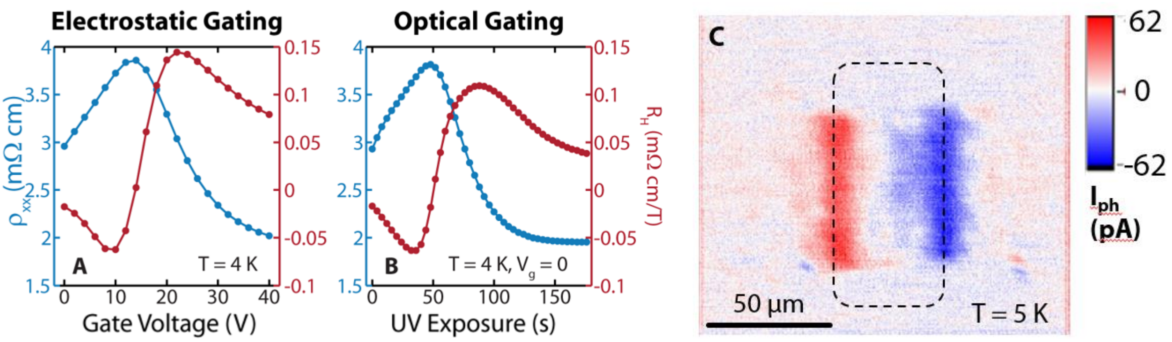


Fig. 1. (A) Hall effect measurement of a $(Bi,Sb)_2Te_3/SrTiO_3$ heterostructure showing the longitudinal resistivity ρ_{xx} (blue) and Hall coefficient R_H (red) as a function of electrostatic back-gating. The peak in resistivity and change in Hall coefficient sign show the ambipolar response of the TI channel. **(B)** Resistivity and Hall coefficient after a series of consecutive timed exposures to UV light, illustrating the persistent optical gating effect. **(C)** Scanning photocurrent image showing the chemical potential gradient from a *p*-*n* junction patterned with the optical gating technique. The field of view was first initialized *p*-type by exposure to red light. The rectangular area (dotted lines) was exposed to UV light before imaging, locally gating this regions *n*-type.

This work is supported by the ONR, the AFOSR MURI, the ARO, and the NSF MRSEC.

[1] A.L. Yeats, Y. Pan, A. Richardella, P.J. Mintun, N. Samarth, D.D. Awschalom, *submitted* (2015); *arXiv:*1503:01523.

Correlated Nanoelectronics at $LaAlO_3/SrTiO_3$ Interface

Guanglei Cheng[1,2], Michelle Tomczyk[1,2], Shicheng Lu[1,2], Josh Veazey[1], Mengchen Huang[1,2], Patrick Irvin[1,2], Sangwoo Ryu[3], Hyungwoo Lee[3], Chang-Beom, Eom[3], C. Steve Hellberg[4], David Pekker[1,2], Jeremy Levy[1,2]
[1]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA USA*
[2]*Pittsburgh Quantum Institute, Pittsburgh, PA, USA*
[3]*University of Wisconsin Madison, Madison, WI USA*
[4]*Naval Research Laboratory, USA*

The strongly enhanced electron-electron correlations at oxide interfaces have given rise to a set of novel electronic phases not present in the bulk. The $LaAlO_3/SrTiO_3$ (LAO/STO) interface is a prime example that possesses superconductivity, spin-orbit interaction, magnetism and metal-insulator transition, ingredients essential for spin related technologies. The superconductivity in STO has long thought to be unconventional since it has the highest known transition temperature/carrier density (T_c/n), a quantity suggesting possible strong electron pairing, as well as a phase diagram like high-T_c superconductors. Despite sustained interest in the superconducting properties of STO, direct experimental insight into the nature of electron pairing in this superconducting semiconductor has remained elusive. Here we investigate quantum transport through superconducting single-electron transistors (SSET) created by the conductive atomic force microscopy (c-AFM) at the LAO/STO interface (Fig. 1a). The results show sharp resonant transitions corresponding to changes in electron occupation by two. The paired electrons form spin singlet states that are stable at magnetic fields and temperatures well outside of the range at which superconductivity is observed (Fig. 1b), suggesting a novel phase of electron pairing without superconductivity. These experimental findings are qualitatively consistent with a real-space strong pairing mechanism, providing parameters for an attractive-U Hubbard model description [1].

Above the Lifshitz transition in the SSET, “loop” like transport features are observed (Fig. 1c), signifying the emergence of Andreev bound state. Meanwhile, electron pairs can tunnel through the device either resonantly or non-resonantly. Combined with the re-configurability of c-AFM technology, the nanoelectronics at the LAO/STO interface holds great promise for studying strongly correlated electronic phases and Majorana fermions.

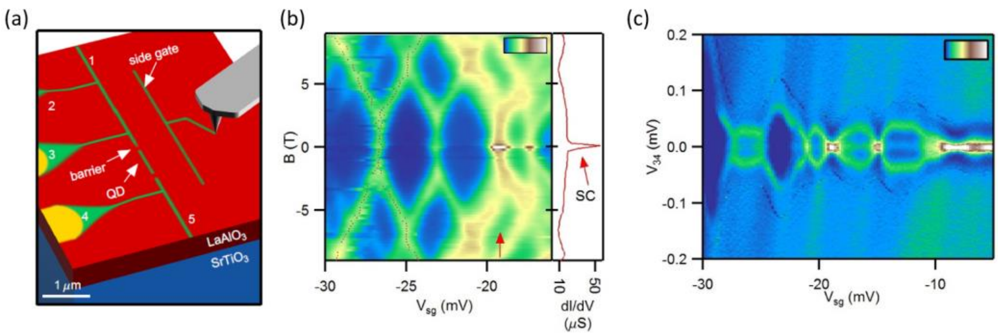


Fig. 1(a). Device schematic of the SSET created by the c-AFM lithography. Nanowires of 5 nm width are written by the c-AFM tip first, then two tunneling potential barriers are created through gentle cutting. (b) The characteristic zero-bias conductance peaks split above critical fields (~2 T), one order higher than superconducting critical field H_{c2} (~0.2 T), suggesting electron pairing without superconductivity. (c) In a different device with the same geometry, “loop” like features emerge.

[1] Guanglei Cheng et al., “Electron pairing without superconductivity”. *Nature* **521**, 196-199 (2015).

Cavity quantum electrodynamics with mesoscopic topological superconductors

Mircea Trif,[1] Olesia Dmytruk,[1] and Pascal Simon[1]
[1] *Laboratoire de Physique des Solides, CNRS UMR-8502, UniversitParis Sud, 91405 Orsay cedex, France*

Electronic transport is the foremost experimental tool for investigating the Majorana fermions physics but alternative, *non-invasive*, methods that preserve the quantum states would be highly desired to address these objects. Cavity quantum electrodynamics (cavity QED) has been established as an extremely versatile tool to address equilibrium and out-of-equilibrium electronic and spin systems non-invasively [1,2]. Majorana fermions, too, have been recently under theoretical scrutiny in the context of cavity QED physics [3,4]. However, most of the studies in this direction dealt with effective models that involved Majorana fermions only, leaving the bulk properties, which are at the heart of the Majorana physics, largely unexplored.

Motivated by this issue, we studied a one-dimensional p-wave superconductor capacitively coupled to a microwave cavity. We showed that by probing the light exiting from the cavity, one can reveal the electronic susceptibility of the p-wave superconductor allows to determine the topological phase transition point, the emergence of the Majorana fermions, and the parity of the ground state of the topological superconductor [5]. We also discuss the possibility to reveal the so called fractional Josephson effect associated with the Majorana fermions by utilizing the method of cavity QED [6]. Finally, we applied our theory to the experimentaly relevant case of a spin-orbit coupled nanowire in the proximity of an s-wave superconductor and subject to an external magnetic field [6].

Our theory demonstrates that all the above effects, which are absent in effective theories that take into account the coupling of light to Majorana fermions only, are due to the interplay between the Majoranas and the bulk states in the superconductor.

[1] M. Trif, V. N. Golovach, and D. Loss, Phys. Rev. B, **77**, 045434 (2008).

[2] K. D. Petersson, L. W. McFaul, M. D. Schroer, et al., Nature **490**, 380 (2012).

[3] M. Trif and Y. Tserkovnyak, Phys. Rev. Lett. **109**, 257002 (2012).

[4] A. Cottet, T. Kontos, and B. Douçot, Phys. Rev. B, **88** 195415 (2013).

[5] O. Dmytruk, M. Trif, and P. Simon arXiv:1502.03082.

[6] O. Dmytruk, M. Trif, and P. Simon (unpublished).

Spin-orbit induced electrical spin generation and detection in InGaAs quantum point contacts

Takanori Okayasu, Makoto Kohda, and Junsaku Nitta
[1]*Department of Materials Science, Tohoku University, 980-8579 Sendai, Japan*

Spin orbit interaction (SOI) induces an effective magnetic field for moving electrons and enables electrical spin manipulation by gate electric fields. In III-V semiconductor heterostructures, while electrical spin manipulation has been demonstrated by gate controlled spin orbit interaction [1], electrical spin generation and detection by utilizing SOI is still challenging. Recently, by modulating SOI spatially, electrical spin generation has been demonstrated in an InGaAs based quantum point contact (QPC) [2]. Since lateral confinement by side gates induces not only 1D confinement but also spin dependent force due to spatially modulated effective magnetic fields, spin up and spin down electrons are separated without any external magnetic fields and magnetic materials. As a result, integration of spin generation, manipulation and detection through SOI would be possible in semiconductors and it would pave the way towards future spintronic devices. Here, by using a magnetic focusing technique with two lateral QPC structures, we demonstrated the electrical spin generation and detection with $G = 0.5(2e^2/h)$ spin polarized plateau.

We employed a 10nm $In_{0.8}Ga_{0.2}As$ quantum well (QW) and processed into two parallel QPC structures with side gates as shown in Fig. 1. Top gate electrode was also deposited with AuGeNi/Cr for controlling the SOI strength. We measured the conductance by changing the side gate bias voltage with fixed top gate voltage V_{tg} at $T = 1.5$ K. In the magnetic focusing, we additionally applied a perpendicular magnetic field to detect spin states in a collector QPC. By measuring each QPC structure, we first confirmed quantized plateaus in steps of $2e^2/h$ as well as a spin polarized plateau as $0.5(2e^2/h)$ to reproduce previous results [2]. Then, in the lateral QPC structure (Fig.1), we investigate the magnetic focusing signal by changing the emitter and collector conductance, G_e and G_c between $0.5(2e^2/h)$ and $1.0(2e^2/h)$. Figure 2 shows the collector voltage as a function of perpendicular magnetic field in different G_e and G_c. When $G_e = G_c = 1.0(2e^2/h)$, corresponding to no spin polarized current regime (green line), first and second peak are observed around -0.3 and -0.7 T, respectively, which corresponds to the direct and reflected focusing trajectories as shown in Fig.1. When $G_e = G_c = 0.5(2e^2/h)$, which is the spin polarized current regime (red line), first peak voltage is enhanced due to injected current to collector QPC being only one spin species. Such an enhancement of collector voltage has been observed in the case of Zeeman spin splitting with an in-plane magnetic field [3]. In the present study, spontaneous spin polarization is induced by the SOI. This behavior is also reproduced in Monte Carlo simulation by taking into account the SOI induced spin polarization. As a result, we demonstrated the electrical spin generation and detection with spin resolved QPC structures.

[1] T. Bergsten *et al*., Phys. Rev. Lett. **97** 196803 (2006). [2] M. Kohda *et al*., Nat. Commun. **3** 1082 (2012). [3] R. M. Potok *et al*., Phys. Rev. Lett. **89** 266602 (2002).

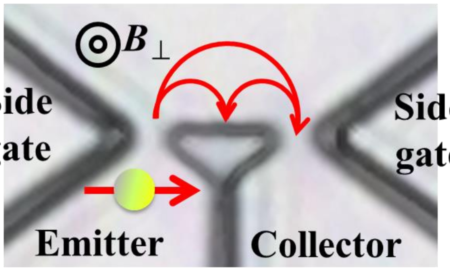


Fig. 1. SEM image of lateral QPC structures and measurement setup.

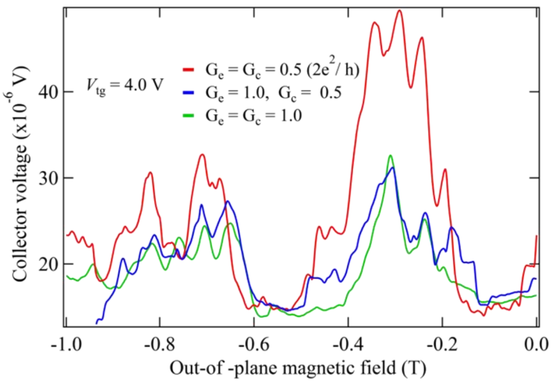


Fig. 2. Collector voltage as a function perpendicular magnetic field with different emitter and collector conductance

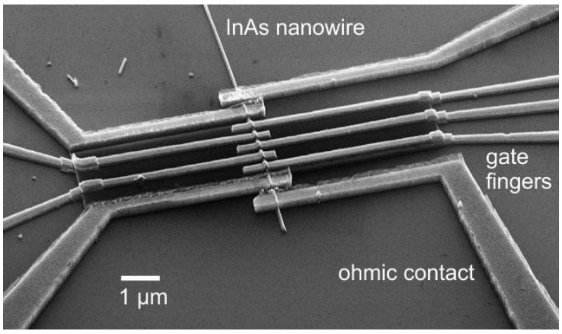
Spin-transport in InAs nanowire quantum point contacts

Sebastian Heedt,[1] Werner Prost,[2] Jürgen Schubert,[1] Detlev Grützmacher,[1] and Thomas Schäpers[1]

[1] *Peter Grünberg Institut (PGI-9) and JARA-Fundamentals of Future Information Technology, Forschungszentrum Jülich, 52425 Jülich, Germany*

[2] *Solid State Electronics Department, University Duisburg-Essen, 47057 Duisburg, Germany*

One possible option to create Majorana bound states is to use a semiconductor nanowire in proximity to a superconducting electrode [1,2]. Regarding the nanowire it is required that by combining spin-orbit coupling with Zeeman splitting a helical gap is formed [3,4]. Furthermore, only a single channel should be present in the nanowire. We have investigated high-mobility InAs nanowires ($\mu > 10^4$ cm^2/Vs) covered with a number of top gate fingers (see left figure). By applying a voltage to one of these gates a quantum-point contact is formed, resulting in a stepwise change in conductance due to ballistic transport [5,6]. Upon applying a perpendicular magnetic field, regions of large transconductance corresponding to the transition between two conductance plateaus, separate in energy and also exhibit a Zeeman splitting according to their g-factor (see right figure). Thus, at large magnetic fields the e^2/h plateau corresponding to spin-polarized transport inside a single spin-split subband becomes clearly visible. Furthermore, at moderate magnetic fields the $2e^2/h$ conductance step contains an intermediate dip structure, which indicates the formation of a helical state [3,4]. The latter is one of the requirements for the realization of Majorana bound states.



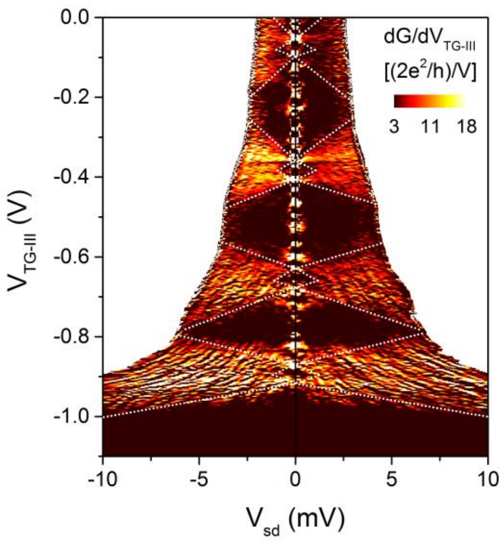


Figure 2: *Left:* InAs nanowire device with source-drain electrodes and multiple top gates strongly coupled to the nanowire via $LaLuO_3$. *Right:* Transconductance of a quantum point contact defined in an InAs nanowire at an external field of 4.5 T and a temperature of 90mK. From the width of the dark diamonds information on the energy splitting can be gained.

[1] R. M. Lutchyn, et al., Phys. Rev. Lett. 105, 077001 (2010).
[2] Y. Oreg, et al., Phys. Rev. Lett. 105, 177002 (2010).
[3] C. H. L. Quay, et al., Nat. Phys. 6, 336 (2010).
[4] C. Kloeffel, et al., Phys. Rev. B 84, 195314 (2011).
[5] I. van Weperen, et al., Nano Lett. 13, 387 (2013).
[6] F. Vigneau, et al., Phys. Rev. Lett. 112, 076801 (2014).

Subgap spectrum of normal-superconductor nanowire junctions: helical regime and Majorana bound states from exceptional points

Ramón Aguado,[1] Pablo San-Jose,[1] Elsa Prada,[2] and Jorge Cayao[1]
[1]*Instituto de Ciencia de Materiales de Madrid (ICMM), Consejo Superior de Investigaciones Científicas (CSIC), Cantoblanco, 28049 Madrid, Spain*
[2]*Departamento de Física de la Materia Condensada), Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain*

The linear conductance through a helical region, such as a depleted semiconducting nanowire with strong Rashba spin-orbit coupling and in the presence of a Zeeman field, is expected to exhibit a reentrant behavior with a helical gap of half-quantum conductance [1]. If one takes into account the finite length of the depleted section, this ideal scenario changes and the conductance acquires superimposed Fabry-Perot oscillations [2,3]. These normal transport features translate into distinct subgap states when the leads become superconducting (i.e. in a SNS junction geometry). In particular, Fabry-Perot resonances within the helical gap become zero-energy crossings, well below the critical field Bc at which the superconducting leads become topological. As a function of Zeeman field or Fermi energy, these crossings form characteristic loops and evolve continuously into Majorana bound states as the Zeeman field exceeds Bc. As I will argue, this characteristic loop pattern could be used to unambiguously identify the helical regime in nanowires [3].

Interestingly, when a helical normal region becomes a long contact in a NS geometry, the junction may host Majorana states well below Bc (namely with S in the trivial regime) after crossing an `exceptional point' in parameter space, defined as a degeneracy in the complex eigenvalues of the effective non-Hermitian Hamiltonian of the NS junction. The Majorana character of these states, derived from the eigenvalue bifurcation at the exceptional point, is protected by particle-hole symmetry and is not a result of fine tuning while their finite lifetime can be tuned to arbitrarily large values as the junction approaches perfect Andreev reflection. I will show how exceptional-point Majoranas exhibit the full range of properties associated to conventional closed-system Majorana bound states, while not requiring topological superconductivity [4].

[1] P. Streda and P. Seba, , PRL, 90, 256601 (2003).
[2]D. Rainis and D. Loss, PRB, 90, 235415 (2014).
[3] J. Cayao, E. Prada, P. San-Jose and R. Aguado, PRB 91, 024514 (2015)
[4] P. San-Jose, J. Cayao, E. Prada, and R. Aguado, arXiv:1409:7306

Giga-Hertz quantized charge pumping in bottom gate defined InAs nanowire quantum dots

A. Baumgartner,[1] M. Jung,[1] S. d'Hollosy,[1] V.A. Guzenko,[2]
M.H. Madsen,[3] J. Nygård,[3] and C. Schönenberger[1]
[1] *Institute of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*
[2] *Laboratory for Micro- and Nanotechnology, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland*
[3] *Center for Quantum Devices and Nano-Science Center, Niels Bohr Institute, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen, Denmark*

Due to the good electrical tunability and the large and variable g-factor [1,2] semiconducting nanowires (NWs) have become essential to a series of new developments in electronic quantum systems, e.g. the search for Majorana bound states [3], Cooper pair splitting [4,5] and single-spin manipulation and detection [1].

Here we demonstrate high-frequency charge pumping (CP) in InAs NWs, i.e., the controlled transport of individual electrons through a NW quantum dot (QD) at frequencies up to 1.3 GHz. The QD is induced electrostatically in a NW using 3 out of 12 narrow bottom gates in a device geometry suitable for modern experiments. A periodic voltage modulation applied to a single barrier gate results in a dc current proportional to the modulation frequency with a constant number of electrons conveyed per cycle. This number can be controlled by various external parameters, which leads to characteristic plateaus in the current. At low frequencies (5 – 50 MHz) we investigate the gate dependence of CP, as well as the effects of a dc bias and the modulation amplitude. These experiments can be understood in an intuitive electrostatic model that allows one to identify the CP-limiting processes and to extract the QD addition energies at two different times of the modulation cycle.
At higher modulation frequencies (50 MHz – 1.3 GHz) we identify several effects due to non-equilibrium carrier dynamics, in which transport mediated by excited QD states become relevant.

In InAs NWs the small effective mass results in a large level spacing, ideal for CP applications in metrology. However, CP in NWs also opens up the opportunity to investigate a variety of exotic quantum states by single electron spectroscopy and correlation experiments, e.g. Majorana [6] or fractional Fermions [7].

[1] Petersson *et al.*, Nature 380, 490 (2012)
[2] d'Hollosy *et al.*, AIP Conf. Proc. **1566**, 359 (2013)
[3] Mourik *et al.*, Science 336, 1003 (2012)
[4] Hofstetter *et al.*, Nature **461**, 960 (2009)
[5] Fülöp *et al.*, Phys. Rev. B **90**, 235412 (2014)
[6] Gibertini *et al.*, Phys. Rev. B **88**, 140508R (2013)
[7] Saha *et al.*, Phys. Rev. B **90**, 035422 (2014)

POSTERS
A

Coherent coupling of a single spin to microwave cavity photons

J.J. Viennot[1,2], M.C. Dartiailh[1], A. Cottet[1] and T. Kontos[1]
[1]*Laboratoire Pierre Aigrain, Ecole Normale Supérieure-PSL Research University, CNRS, Université Pierre et Marie Curie-Sorbonne Universités, Université Paris Diderot-Sorbonne Paris Cité, 24 rue Lhomond, 75231 Paris Cedex 05, France*
[2]*JILA, Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*

Electron spins and photons are complementary quantum mechanical objects which can be used to carry, manipulate and transform quantum information. Combining them into a scalable architecture is an outstanding challenge, as the natural coupling of the spin to the magnetic part of the electromagnetic field is very weak. In order to coherently couple a single spin to photons one has to build an artificial interface enhancing the spin/photon coupling while preserving ~~the~~ spin coherence. Spin/photon interfaces have generated a lot of interest in the optical domain. However, the use of a circuit design in the microwave range is particularly appealing due to the versatility and the scalability offered by nanofabrication techniques.

Using a circuit design based on a nanoscale spin-valve (see figure 1), we engineer a strong artificial spin orbit coupling in carbon nanotube based double quantum dot. This artificial spin orbit coupling coherently hybridize the individual spin and charge states of the double quantum dot while preserving the spin coherence [1,2]. This scheme allows us to increase by five orders of magnitude the natural (magnetic) spin-photon coupling, up to the MHz range at the single spin level. Our coupling strength yields a cooperativity which reaches 2.3, with a spin coherence time of about 60ns [2]. We thereby demonstrate a mesoscopic device which could be used for non-destructive spin read-out and distant spin coupling.

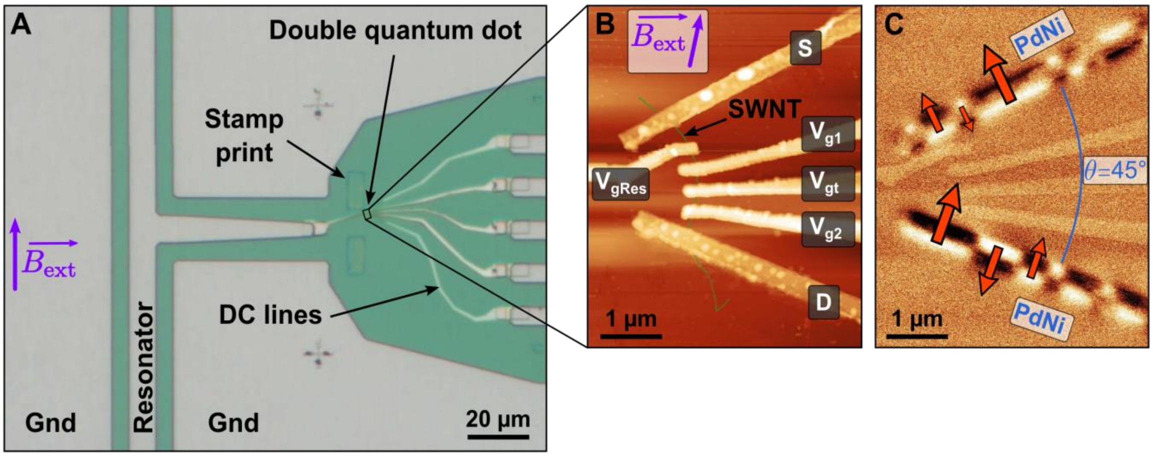


Figure 1 : A. Optical micrograph of the main part of the device. B. AFM picture of the carbon nanotube double quantum dot C. Magnetic force microscope picture of the non-collinear ferromagnetic electrodes inducing the artificial spin-orbit interaction needed for the coherent spin/photon interface.

[1] A. Cottet, T. Kontos, *Phys. Rev. Lett.* **105**, 160502 (2010).
[2] J.J. Viennot, M.C. Dartiailh, A. Cottet and T. Kontos, submitted (2014)

Magnetic and structural properties of MBE grown wurtzite (Ga,Mn)As shells in a radial quantum well nanowire heterostructures

A. Šiušys[1], J. Sadowski[1,2], S. Kret[1], T. Wojciechowski[1], T. Story[1], and M. Sawicki[1]

[1]*Institute of Physics, Polish Academy of Sciences, Warszawa, Poland*
[2]*MAX-IV Laboratory, Lund University, Sweden*

Investigation of (Ga,Mn)As ferromagnetic semiconductor in a form of quasi 1-dimensional nanostructures is important in the context of ferromagnetic nanowires which were proposed as a base for a new type of nano-magnetic memory structures [1] and magnetic logics [2] manufactured from nanowire grids [3]. Conditions required to prepare a ternary (Ga,Mn)As alloy, which are dictated by low temperature MBE growth are in contradiction to the growth procedure of metal-induced formation of NWs. Hence, the only way to produce (Ga,Mn)As in a nanowire geometry can be realised as a shell deposited on a beforehand grown semiconductor core nanowire templates. Here, in order to additionally tune the magnetic anisotropy by strain, cores made from (In,Ga)As alloy were chosen. Variation of In concentration in the core allows to achieve desired strain state in the shell. In addition, the presence of In in the cores not only determines strain, but also induces wurtzite crystalline structure, which is inherited by magnetic (Ga,Mn)As shells. However, in earlier studies we found that such core-shell NWs lack a long-range magnetic order and magnetically behave as super-paramagnets [4], despite, 5 % of Mn content, what is more than sufficient to induce ferromagnetism in planar (Ga,Mn)As. We attribute this behaviour to a lack of itinerant holes, which mediate the long-range ferromagnetic interactions. Assuming that the shell growth is optimised to obtain both smooth morphology and the lowest concentration of defects while keeping the highest amount of Mn possible, the lack of the mobile holes was attributed to their out diffusion towards the core and/or to the surface depletion. To counter act these effects, NWs with high temperature $Al_{0.4}Ga_{0.6}As$ or low temperature grown GaAs post-growth annealed at 600 ^{o}C in order to create metallic As nanoclusters pinning the Fermi level in the middle of the GaAs band-gap [5] barriers for holes between the $In_{0.2}Ga_{0.8}As$ core and the $Ga_{0.95}Mn_{0.05}As$ shell were prepared. The high crystalline quality of these multi-shells of NWs has been confirmed by dedicated XRD for the ensembles of NWs and high resolution TEM studies of individual NWs in two geometries: cross-sectional and perpendicular to the side facets. For these NWs a weak spontaneous magnetisation has been observed below 24 K during a cool down from high temperatures, which is the first such observation in the MBE grown NWs with (Ga,Mn)As shells - a form different than planar epilayer. By comparing these results with our previous findings [4] we can conclude that in the re-designed NWs we literally witness the birth of the long range FM order, which is just surfacing from the still (present) overwhelming SP component.

[1] Hayashi, M., Thomas, L., Moriya, R., Rettner, C., Parkin, S. S. *Science*, **320**, 209 (2008).
[2] Omari, K. A., Hayward, T. J. *Phys. Rev. Appl.*, **2**, 044001 (2014).
[3] Kang, J. H., Cohen, Y., Ronen, Y., Heiblum, M., Buczko, R., Kacman, P., Popovitz-Biro, R., Shtrikman, H. *Nano lett.*, **13**, 5190 (2013).
[4] Siusys, A., Sadowski, J., Sawicki, M., Kret, S., Wojciechowski, T., Dluzewski, P., Gas, K., Szuszkewicz, W., Kaminska, A., Story, T. *Nano lett.*, **14**, 4263 (2014).
[5] Maranowski, K. D., Ibbetson, J. P., Campman, K. L., Gossard, A. C. *Appl. Phys. Lett.*, **66**, 3459 (1995).

Exact nonadiabatic qubit manipulation and non-Abelian geometric phases

Anton Ramsak,[1,2] Ambroz Kregar,[2] and Lara Ulcakar[1,2]
[1]*Faculty of Mathematics and Physics, University of Ljubljana*
[2]*J. Stefan Institute, 1000 Ljubljana, Slovenia*

First we will present an exact solution for the wavefunction of an electron in a semiconductor quantum wire with spin-orbit interaction and driven by external time-dependent harmonic confining potential [1]. The motivation is the manipulation of electron spin by locally applying an external electric field -- in the absence of magnetic fields which in practice can not selectively be applied in spatially small regions. Next, the solution will be extended to a more general system, where also the spin-orbit interaction can be time dependent. This additional time dependent degree of freedom enables a holonomic non-Abelian qubit manipulation [2] and the generalization of the formalism to mesoscopic ring systems opens the possibility to perform arbitrary qubit transformations on the Bloch sphere [3].

For a broad class of driving functions one can by the virtue of the exact solution also in the non-adiabatic regime construct analytically the corresponding dynamical and the geometric Anandan phase [4] or in the adiabatic limit the Wilczek-Zee phase [5]. By breaking the time reversal symmetry the results lead to the corresponding Aharonov-Anandan phase [6] which in the adiabatic limit reduces to the usual Berry phase [7]. A short introduction to the concept of geometric phases in quantum mechanics will be given.

[1] T. Cadez, J. H. Jefferson, and A. Ramsak, New J. Phys. 15, 013029 (2013).
[2] T. Cadez, J. H. Jefferson, and A. Ramsak, Phys. Rev. Lett. 112, 150402 (2014).
[3] A. Kregar, J. H. Jefferson, and A. Ramsak, to be submitted.
[4] J. Anandan, Physics Letters A 133, 171 (1988).
[5] F. Wilczek and A. Zee, Phys. Rev. Lett. 52, 2111 (1984).
[6] Y. Aharonov and J. Anandan, Phys. Rev. Lett. 58}, 1593 (1987).
[7] M. V. Berry, Proceedings of the Royal Society of London, A. Mathematical and Physical Sciences 392, 45 (1984) .

Universal Quantum Transducers based on Surface Acoustic Waves

M. J. A. Schuetz,[1] E. M. Kessler,[2,3] G. Giedke,[4,5] L. M. K. Vandersypen,[6] M. D. Lukin,[2] and J. I. Cirac[1]
[1] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
[2] Physics Department, Harvard University, Cambridge, MA 02318, USA
[3] ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02318, USA
[4] Donostia International Physics Center, Paseo Manuel de Lardizabal 4, 20018 San Sebastián, Spain
[5] Ikerbasque Foundation for Science, Maria Diaz de Haro 3, 48013 Bilbao, Spain
[6] Kavli Institute of NanoScience, TU Delft, P.O. Box 5046, 2600 GA Delft, The Netherlands

We propose a universal, on-chip quantum transducer based on surface acoustic waves in piezo-active materials [1]. Because of the intrinsic piezoelectric (and/or magnetostrictive) properties of the material, our approach provides a universal platform capable of coherently linking a broad array of qubits, including quantum dots, trapped ions, nitrogen-vacancy centers or superconducting qubits. The quantized modes of surface acoustic waves lie in the gigahertz range, can be strongly confined close to the surface in phononic cavities and guided in acoustic waveguides. We show that this type of surface acoustic excitations can be utilized efficiently as a quantum bus, serving as an on-chip, mechanical cavity-QED equivalent of microwave photons and enabling long-range coupling of a wide range of qubits.

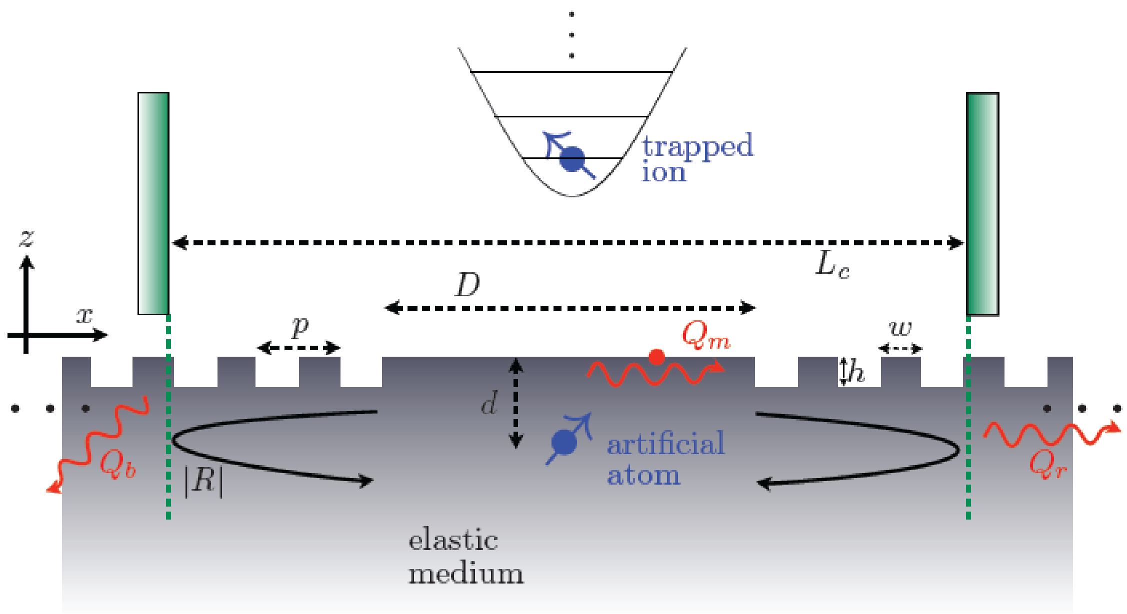


Figure 1: SAW as a universal quantum transducer. Distributed Bragg reflectors made of grooves form an acoustic cavity for surface acoustic waves. The resonant frequency of the cavity is determined by the pitch p. Reflection occurs effectively at some distance inside the grating; the fictitious mirrors above the surface are not part of the actual experimental setup, but shown for illustrative purposes only. Red arrows indicate the relevant decay channels for the acoustic cavity mode: leakage through the mirrors, internal losses due to for example surface imperfections, and conversion into bulk modes. Qubits inside and outside of the solid can be coupled to the cavity mode. In more complex structures, the elastic medium can consist of multiple layers on top of some substrate.

[1] arXiv: 1504.05127.

Coherent control of a nitrogen-vacancy center spin with a diamond mechanical resonator

E. R. MacQuarrie,[1] T. A. Gosavi,[1] A. M. Moehle,[1] N. R. Jungwirth,[1] S. A. Bhave,[1] and G. D. Fuchs[1]
[1] *Cornell University, Ithaca, New York 14853, USA*

Coherent control of the nitrogen-vacancy (NV) center in diamond's triplet spin state has traditionally been accomplished with resonant ac magnetic fields. Lattice strain within the host diamond can interact coherently with the NV center spin state, enabling mechanical spin control as a new degree of freedom within the NV center Hamiltonian [1-5]. Here, we use a bulk-mode mechanical microresonator fabricated from single-crystal diamond (Fig. 1a) to generate intense ac strain within the diamond substrate and drive mechanical Rabi oscillations between the $|(m_s =) - 1\rangle$ and $|+1\rangle$ spin states of a single NV center spin (Fig. 1b). This mechanical driving generates hybridized states that are less sensitive to magnetic field fluctuations than the bare $|-1\rangle$ and $|+1\rangle$ spin states [5, 6]. A qubit composed of these mechanically dressed states can thus remain coherent more than ten times longer than its counterpart made of undressed m_s states. This mechanical decoupling protocol could be used to enhance NV-based metrology and prolong quantum memories. Mechanical driving of NV centers also provides a means of creating a phase-sensitive Δ-system inside the NV center ground state with potential applications in quantum sensing.

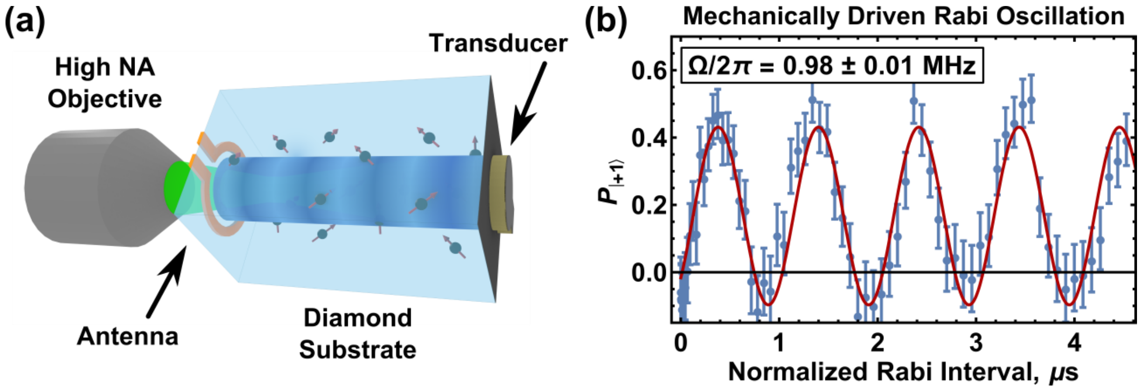


Fig. 1: (a) Device schematic. A high-overtone bulk acoustic resonator (HBAR) generates ac lattice strain for mechanical spin control, and a magnetic antenna provides conventional magnetic field control [1, 4]. (b) Mechanically driven Rabi oscillations between the $|-1\rangle$ and $|+1\rangle$ spin states of a single NV center.

[1] E. R. MacQuarrie, T. A. Gosavi, N. R. Jungwirth, S. A. Bhave, and G. D. Fuchs, *Phys. Rev. Lett.*, **111**, 227602 (2013).
[2] J. Teissier, A. Barfuss, P. Appel, E. Neu, P. Maletinsky, *Phys. Rev. Lett.*, **113**.
[3] P. Ovartchaiyapong, K. W. Lee, B. A. Myers, A. C. B. Jayich, *Nat. Commun.*, **5**, 4429 (2014).
[4] E. R. MacQuarrie, T. A. Gosavi, A. M. Moehle, N. R. Jungwirth, S. A. Bhave, and G. D. Fuchs, *Optica* **2**, 233 (2015).
[5] A. Barfuss, J. Teissier, E. Neu, A. Nunnenkamp, and P. Maletinsky, *arXiv:1503.06793* (2015).
[6] E. R. MacQuarrie, T. A. Gosavi, S. A. Bhave, and G. D. Fuchs, *in preparation* (2015).

Coulomb blockade effect in graphene-like nanoribbons with in-plane edge magnetization

I. Weymann,[1] J. Barnaś,[1,2] and S. Krompiewski[2]
[1]*Adam Mickiewicz University, 61-614 Poznań, Poland*
[2]*Institute of Molecular Physics, Polish Academy of Sciences, 60-179 Poznań, Poland*

This contribution deals with a new emerging class of the so-called graphene-like nanomaterials (incl. silicene, stanene, germanene etc.), which may outperform graphene in the near future. The main attention is directed to the influence of magnetic anisotropy - induced by the intrinsic spin-orbit interaction (ISOI) - on electronic, magnetic and transport properties. Of particular interest here is the in-plane magnetic configuration which has been recently shown to be energetically more stable than the out-of-plane one [1].

By means of a tight-binding method with the Hubbard type correlations and the real-time diagrammatic technique, we show that Coulomb-blockade (CB) spectra contain information about both the ISOI and the edge magnetic moment configuration. Fig.1 corresponds to a small graphene-like flake with a finite ISOI parameter t_{SO}=0.025t, where t stands for the nearest-neighbor hopping. In this case edge magnetic moments lie within the nanostructure plane and amount up to *ca* 0.3 μ_B.

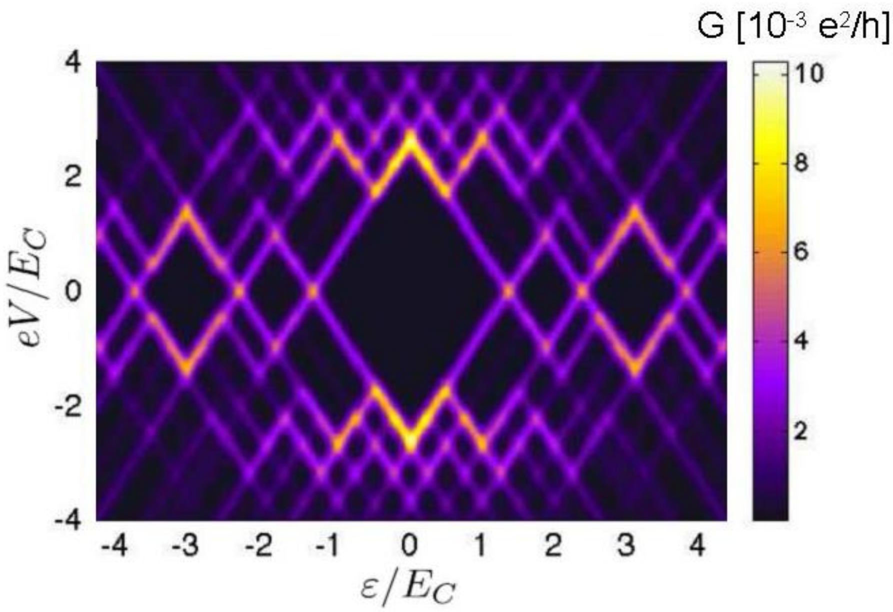


Fig.1 Differential conductance in the Coulomb blockade regime as a function of bias voltage (V) and a normalized energy shift (with respect to the charge neutrality point) proportional to the gate voltage.

Acknowledgments: Supported by the Polish National Science Centre from funds awarded through the decision No. DEC-2013/10/M/ST3/00488.

[1] J. L. Lado and J. Fernández-Rossier, Phys. Rev. Lett. **113**, 027203 (2014).

A Majorana Analogue to the Kondo State

Ian van Beek and Bernd Braunecker
University of St Andrews

In addition to their much vaunted potential for realizing topologically protected quantum computation, Majorana Bound States (MBSs) offer access to other novel physics. In this work we study the MBS hosted in the popular one-dimensional topological superconductor system [1, 2], but with an additional charging energy. Previous studies [3] have shown how electronic transport in this system can display striking non-local effects. We extend this analysis and explore the parallels between the well-known Kondo state, and the state formed by the Majorana-mediated interaction between metallic leads and the floating superconductor, in particular considering its spin properties. We note that the subject of our study is distinct from the so-called Topological Kondo Effect [4], which arises from the topological degeneracy associated with multiple MBSs.

[1] Y. Oreg et al., Phys. Rev. Lett. **17**, 177002(2010) ; R. Lutchyn et al., Phys. Rev. Lett. **105**,077001(2010).
[2] V. Mourik et al., Science **336**, 6084 (2012) ; A. Das et al., Nat. Phys. **8**, 887-95 (2012) ; M.T. Deng et al., Nano Lett. **12**, 6414-19 (2012) ; H. O. H. Churchill et al., Phys. Rev. B **87**, 241401 (2013).
[3] L. Fu, Phys. Rev. Lett. **5**, 056402 (2010); A. Zazunov et al., Phys. Rev. B **84**, 165440 (2011); A. Zazunov and R. Egger, Phys. Rev. B **85**, 104514(2012); R. Hützen, A. Zazunov, B. Braunecker, A. Levy Yeyati and R. Egger, Phys. Rev. Lett. **109**, 166403 (2012).
[4] B. Béri and N. Cooper, Phys. Rev. Lett. **109**, 156803 (2012); A. Altland et al., Phys. Rev. Lett. **113**, 076401 (2014); M. R. Galpin et al., Phys. Rev. B **89**, 045143 (2014); E. Eriksson et al., Phys. Rev. B **90**, 245417 (2014).

Co/C_{60} Spinterfaces

K. Wang*, J. G. M. Sanderink, T. Bolhuis, W. G. van der Wiel and M. P. de Jong

NanoElectronics Group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, Enschede, 7500AE, The Netherlands
*Correspondence to: k.wang@utwente.nl

An intriguing phenomenon occurring at ferromagnet/organic interfaces is magnetic interfacial hybridization: The mutual interaction induces interfacial electronic energy states with distinct magnetic properties, mainly due to spin-polarized electron transfer from the ferromagnet. Spin-related transport across such tailored interfaces can be significantly influenced by these hybridization effects.[1] Here, we focus on magneotransport studies in devices containing interfaces between epitaxial face-centered-cubic (fcc) cobalt (Co) and non-magnetic fullerenes (C_{60}). In one set of junctions, a C_{60} molecular layer is in direct contact with a Co bottom contact, and is capped with an AlO_x tunneling barrier and an Al top contact [layer structure: sapphire(substrate)/Co(8 nm)/C_{60}(4 nm)/AlO_x (3.3 nm)/Al (35 nm)]. Since only one ferromagnetic contact (Co) is present, tunneling anisotropic magnetoresistance (TAMR) determines the effects. The TAMR of Fig.1(a) shows distinctly different magnetic switching behavior than that observed in anisotropic magnetoresistance (AMR) measurements of the Co/C_{60} bi-layer (see Fig.1 (b)). Fig.1 (c) reveals a two-fold symmetric TAMR upon rotating an in-plane 800 mT magnetic field, with a maximum ratio of 0.7% at a bias current of 0.5 μA measured at 5 K, which is markedly different from that of devices based on fcc-Co without C_{60} [2,3]. We believe these phenomena can be attributed to the magnetic coupling between Co and the C_{60}-derived hybrid interfacial states, which is expected to bring some interesting functionalities for organic spintronic applications.

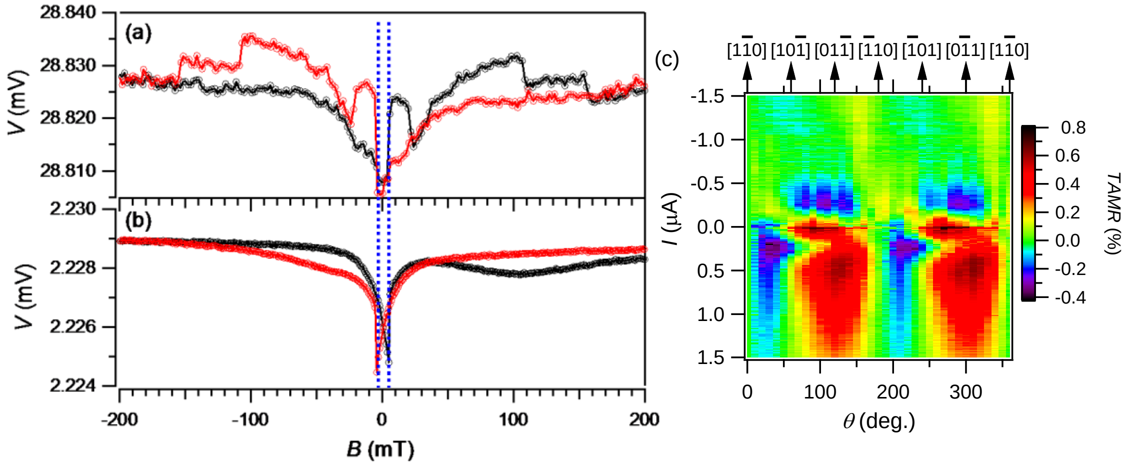


Figure 1. (a) TAMR measured at 5 K for the sapphire/Co(8 nm)/C_{60}(4 nm)/AlO_x (3.3 nm)/Al (35 nm) junction, (b) the in-plane AMR for the Co/C_{60} bi-layer, and (c) TAMR measured at 5 K upon rotating a 800 mT magnetic field over an in-plane angle θ.

References:

[1] S. Sanvito, *Nat. Phys.* **6**, 562 (2010).
[2] K. Wang, et. al, *Phys. Rev. B* **88**, 054407 (2013).
[3] K. Wang, et. al, *Phys. Rev. B* **89**, 174419 (2014).

Carbon nanotube *n-p* quantum dots

E. N. Osika and B. Szafran
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059 Kraków, Poland

Semiconducting carbon nanotubes (CNTs) provide a good environment for carrier confinement in electrostatically defined quantum dots (QDs). This feature is particularly relevant in context of spin manipulation of individual electrons, which is a prerequisite for quantum information processing devices. Recently, a few experiments focused on spin manipulation in ambipolar carbon nanotube quantum dots have been conducted [1-2]. Part of the results still remains unexplained and can not be described basing only on assumed ambi- and unipolar dots similarities. A comprehensive description of unipolar QDs in CNT is available in the literature. No similar description has been provided so far for ambipolar QDs.

We consider ambipolar *n-p* double quantum dot in (1e,3h) configuration - one electron localized in *n* dot and three holes localized in *p* dot. This system has been investigated experimentally in context of the valley and/or spin blockade of the current flow through a double QD [1]. We describe the spectra of such system using an exact diagonalization method within the tight-binding approach. In the model we take into account curvature-induced spin-orbit interaction [3], external fields, the electron-electron interaction and the intervalley scattering mediated by the atomic defects.

We show that the electronic structure of the double *n-p* dot differs from the *n-n* dot in a few elementary aspect [4]. The energy splitting due to exchange interaction is found only for specific two-electron states and for limited range of external magnetic field, while in *n-n* unipolar dots well defined singlet- and triplet-like states are formed with exchange interaction independent of the magnetic field. Also, in contrast to *n-n* system, the two-electron ground state in ambipolar DQD is fourfold degenerate.We indicate that observed differences for *n-n* and *n-p* systems are an effect of opposite electron circulation in the conductance and valence bands for a given valley. We discuss universality of our results for CNTs of various chirality and quantum dots sizes.

[1] F. Pei, E. A. Laird, G. A. Steele, and L. P. Kouwenhoven, Nature Nano. 7, 630 (2012).
[2] E.A. Laird, F. Pei, and L.P. Kouwenhoven, Nature Nano. 8, 565 (2013).
[3] T. Ando, J. Phys. Soc. Jpn. 69, 1757 (2000).
[4] E. N. Osika and B. Szafran, Phys. Rev. B 91, 085312 (2015).

Nanomechanical single- and two-qubit gates of single-electron spins in a carbon nanotube

Heng Wang and Guido Burkard
University of Konstanz, Germany

We investigate the manipulation of a single spin in a suspended carbon nanotube (CNT) quantum dot [1]. The manipulation is based on the spin-mechanical coupling induced from the intrinsic spin-orbit coupling [2]. We use a Jaynes-Cummings model with a quantized flexural mode of the resonator to describe the system. An external electric field is used to drive the resonator and to induce an interaction between the single electron in the quantum dot and the external driving field. Arbitrary-angle rotations about arbitrary axes of the single electron spin can be achieved by varying the frequency and the strength of the external electric driving field.

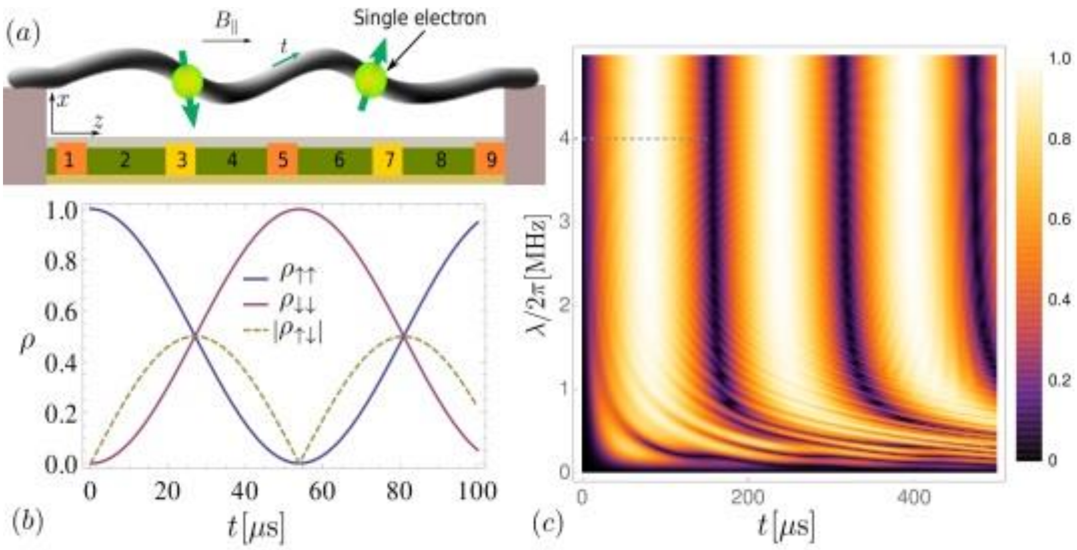


FIG. (a) Schematic of the nanomechanical system where two quantum dots lie in a doubly clamped, suspended CNT which is fixed by two supports at two ends. (b) The time evolution of the density matrix elements under the conditions of electron spin resonance. (c) The time evolution of the concurrence as a function of the driving strength.

With two separated single-electron spins trapped in two quantum dots in a suspended CNT, an indirect coupling between two single-electron spins is induced based on the simultaneous interaction of the two spins with the mechanical mode of the CNT. We show how a two-qubit iSWAP gate and arbitrary single-qubit gates can be obtained by analyzing the effective Hamiltonian from the time-dependent Schrieffer-Wolff transformation and the time evolution operator. Combining the iSWAP gate and single-qubit gates, maximally entangled states of two spins can be generated within a single step by adjusting the frequency and the strength of the external electric driving field. The iSWAP gate and single-qubit gates can be turned off when suppressing the spin-phonon coupling by electrostatically shifting the electron wave function on the nanotube.

[1] H. Wang and G. Burkard, Phys. Rev. B 90, 035415 (2014).
[2] A. Pályi, P. R. Struck, M. Rudner, K. Flensberg, and G. Burkard, Phys. Rev. Lett. 108, 206811 (2012).

High sensitivity diamond-piezomagnetic hybrid sensor for nanoscale stress measurement

Phani Peddibhotla,[1] Benjamin Riedmueller,[2] Farzaneh Vaghefikia,[1] Liam McGuinness,[1] Jianming Cai,[3] Martin Plenio,[3] Berndt Koslowski,[4] Ulrich Herr,[2] and Fedor Jelezko[1]

[1] *Instittute for Quantum Optics, University of Ulm, Germany*

[2] *Institute for Micro- and Nanomaterials, University of Ulm, Germany*

[3] *Institute for Theoretical Physics, University of Ulm, Germany*

[4] *Institute for Solid State Physics, University of Ulm, Germany*

We report on the development of a hybrid diamond-piezomagnetic system for the measurement of stress (force). The hybrid device consists of a thin magnetostrictive film deposited onto the diamond sample containing nitrogen-vacancy (NV) centers. Application of a stress on the thin film results in a change in the stray magnetic field outside the magnetostrictive material. Optical readout of the spin quantum state of the NV center encodes information about the change in the magnetic field thereby resulting in a transduction of force or pressure.

It is demonstrated theoretically that this hybrid architecture has the potential to dramatically improve the sensitivity for the measurement of stress [1]. By taking advantage of the strong magnetic response of a piezomagnetic layer to an external stress, the minimum stress that can be measured is smaller by three orders of magnitude in comparison to current state-of-the-art diamond sensing devices. This hybrid approach also opens the door for significantly enhancing the coherent coupling between the vibrational mode of a diamond nanomechanical resonator and NV electron spin.

We have developed the techniques for the deposition and characterization of piezomagnetic Terfenol-D thin film deposited onto a diamond sample containing NV center spins. Our optically detected magnetic resonance (ODMR) measurements have shown that the NV spin qubit energy splitting is modified due to the presence of the stray magnetic field from the piezomagnetic film (Fig. 1). The next step would be to determine how the application of stress on a thin film changes the spin properties of an NV center.

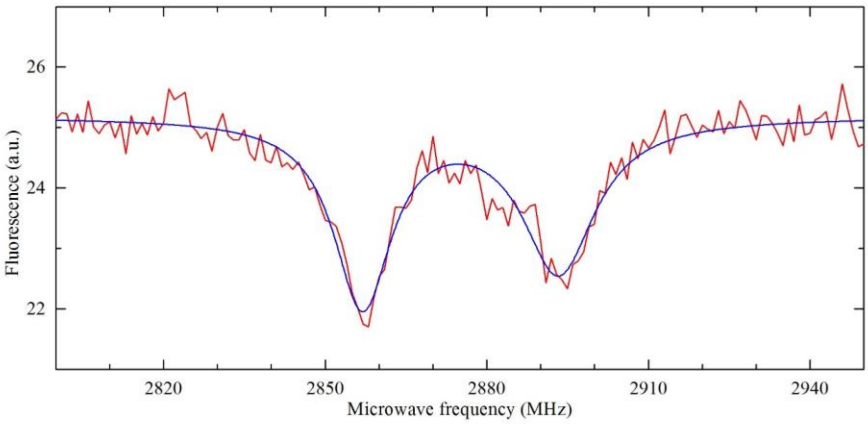


Figure 1. The response of NV center ODMR spectra in the presence of a thin film of Terfenol-D

[1] J. Cai, F. Jelezko, and M. Plenio, Nat. Commun. 5:4065 (2014).

Electrical spin injection into two-dimensional electron gas: spin valve and spin precession signals

M. Oltscher, T. Kuczmik, J. Loher, D. Schuh, D. Bougeard, M. Ciorga, and D. Weiss

Institute for Experimental and Applied Physics, University of Regensburg,
93040 Regensburg, Germany

Electrical spin injection into a two-dimensional electron gas (2DEG) is a prerequisite for many new functionalities in spintronic device concepts, with the Datta-Das spin field effect transistor [1] being a prototypical example. Whereas spin injection phenomena in bulk semiconductors has been extensively studied in recent years, spin injection into high mobility 2D systems still remains a relatively unexplored area of research.

In this contribution we present a summary of our recent investigations on spin injection into a high mobility 2DEG confined in an (Al,Ga)As/GaAs structure [2]. In general, we observe large nonlocal spin valve (SV) signals, which can be widely tuned by a voltage applied to the injecting contact. A particularly large enhancement is observed at negative bias. At maximum the signal significantly exceeds the value predicted by the standard model of spin injection based on spin drift-diffusion equations. A strong correlation of this enhancement with the width of the contacts and with the electron mean free path leads us to the conclusion that ballistic transport in the 2D region directly below the injector should be taken into account to fully describe the experimental results.

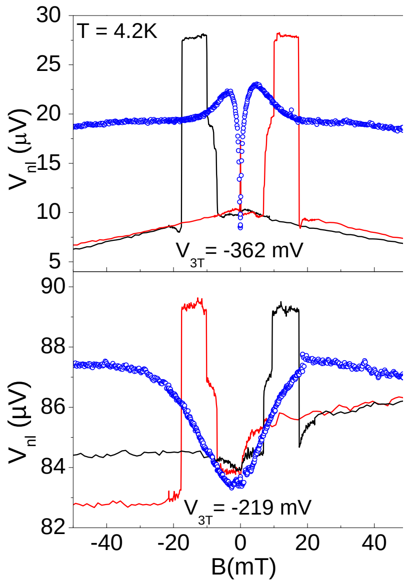


Fig.1 Nonlocal voltage V_{nl} in spin valve (solid lines) and Hanle (points) measurements for two different values of bias voltage V_{3T}.

Additionally to SV measurements, we employed also Hanle measurements of spin precession in an out-of-plane magnetic field to probe the spin accumulation in the 2DEG. We observe that not only the amplitude of the precession signal but also its full-width-at-half-maximum strongly changes with the bias voltage V_{3T} applied across the injector (see Fig. 1). The narrowest curves are observed in the region of the enhanced signal at negative bias. In the region of low bias -0.1 V < V_{3T} < 0.1 V, on the other hand, no precession curves are observed. What is more, spin lifetimes extracted from the measurements (~23 ns for the narrowest curve) differ by orders of magnitude from the values expected for 2DEGs and from the value of 24 ps extracted earlier from spin-valve measurements [2]. We discuss the results in connection to dynamic nuclear polarization (DNP) effects in the system, which are known to narrow the experimental Hanle curves. Such an interpretation is supported by the observed correlation between the Hanle curves and the appearance of a DNP-related depolarization peak in spin valve measurements.

The work has been supported by the German Science Foundation (DFG) through the project SFB689.

[1] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
[2] M. Oltscher *et al.*, Phys. Rev. Lett. **113**, 236602 (2014).

Impurity Induced Quantum Phase Transitions and Magnetic Order in Conventional Superconductors: Competition between Bound and Quasiparticle States

Silas Hoffman[1], Jelena Klinovaja[1], Tobias Meng[2,1], and Daniel Loss[1]
[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland and* [2]*Institut fur Theoretische Physik, Technische Universitat Dresden, 01062 Dresden, Germany*

We theoretically study bound states generated by magnetic impurities within conventional *s*-wave superconductors, both analytically and numerically. In determining the effect of the hybridization of two such bound states on the energy spectrum as a function of magnetic exchange coupling, relative angle of magnetization, and distance between impurities, we find that quantum phase transitions can be modulated by each of these parameters. Accompanying such transitions, there is a change in the preferred spin configuration of the impurities. Although the interaction between the impurity spins is overwhelmingly dominated by the quasiparticle contribution, the ground state of the system is determined by the bound state energies. Self-consistently calculating the superconducting order parameter, we find a discontinuity when the system undergoes a quantum phase transition as indicated by the bound state energies.

A donor/dot surface code insensitive to inter-qubit coupling for parallel fault-tolerant silicon quantum computing

G. Pica[1], S. A. Lyon[2], R. N. Bhatt[2], T. Schenkel[3], and B. W. Lovett[1]

[1]*SUPA, School of Physics and Astronomy, University of St Andrews, KY16 9SS, UK*

[2]*Dept. of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA*

[3]*Ion Beam Technology Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Entangling two-qubit operations based on the exchange interaction between spins are crucial for universal silicon quantum computing. Scaling such gates to large, practical quantum computers poses strict limitations to the placement of donor atoms [1], while it is easily achieved with flexible quantum dots. The latter, however, suffer from coherence times several orders of magnitude smaller than those provided by bismuth donors in silicon tuned to clock-transitions ($T_2 \sim 3$s) [2].

We present a surface code architecture that combines Si:Bi spins hosting measurement qubits (MQ) to MOS quantum dots playing the role of data qubits (DQ), as shown in Fig. 1. Most of the steps of a generic surface code, as e.g. proposed in Ref. [3], could be implemented via well established microwave driven ENDOR transitions on the bismuth donors and realistic shuttling of the array of the interface dot electrons with CCD-like gates. A detailed plan is suggested to fill the fundamental gap of how to perform CNOT gates between the MQ and the DQ: rather than pulsing an exchange interaction *J* to generate a dynamical phase, as in previous proposals, the exchange is used to SWAP spin states between the quantum dots and the donors through robust, addressable adiabatic transfer. Most notable is that such SWAP gates are insensitive to even order of magnitude variations in the *J* interaction strength, as shown in Fig. 2: it is possible to achieve gate fidelities easily tolerated by the surface code error threshold (about 1% per-operation error rate [3]) across almost the entire array. Since all the manipulations proposed here require μs operating times, our scheme promises fast, fault-tolerant parallel silicon quantum computing. While other approaches (such as Kane's quantum computer [4]) require tuning individual qubits in resonance with a global microwave field, our structures only require the control of the SWAP in a site-selective manner, which is accomplished simply with a dc gate voltage that tunes the exchange coupling.

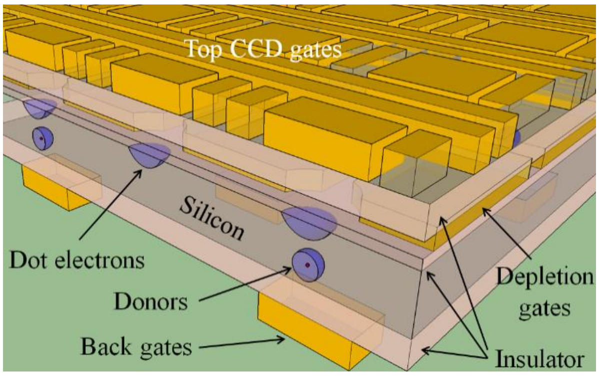


Fig. 1: Schematic diagram of the donor-dot array structure, where the back gates selectively control the exchange coupling between the donor electrons and the electrons in the quantum dots placed above them.

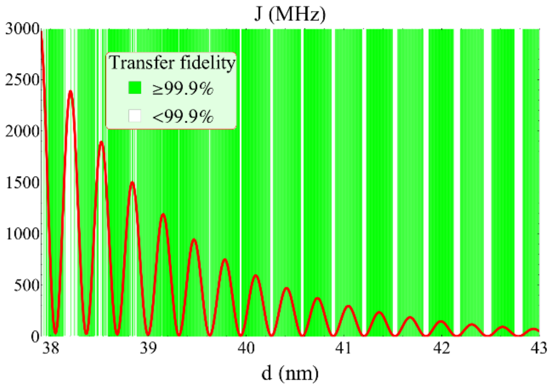


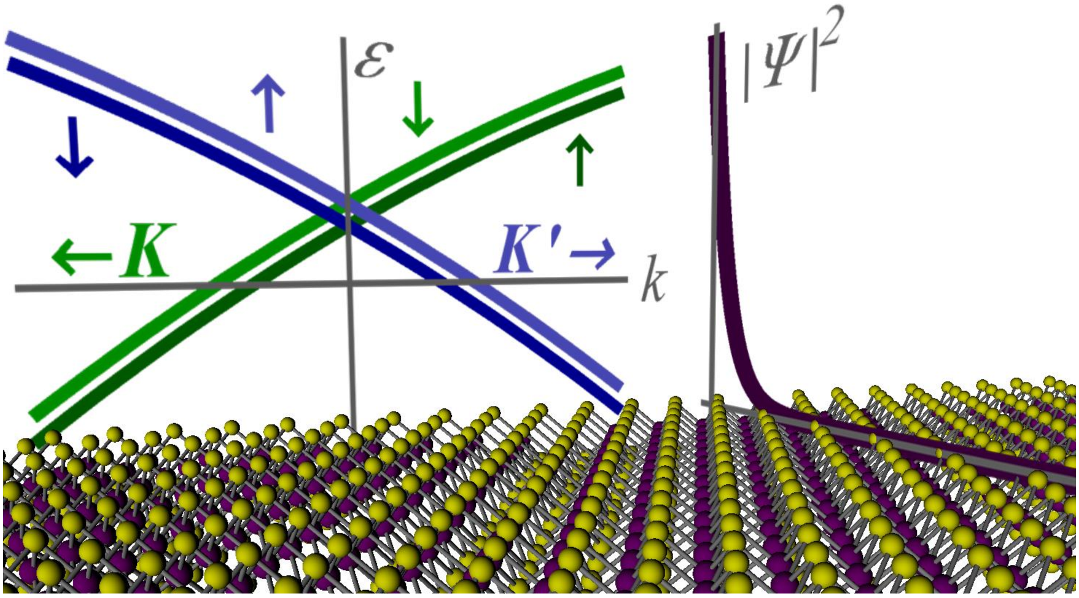
Fig. 2: Though different donor/dot electron pairs experience a wide range of *J* couplings within a scaled architecture with imprecise donor positioning *d*, almost all pairs in the array, i.e. those highlighted in green, would undergo successful SWAPs.

[1] G. Pica *et al.*, Phys. Rev. B **89**, 235306 (2014)
[2] G. Wolfowicz *et al.*, Nature Nanotechnology **8**, 561 (2013)
[3] A.G. Fowler *et al.*, Phys. Rev. A **86**, 032324 (2012)
[4] B.E. Kane, Nature **393**, 133-137

Boundary conditions for monolayer transition-metal dichalcogenides in the continuum model

Csaba G. Péterfalvi, Andor Kormányos, and Guido Burkard
Department of Physics, University of Konstanz, D-78464 Konstanz, Germany

We derive the boundary conditions for monolayer MoS_2 and similar transition-metal dichalcogenide honeycomb lattices with the same type of $\boldsymbol{k}.\boldsymbol{p}$ Hamiltonian within the continuum model around the K point [1]. In the effective 2-band description, the electron-hole symmetry-breaking quadratic terms are also taken into account. We model the effect of the edges with the M matrix method that has also been applied previously to graphene [2,3]. Focusing mainly on zigzag edges, we find that different reconstruction geometries with different edge atoms can be generally described with one scalar parameter varying between 0 and 2π. We analyze the edge states and their dispersion relation in MoS_2 in particular, and we find good agreement with the results of DFT calculations for all the various edge types studied in Reference [4].



Electrons in the K and K' valleys propagate in opposite directions with opposite spins along the purely sulphur terminated zigzag edge in MoS_2 (Fig.1a of Ref.[4]). The bands are spin-split by 70 meV.

[1] A. Kormányos, V. Zólyomi, N. D. Drummond, P. Rakyta, G. Burkard, and V. I. Fal'ko, Phys. Rev. B **88**, 045416 (2013).
[2] A. R. Akhmerov and C. W. J. Beenakker, Phys. Rev. B **77**, 085423 (2008).
[3] E. McCann and V. I. Falko, J. Phys.: Condens. Matter **16**, 2371 (2004).
[4] E. Erdogan, I. H. Popov, A. N. Enyashin, and G. Seifert, Eur. Phys. J. B **85**, 1 (2012).

Magnetic moments in superconductors: from Shiba to Majorana bound states

Pascal Simon

Laboratoire de Physique des Solides, University Paris Sud, 91405 Orsay

The study of magnetic impurities in superconductors has a long history. Important effects include the renormalization reduction of the gap in the host superconductor by the impurities and the induced Yu-Shiba-Rusinov bound states. In recent years, a renewed interest in chains of magnetic impurities in superconductors was furthermore driven by their potential to host Majorana zero modes.

I will first review and present new results for the single classical magnetic impurity case embedded in some exotic superconductors. In particular, I will show on the real space spectroscopy oft he bound state wave function brings information on the nature of the order parameter of the superconductor [1]. Analyzing two magnetic moments in a superconductor, I will show how the gap renormalizes for weakly and strongly coupled bound states. In the latter case, a transition from Shiba to Andreev states which is accompanied by two subsequent quantum phase transitions as the exchange coupling is varied is found [2]. These predictions lead to dramatic spectral changes which could be observed, for instance, by STM techniques. Finally, I will discuss the one-dimensional chain limit and show that at low energy and temperature the magnetic moments and the electrons become strongly entangled and that a magnetic spiral structure emerges without any adjustable parameters. For strong enough coupling between the impurities and the superconductor, the 1D electronic liquid is driven into a topological superconducting phase supporting Majorana fermions without any fine-tuning of external parameters [3]

[1] V. Kaladzhyan, C. Bena, P. Simon, submitted.
[2] T. Meng, J. Klinovaja, S. Hoffman, P. Simon, D. Loss, arXiv:1501.07901.
[3] B. Braunecker, P. Simon, Phys. Rev. Lett. 111, 147202 (2013); B. Braunecker, P. Simon, submitted.

Evidence for metallic zero energy modes in graphene with strong chiral disorder

Aires Ferreira[1] and E. R. Mucciolo[2]
[1]*Department of Physics, University of York, York YO10 5DD, United Kingdom*
[2]*Department of Physics, University of Central Florida, Orlando, Florida 32816, USA*

Graphene subjected to chiral disorder is believed to host zero energy modes resilient to localisation, as dictated by renormalisation group analysis of the underlying effective field theory [1]. For "C-z" chiral disorder – such as vacancies and bond disorder – a line of fixed points with conductivity ~e^2/h is predicted. Such an unconventional quantum transport regime is found at variance with recent numerical works, however, which report the localisation of all states [2-4]. In this talk, I introduce an exact expansion of the Kubo formula in Chebyshev polynomials, whose efficient numerical implementation allows to tackle disordered systems with in excess of 10^9 atoms and fine meV resolutions. Its application to the honeycomb lattice with random dilute vacancy defects reveals a remarkably robust metallic state at the band's centre [5]. The Kubo conductivity of zero energy modes is found to match graphene's universal ballistic conductivity - 4e^2/(pi h) - within 1% accuracy, for a wide range of vacancies' concentration. Our results provide strong evidence that the field-theoretical picture [1] is valid well beyond its controlled weak-coupling regime.

[1] P. M. Ostrovsky, I.V. Gornyi, and A. D. Mirlin, Physical Review B **74**, 235433 (2006)
[2] Z. Fan, A. Uppstu, and A. Harju, Phys. Rev. B **89**, 245422 (2014)
[3] G.T. de Laissardiere, and D. Mayou, Phys. Rev. Lett. **111**, 146601 (2013)
[4] A. Cresti, F. Ortmann, T. Louvet, D.V. Tuan, and S. Roche, Phys. Rev. Lett. **110**, 196601 (2013).
[5] A. Ferreira, and E. R. Mucciolo, to be published (2015).

Parafermions in a Kagome lattice of qubits for topological quantum computation

Adrian Hutter, James R. Wootton, and Daniel Loss

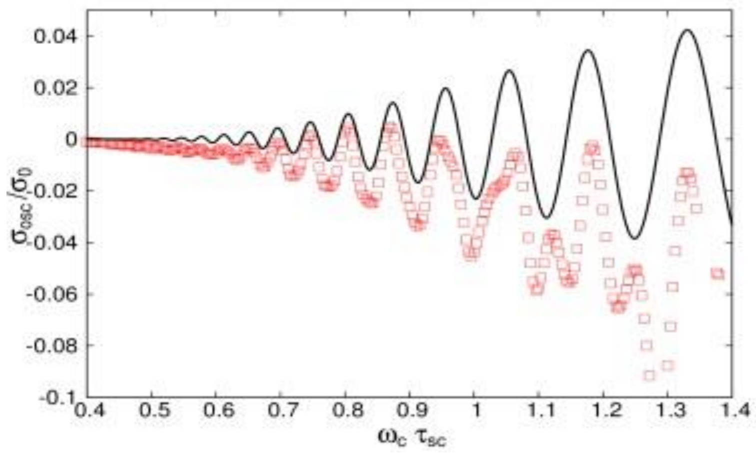
University of Basel, Switzerland

We show how Z_4 parafermions emerge in a Kagome lattice composed of qubits with nearest neighbor two-qubit interactions. The low-energetic excitations of our model correspond to the Abelian D(Z_4) anyon model, and non-Abelian parafermion modes appear at the ends of defect lines. We prove that braiding of these parafermions with each other and with the D(Z_4) anyons allows us to generate the entire 4-level Clifford group. We study the error correction problem for our model in detail, guaranteeing fault-tolerance of the topological operations. Crucially, we do not need non-Abelian error correction but can correct the underlying Abelian model.

Valley degeneracy breaking and spin-orbit coupling effects in the magnetoconductance oscillations of monolayer MoS_2

Andor Kormányos,[1] Péter Rakyta,[2] and Guido Burkard[1]
[1] *Department of Physics, University of Konstanz, D-78464 Konstanz, Germany*
[2] *MTA-BME Condensed Matter Research Group, Budapest University of Technology and Economics, Budafoki út 8, H-1111 Budapest, Hungary*

Motivated by recent experimental progress [1,2] in the measurement of magnetoconductance properties of monolayer MoS_2 , we investigate how the spin-orbit coupling and the broken valley degeneracy of the Landau levels (LL) affect the Shubnikov-de Haas oscillations in monolayer transition metal dichalcogenides. To this end we first study the Landau level spectrum using a multi-band **k.p** theory [3]. We find that in a wide magnetic field regime the valley degeneracy breaking of the LLs is linear in magnetic field. The effect of the non-parabolicity of the band-dispersion on the LL spectrum is also discussed. We then use the self-consistent Born approximation and the Kubo formalism to calculate the Shubnikov-de Haas oscillations of the longitudinal conductivity. We point out how the doping level affects the magnetoconductance and compare the results of numerical calculations and an analytical formula which is valid in the semiclassical regime [4].



Comparison of the numerical calculations (symbols) and analytical result (solid line) for the Subhnikov de-Haas oscillations in n-doped monolayer MoS_2. Here σ_{osc} is the oscillatory part of the magnetoconductance, ω_c is the cyclotron frequency and τ_{sc} is the scattering time caclulated in the Born approximation.

[1] Xu Cui *et al*, advanced online publication in Nature Nanotechnology (2015).
[2] H Schmidt, I Yudhistira, L Chu, A. H. Castro Neto, B. Özyilmaz, S. Adam, and G. Eda, arXiv:1503.00428.
[3] A. Kormányos, G. Burkard, M. Gmitra, J. Fabian, V. Zólyomi, N. D. Drummond, and V. I. Fal'ko, 2D Materials **2**, 022001 (2015).
[4] A. Kormányos, P. Rakyta, and G. Burkard, in preparation.

The hole spin qubit: decoupling from the nuclear spins

Andreas V. Kuhlmann,[1] Jonathan H. Prechtel,[1] Julien Houel,[1,2] Arne Ludwig,[3] Sascha R. Valentin,[3] Andreas D. Wieck,[3] and Richard J. Warburton[1]

[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*

[2]*Institut Lumière Matière, UMR5306 Université Lyon 1/CNRS, Université de Lyon, 69622 Villeurbanne Cedex, France*

[3]*Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany*

Huge effort is underway to develop semiconductor nanostructures as low noise hosts for qubits. The main source of dephasing of an electron spin qubit in GaAs is the nuclear spin bath. The electron states are constructed from atomic s orbitals with large wavefunction amplitude at the location of the nuclei. The Fermi contact hyperfine interaction therefore dominates the electron spin dephasing. A hole spin may circumvent the nuclear spin noise as it has a fundamentally different hyperfine interaction [1]. The hole states are constructed from atomic p orbitals with zero wavefunction amplitude at the location of the nuclei. The Fermi contact hyperfine interaction is therefore suppressed. The dipole-dipole hyperfine interaction of a pure heavy hole spin has a term along the growth direction only. In principle therefore, the nuclear spins can be switched off for a pure heavy hole spin by application of a transverse magnetic field. In practice, it is unknown to what extent this ideal limit can be achieved. A major hindrance experimentally is that p-type devices are often far too noisy.

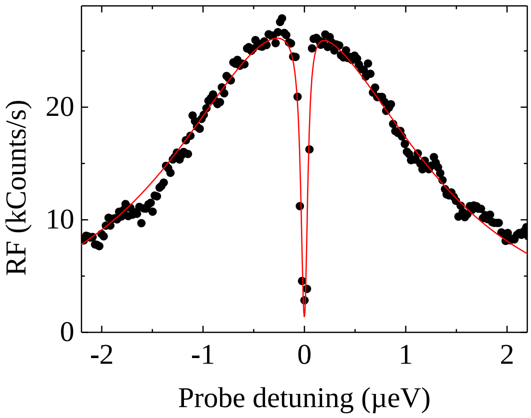


Fig. 1. Resonance fluorescence spectrum on a single quantum dot. The pronounced dip signifies CPT. A dip linewidth as small as ~ 30 neV is observed.

We investigate here a single hole spin in an InGaAs quantum dot embedded in a new generation of low-noise p-type device. We measure the hole Zeeman energy in a transverse magnetic field with 10 neV resolution by dark state spectroscopy. We then create a large transverse nuclear spin polarization to determine the hole hyperfine interaction. Our results show that the hole hyperfine interaction is highly anisotropic: the transverse coupling is < 1% of the longitudinal coupling. For unpolarized, randomly fluctuating nuclei, the ideal heavy hole limit is achieved down to neV energies; equivalently dephasing times up to a μs. The combination of large T_2^* and strong optical dipole make the single hole spin in GaAs an attractive quantum platform.

[1] J. Fischer *et al*, Phys. Rev. B **78**, 155329 (2008).

Skyrmion Phase in MnSi Nanowires Detected by Dynamic Cantilever Magnetometry

A. Mehlin[1, *], F. Xue[1, 2], D. Liang[3], B. Groß[1], H.F.Du[2], M.J. Stolt[3], S. Jin[3], M.L. Tian[2] and M. Poggio[1]

[1] Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland
[2] High Magnetic Field Laboratory, Chinese Academy of Science, Shushanhu Road 350, Hefei 230031, Anhui, P.R. China
[3] Department of Chemistry, University of Wisconsin-Madison, 1101 University Avenue, Wisconsin 53706, USA

Since their initial observation in 2009, magnetic skyrmions have been considered promising as carriers of information in high density magnetic media, due to favorable properties such as their nanometer-scale size or the tiny electrical currents required to move them [1]. Here we present the first measurements of a magnetic skyrmion phase by dynamic cantilever magnetometry, an extremely sensitive technique for the investigation of nanometer-scale magnetism [2]. More precisely, by mounting an individual MnSi nanowire (NW) on an ultrasoft Si cantilever and varying an applied magnetic field, we measure the magnetic torque associated with the magnetization of the NW. Our technique makes it possible to identify different magnetic phases of the NWs – including a sizable skyrmion phase – as a function of both temperature and applied magnetic field. Magnetometry measurements are performed with MnSi NWs oriented both parallel and perpendicular to the applied magnetic field. The compatibility of this technique with nanometer-scale samples promises to allow the study of reduced dimensionality on magnetic skyrmions. In addition, with a few modifications to the technique similar to those made in the detection of half-quantum vortices [3,4], we expect to improve its sensitivity, perhaps reaching the single skyrmion level or better.

*Corresponding author: Andrea.Mehlin@unibas.ch

[1] A. Fert et al., Nature Nanotech. 8, 152 (2013).
[2] D.P. Weber et al., Nano Lett. 12, 6139 (2012).
[3] J. Jang et al., Appl. Phys. Lett. 98, 132510 (2011).
[4] J. Jang et al., Science 331. 186 (2011).

Quantized single mode guiding in ultraclean suspended graphene

Peter Rickhaus[1],Peter Makk [1], Ming-Hao Liu[2], Simon Zihlmann[1], Samuel Hess[1], Markus Weiss[1], Romain Maurand[1], Klaus Richter[2] and Christian Schönenberger[1]
[1]*Dept. of Physics, University of Basel, Switzerland*
[2] *Institute for Theoretical Physics, University of Regensburg, Germany*

Suspended graphene offers a perfect platform for electron-optical experiments due to the high-mobilities achieved in these structures [1]. We have recently shown that Fabry-Perot cavities can be realized by local gating of suspended graphene [2], and snake states are formed on the p-n interfaces in magnetic fields [3]. By using multi-terminal samples with complex local gating other optical elements such as mirrors, or guiding channels can be realized.
Here we show that the electrons can be guided using smooth electrostatic potentials (Fig.1). Different guiding regimes are shown: optical fiber guiding, the analogue of the mechanism in optical fibers, and p-n guiding which relies on the angle-selectivity of transmission through a p-n junction. Moreover, as the guiding channel is depleted, we can resolve the mode filling for the first time in a gate defined channel. The measurements are supported by quantum transport simulations [4]. We show finally, that by using suspended graphene other structures, such as mirrors and gate defined quantum point contacts can be fabricated.

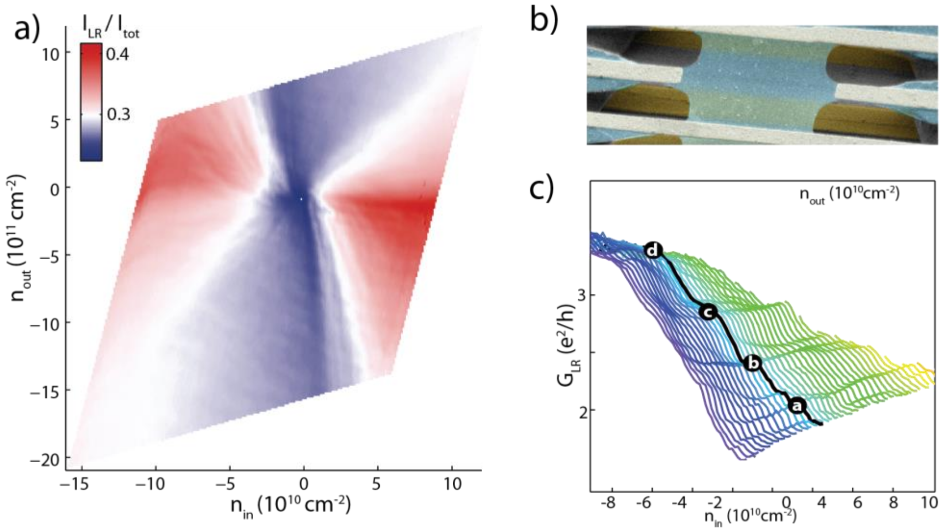


Fig. 1. a) Guiding efficiency as a function of local gate voltages in a guiding channel. b) False-colored SEM image of the guiding sample, with graphene colored blue and the bottom-gates yellow. c) Mode filling in a guiding channel appearing as steps in the conductance.

References

[1] R. Maurand, P. Rickhaus, P. Makk et al., Carbon 79, 486 (2014)
[2] P. Rickhaus, R. Maurand, Ming-Hao Liu et al., Nature Comm. 4, 2342 (2013)
[3] P. Rickhaus, P. Makk, Ming-Hao Liu et al., Nature Comm. 6, 6470 (2015)
[4] M.-H. Liu, P. Rickhaus, P. Makk, et al., Phys. Rev. Lett. 114, 036601 (2015)

Superradiant quantum phase transition with molecular magnets in a microwave cavity

Dimitrije Stepanenko[1], Mircea Trif[2], Oleksandr Tsyplyatyev[3], and Daniel Loss[4]
[1]Center for Solid State Physics and New Materials, Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia, [2]Laboratoire de Physique des Solides, CNRS UMR-8502, Université Paris Sud, 91405 Orsay Cedex, France, [3]Institut für Theoretische Physik, Universität Frankfurt, Max-von-Laue Strasse 1, 60438 Frankfurt, Germany, [4]Department of Physicss University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

Molecular antiferromagnets with broken inversion symmetry have well defined chirality of spin texture in the low-energy sector. This degree of freedom shows, long coherence times for quantum error correction, interaction with electric fields for design of quantum logic gates. Through the spin-electric coupling, molecules can control the ground-state field in a cavity quantum electrodynamics setup.

A crystal of triangular molecular antiferromagnets coupled to a resonant cavity shows superradiant phase transition. When the coupling between the molecular spins and the electric component of the cavity field exceeds a critical value, the ground state of molecules and the cavity contains photons. The critical coupling strength for transition depends on the external magnetic field, in sharp contrast to the standard case of two-level emitters, where the critical coupling was set by the structure of emitter alone. The source of modification is traced to the entanglement of spin and chirality in the low-energy states of the cluster. We propose that the number of photons in the cavity can be switched between zero and some macroscopic value. This effect can be used to detect spin-electric coupling in molecules.

Conserved Spin Quantity in Strained Hole Systems with Rashba and Dresselhaus Spin-Orbit Coupling

Paul Wenk,[1] Michael Kammermeier,[1] John Schliemann,[1] and Roland Winkler[2]
[1]*Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany*
[2]*Department of Physics, Northern Illinois University, De Kalb, IL 60115, USA*

One of the most critical challenges for spintronic devices, as the often mentioned spin-field-effect-transistor due to Datta and Das, lies in the control of the carrier spin lifetime, which is limited by the spin relaxation and dephasing processes in semiconductors. The predominant mechanism of the spin relaxation in such devices is of Dyakonov-Perel type. To extend the application of spintronic devices to the non-ballistic/diffusive regime with spin-independent scattering, it is of particular interest to find conditions for the electrons/holes in the semiconductors which result in symmetries that correspond to the conservation of spin. These symmetries enable to detect long-lived or even persistent spin states. In structurally confined two-dimensional electron gases such persistent solutions have been predicted in [1] for a special interplay between the linear-in-momentum Dresselhaus and Bychkov-Rashba spin-orbit coupling (SOC) and later also confirmed [2,3].
An appealing continuation of the findings on spin-preserving symmetries in electron systems is the analysis of persistent spin states in hole systems as presented recently in [4,5]. However, these publications presuppose materials with strongly restricted and unusual band structures. To give an example, a strainless sample with both Rashba and Dresselhaus SOC allows for the existence of a persistent spin helix in a two dimensional hole gas (2DHG) only in case of a vanishing Luttinger parameter γ_3 with $\gamma_1 > 0$ and $\gamma_2 > 0$.[5]

In our recent work [6] we first derive an effective Hamiltonian for a (001)-confined quasi 2DHG in a strained zinc blende semiconductor heterostructure including both Rashba and Dresselhaus SOC. Thereby, we derive the dominant contribution to the spin-orbit field due to Rashba SOC directly from an external electric field, which was missing in our previous publication, [5]. The significant effect due to Rashba SOC is controlled by the subband gaps and not, as in the case of Dresselhaus SOC, by the conduction band gap. The proper determination of the spin-orbit field enables us in a next step to conclude that the requirements for long-lived spin states are a non-vanishing [110] shear strain component, ϵ_{xy}, and a symmetric in-plane normal strain $\epsilon_{xx} = \epsilon_{yy}$. Moreover, we show that for the existence of a conserved spin quantity in semiconductors which are accessible for experiments (e.g., systems with $\gamma_2/\gamma_3 \approx 1$) the interplay between Dresselhaus SOC, Rashba SOC and strain is crucial. An important message is that we do not find a conserved spin quantity for realistic band parameters if one of these constituents is missing.

[1] J. Schliemann, J. C. Egues, and D. Loss, Phys. Rev. Lett. **90**, 146801 (2003).
[2] J. D. Koralek, C. P. Weber, J. Orenstein, B. A. Bernevig, S.-C. Zhang, S. Mack, and D. D. Awschalom, Nature **458**, 610 (2009).
[3] M. P. Walser, C. Reichl, W. Wegscheider, and G. Salis, Nat Phys **8**, 757 (2012).
[4] V. E. Sacksteder and B. A. Bernevig, Phys. Rev. B **89**, 161307 (2014).
[5] T. Dollinger, M. Kammermeier, A. Scholz, P. Wenk, J. Schliemann, K. Richter, and R. Winkler, Phys. Rev. B **90**, 115306 (2014).
[6] P. Wenk, M. Kammermeier, J. Schliemann, arXiv:1506.07639 (2015)

Single-charge occupation in single hole transistors with implanted boron atoms

S.V. Amitonov, F. Mueller, P.C. Spruijtenburg, J. Ridderbos, M. Brauns, A.A.I. Aarnink, W.G. van der Wiel and F.A. Zwanenburg
NanoElectronics Group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
E-mail: f.a.zwanenburg@utwente.nl

Spin states of holes in silicon are promising candidates for solid-state qubits because of the expected long coherence time due to the weak hyperfine and spin-orbit interaction. At the same time, the latter interaction provides a way to electrically control hole spins while silicon microfabrication technology allows mass production of Si devices, crucial for quantum computer implementation. Based on the design by Angus et al. [1] we fabricated ambipolar (electron and hole) gate defined quantum dots in silicon [2]. For the devices in this work we implanted a few acceptor ions (B) in the active region of the device where we observed single-charge tunneling at 4.2 K. Measured transport characteristics demonstrate different behavior for electrons and holes and will be discussed. The single-hole regime was reached with a charging energy of 35±3 meV. Investigations are underway to find out whether this corresponds to charging a single-dopant or an unintentional quantum dot.

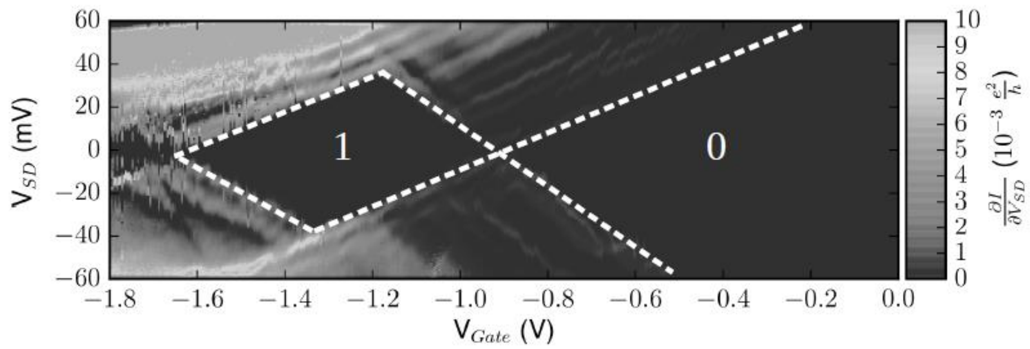


Figure 1: Grayscale plot of the differential conductance ∂I/∂VSD versus gate voltage VGate and source drain voltage VSD. The continuously opening diamond edge indicates an empty Coulomb island. The charging energy in the single-hole regime is roughly 35 meV.

[1] S. J. Angus, A. J. Ferguson, A. S. Dzurak, and R. G. Clark, Nano Lett. 7, 2051 (2007).
[2] F. Mueller, G. Konstantaras, W. G. van der Wiel, and F. A. Zwanenburg, Appl. Phys. Lett. 106, 172101 (2015).

Sensitive radio-frequency reflectometry of a quantum dot at perfect matching

N. Ares,[1] F. Schupp,[1] A. Mavalankar,[1] G. Rogers,[1] J. Griffiths,[2] G.A.C. Jones,[2] I. Farrer,[2] D.A. Ritchie,[2] C.G. Smith,[2] A. Cottet,[3] G.A.D. Briggs,[1] and E.A. Laird[1]

[1] *Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, United Kingdom*
[2] *Cavendish Laboratory, J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom*
[3] *Laboratoire Pierre Aigrain, Ecole Normale Supérieure-PSL Research University, CNRS, Université Pierre et Marie Curie-Sorbonne Universités, Université Paris Diderot-Sorbonne Paris Cité, 24 rue Lhomond, 75231 Paris Cedex 05, France*

Radio-frequency (RF) reflectometry is a sensitive technique for quantum state readout [1-6]. It also allows us to avoid the use of separate mesoscopic detectors, which complicates scalable fabrication [7-12]. With this goal, a RF resonant circuit is coupled directly to the quantum device. Changes in device resistance and capacitance cause a dispersive or absorptive shift in the response of the circuit. However, the high resistances that quantum devices present make impedance matching complex.

We present an in-situ tunable RF-circuit coupled to the ohmic contacts of a AlGaAs/GaAs quantum dot which allows us to achieve perfect matching even when the device is completely pinched off. The use of variable capacitors, first reported in ref. [6], also allow us to estimate the sensitivity of this technique to capacitive changes. We study this sensitivity as a function of the matching condition and the frequency of the carrier signal. We show the performance of this matching network and estimate its bandwidth. Furthermore, considering a simple model of the circuit, we extract the changes in capacitance of the quantum dot from our RF-measurements. We find that these changes are proportional to the DC conductance of the device. This relation is in agreement with the one we derive from a quasi-static theory considering an oscillating voltage applied to the source electrode of the quantum dot, in contrast to what is expected when the dynamics is dominated by the quantum charge relaxation effect [13].

This circuit can be applied to read-out spin qubits either by detecting capacitance changes in a double quantum dot, or using a separate charge sensor. With estimated quantum capacitance of 19 fF, our sensitivity would allow qubit states to be distinguished with unit signal-to-noise ratio in approx. 20 ns. The so-called quantum RC circuit, i.e. a quantum dot with a single fermionic reservoir, can also be studied with our setup.

[1] Schoelkopf, R. J., Wahlgren, P., Kozhevnikov, A. A., Delsing, P. & Prober, D. E. The radio-frequency single-electron transistor (rf-set): A fast and ultrasensitive electrometer. Science 280, 1238-1242 (1998).

[2] Aassime, A., Johansson, G., Wendin, G., Schoelkopf, R. & Delsing, P. Radiofrequency single-electron transistor as readout device for qubits: Charge sensitivity and backaction. Phys. Rev. Lett. 86, 3376-3379 (2001).

[3] Cassidy, M. C. et al. Single shot charge detection using a radio-frequency quantum point contact. Appl. Phys. Lett. 91, 222104 (2007).

[4] Reilly, D. J., Marcus, C. M., Hanson, M. P. & Gossard, A. C. Fast single-charge sensing with a rf quantum point contact. Appl. Phys. Lett. 91, 162101 (2007).

[5] LaHaye, M. D., Suh, J., Echternach, P. M., Schwab, K. C. & Roukes, M. L. Nanomechanical measurements of a superconducting qubit. Nature 459, 960-964 (2009).

[6] Müller, T. et al. An in situ tunable radiofrequency quantum point contact. Appl. Phys. Lett. 97, 202104 (2010).

[7] Petersson, K. et al. Charge and spin state readout of a double quantum dot coupled to a resonator. Nano Lett. 10, 2789-2793 (2010).

[8] Chorley, S. J. et al. Measuring the complex admittance of a carbon nanotube double quantum dot. Phys. Rev. Lett. 108, 036802 (2012).

[9] Jung, M., Schroer, M. D., Petersson, K. D. & Petta, J. R. Radio frequency charge sensing in InAs nanowire double quantum dots. Appl. Phys. Lett. 100, 253508 (2012).

[10] Schroer, M. D., Jung, M., Petersson, K. D. & Petta, J. R. Radio frequency charge parity meter. Phys. Rev. Lett. 109 (2012).

[11] Colless, J. I. et al. Dispersive readout of a few-electron double quantum dot with fast rf gate sensors. Phys. Rev. Lett. 110, 046805 (2013).

[12] Gonzalez-Zalba, M. F., Barraud, S., Ferguson, A. J. & Betz, A. C. Probing the limits of gate-based charge sensing. Nat. Commun. 6, 6084 (2015).

[13] Büttiker, M., Thomas, H. & Prêtre, A. Mesoscopic capacitors. Phys. Lett. A 180, 364-369 (1993).

Engineering topological insulators in quantum wells using lateral superlattice potential

Sigurdur I. Erlingsson[1] and J. Carlos Egues[2]
[1]*School of Science and Engineering, Reykjavik University, IS-101 Reykjavik, Iceland*
[2]*Instituto de Fisica de Sao Carlos, University of Sao Paulo, 13560-970 Sao Carlos, SP, Brazil*

Topological Insulators (TI) showing quantum spin Hall effect (QSHE) were initially theoretically predicted in graphene [1] and in inverted band-gap HgTe-based quantum wells [2]. A year later, in 2007, the QSHE was observed experimentally in HgTe quantum wells [3]. More recently a QSHE system based on InAs/GaSb electron/hole double quantum wells was proposed [4], and subsequently observed experimentally [5]. Although much progress has been made in these systems [6,7], observation of edge state transport can be obscured by background bulk conductance and other sample fabrication issues.

Here we show that electrons in ordinary III-V semiconductor double wells with an lateral modulating periodic potential and spin-orbit interaction can be tunable TIs [8]. The essential TI ingredients, namely, band inversion and the opening of an overall bulk gap in the spectrum arise, respectively, from (i) the combined effect of the double well even-odd state splitting together with the superlattice potential and (ii) the interband Rashba spin-orbit coupling. We will discuss the origins of the interband spin-orbit coupling and using the **k**.**p** approach we will derive an effective Bernevig-Hughes-Zhang model [2]. In addition to the analytical work we perform numerical calculations of the bands and explicitly verify the bulk-edge correspondence by considering a strip configuration and determining not only the bulk bands but also the edge states and their Dirac-like spectrum in the topological phase. Finally we will consider the effects of the intraband spin-orbit coupling, and the breaking of inversion symmetry due to the periodic superlattice potential, and discuss possible experimental implementation.

This work was supported by the Brazilian funding agency CNPq and FAPESP and PRP/USP within the Research Support Center Initiative (NAPQ-NANO).

[1] C.L. Kane and E.J. Mele, Phys. Rev. Lett. **95**, 226801 (2005).
[2] A. Bernevig, T.L. Hughes, and S.-C. Zhang, Science **314**, 1757 (2006).
[3] M. Konig *et al.* , Science **318**, 766 (2007).
[4] C. Liu *et al.* , Phys. Rev. Lett. **100**, 236601 (2008)
[5] I. Knez, R.R. Du, and G. Sullivan, Phys. Rev. Lett. **107**, 136603 (2011).
[6] K.C. Novack *et al.*, Nature Mat. **12**, 787 (2013).
[7] L. Du, I. Knez, G. Sullivan, and R.R. Du, Phys. Rev. Lett. **114**, 096802 (2015).
[8] S.I. Erlingsson, and J.C. Egues, Phys. Rev. B **91**, 035312 (2015).

Entangled absorption of a single photon with a single spin in diamond

Hideo Kosaka and Naeko Niikura
Yokohama National University, 79-5 Tokiwadai, Hodogaya, Yokohama 240-8501, JAPAN

Quantum entanglement, a key resource for quantum information science, is inherent in a solid. It has been recently shown that entanglement between a single optical photon and a single spin qubit in a solid is generated via spontaneous emission [1]. However, entanglement generation by measurement is rather essential for quantum operations [2]. We here show that the physics behind the entangled emission can be time-reversed to demonstrate entangled absorption mediated by an inherent spin-orbit entanglement [3] in a single nitrogen vacancy center in diamond (Fig. 1) [4]. Optical arbitrary spin state preparation and complete spin state tomography revealed the fidelity of the entangled absorption to be 95% (Fig. 2). With the entangled emission and absorption of a photon, materials can be spontaneously entangled or swap their quantum state based on the quantum teleportation scheme.

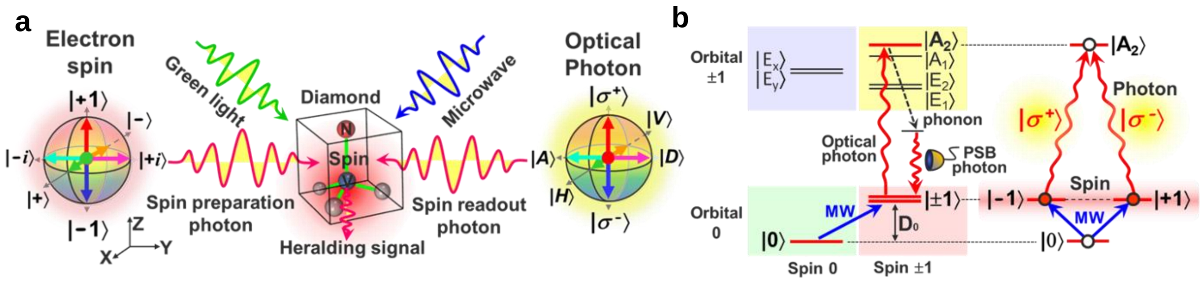


FIG. 1 (**a)** Scheme for entanglement measurement. Quantum correlation between optically stored electron spin and incoming readout optical photon is measured via resonant absorption, which is heralded by a phonon sideband photon detection. (**b)** Related energy levels of the NV center. Spin triplet sublevels $|\pm1\rangle$ are used as spin qubit bases.

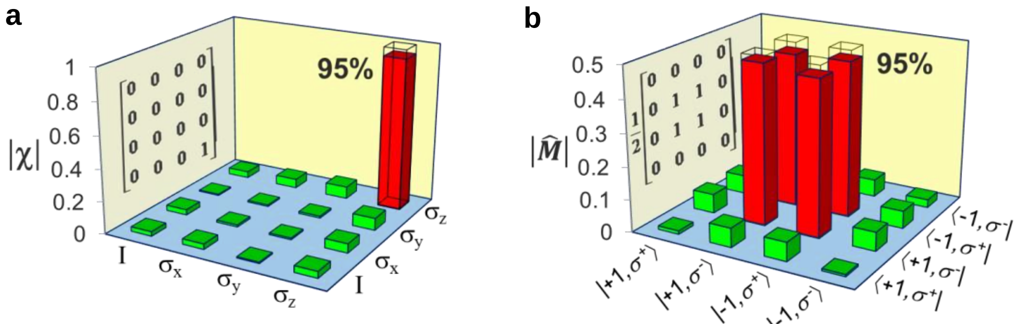


FIG. 2 (**a)** The χ matrix representation of the spin preparation process. The element at (σ_z, σ_z), which corresponds to the phase flip process originating from the relative phase of the dark state, is used for the estimation of the spin preparation fidelity to be 95%. (**b)** The density operator represenatation of the joint measurement between the electron spin and the photon polarization. The elements at middle 2x2 matrix, which corresponds to the spin-photon entanglement originating from the spin-orbit entanglement in the A_2 state, are used for the estimation of the entanglement detection fidelity to be 95%.

[1] E. Togan et al., *Nature* **466**, 730–734 (2010).
[2] H. Bernien et al., *Nature* **497**, 86 (2013).
[3] H. Kosaka et al., *Nature* **457**, 702–705 (2009).
[4] H. Kosaka and N. Niikura, *Phys. Rev. Lett.*, **114**, 053603 (2015).

Initialization, Quantum Operations and Read-out of Spin Qubit Encoded in Three Quantum Dot System

Jakub Łuczak, Bogdan R. Bułka
Institute of Molecular Physics Polish Academy of Sciences ul. M. Smoluchowskiego 17, 60-179 Poznań, Poland

We would like to present theoretical studies on a spin qubit built on three coherently coupled quantum dots (TQD) in a triangular geometry with three electrons [1]. The qubit states are encoded in the doublet subspace and quantum logical operations are performed according to DiVincenzo et al. [2] scheme. A main advantage of this proposal is purely electrically control of exchange couplings between the spins which provides fast operations. Moreover the doublet subspace is pointed as a decoherence-free subspace and immune to decoherence processes [3].

The TQD is modeled by the Heisenberg Hamiltonian with the exchange interaction controlled by potentials applied to local electrodes. We show that the doublet states are sensitive to changes of the triangular symmetry of the system. This effect can be used to initialization of the both qubit states $|0\rangle$ and $|1\rangle$ which are equivalent and can be easy achieved by a proper manipulation of the local gate potentials. It is an advantage compare with the linear configuration of TQD [4]. We show also how to initialize the qubit states by Landau-Zener transitions between charge states of the TQD system. The modification of the triangular symmetry is useful in one-qubit operations, like Pauli X and Z gate as well as Hadamard gate.

We present a new read-out scheme for the qubit states based on electron transport through the TQD connected with electron reservoirs. For some specific symmetry one can observe a doublet blockade effect which is related with the current blockade due to the asymmetry of tunnel rates between the doublet states and the reservoirs. This effect is used to studies qubit dynamics, taking into account decoherence, leakage and spin-flip processes.

In the last part we will consider two interacting qubits each encoded in the triangular TQD with three spins. We found an effective interaction Hamiltonian for different connections and symmetries of the qubits. For the most optimal connections the two-qubit operations SWAP, CPHASE and CNOT can be performed only in a few control impulses. This is an advantage of this proposal in contrast to the previous solutions [2,5] for which one needed at least tens of impulses

Our studies show, that the TQD system with three spins is a good candidate to implement as the spin qubit. We have been motivated by recent experiments [4,5] which were undertaken to perform coherent spin manipulations in TQD systems according to the DiVincenzo scheme [2].

Acknowledgments
This work has been supported by the National Science Centre under the contract DEC-2012/05/B/ST3/03208

[1] J. Łuczak, B. R. Bułka, Phys. Rev. B. **90**, 165427, (2014).
[2] D. P. DiVincenzo, D. Bacon, J. Kempe, G. Burkard, K. B. Whaley, Nature **408**, 339, (2000).
[3] D. A. Lidar, I. L. Chuang, K. B. Whaley, Phys. Rev. Lett **81**, 2594 (1998);
[4] E. A. Laird, et al., Phys. Rev. B **82**, 075403 (2010); L. Gaudreau, et al., Nature Phys. **8**, 54, (2012).
[5] Z. Shi., et al., Phys. Rev. Lett. **108**, 140503 (2012).

Implementation of three spin qubits in a lateral triple quantum dot

A. Noiri[1], T. Nakajima[1,2], J. Yoneda[1,2], M. Delbecq[1,2], T. Otsuka[1,2], S. Amaha[2], K. Takeda[1,2], A. Ludwig[3], A.D. Wieck[3] and S. Tarucha[1,2]
[1]*Department of Applied Physics, University of Tokyo, Bunkyo-ku, Tokyo, Japan*
[2]*Center for Emergent Matter Science, RIKEN, Wako, Saitama, Japan*
[3]*Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, Bochum, Germany*

Multiple quantum dots (QDs) are fascinating systems to explore the physics of electron interactions. The confined electron spins in QDs can be addressed both electrically and optically, which makes QDs highly promising building blocks for quantum information processing [1]. Recent experiments on GaAs QDs have demonstrated the necessary ingredients of universal quantum gate operations: single-spin rotations by electron spin resonance (ESR) [2,3] and pulsed control of two-spin entanglement [4]. Single-spin manipulation with fidelity up to 96% was achieved [5] by employing a magnetic field gradient induced by a specially designed micro-magnet (MM) [3]. The next step to implement quantum algorithms is to scale up this system to three or more. The number of qubits, however, has so far been limited to two.

In this presentation, at first, we will demonstrate addressable initialization/control/readout of single spins in a laterally coupled triple QD (TQD) based on GaAs defined by gate electrodes (Fig. 1). Initialization of individual spins is performed by pulse operation of detuning energies between two adjacent QDs. Also, spin-state readout is realized by Pauli spin blockade with detuning pulse operation. Each spin state can be manipulated individually by frequency-selectable ESR with a maximum Rabi frequency up to 25MHz (Fig. 2). The spin in the right QD shows the largest Rabi frequency in agreement with the simulated local magnetic field property created by the MM. Next, we will show the performance of two-spin entanglement control in two adjacent QDs. We prepare the singlet (S) state as a two-spin initial state by using a detuning pulse with appropriate ramp time. The state coherently evolves between S and triplet (T_0) due to the local Zeeman field difference between the two QDs that is created by the MM. Then, by tuning the exchange coupling between the two QDs, the SWAP operation is realized. These results demonstrate universal quantum gate operations in a TQD, which will lead to the implementation of quantum algorithms on spin qubit systems.

References
[1] D. Loss *et al*., Phys. Rev. A. **57**, 120 (1998).
[2] F. H. L. Koppens *et al*., Nature **442**, 766 (2006).
[3] M. Pioro-Ladrière *et al*., Nat. Phys. **4**, 776 (2008).
[4] J. R. Petta *et al*., Science **309**, 2180 (2005).
[5] J. Yoneda *et al*., Phys. Rev. Lett. **113**, 267601 (2014).

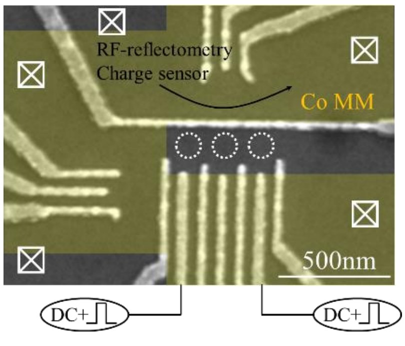


Fig. 1 TQD device structure

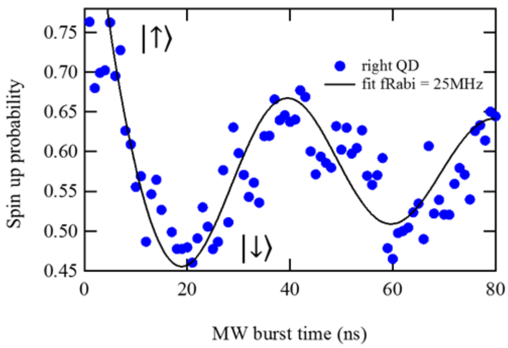


Fig. 2 Rabi oscillation of the electron spin in the right QD

Shape-sensitive Pauli blockade in a bent carbon nanotube

Gábor Széchenyi and András Pályi
Institute of Physics, Eötvös University, Budapest, Hungary

Motivated by a recent experiment [1], we theoretically study the Pauli blockade transport effect in a double quantum dot embedded in a bent carbon nanotube [2]. We establish a model for the Pauli blockade, taking into account the strong g-factor anisotropy that is linked to the local orientation of the nanotube axis in each quantum dot. We provide a set of conditions under which our model is approximately mapped to the spin-blockade model of Jouravlev and Nazarov [3]. The results we obtain for the magnetic anisotropy of the leakage current, together with their qualitative geometrical explanation, provide a possible interpretation of previously unexplained experimental results [1]. Furthermore, we find that in a certain parameter range, the leakage current becomes highly sensitive to the shape of the tube, and this sensitivity increases with increasing g-factor anisotropy. This mutual dependence of the electron transport and the tube shape allows for mechanical control of the leakage current, and for characterization of the tube shape via measuring the leakage current.

[1] F. Pei *et al.*, Nat. Nanotechnol. **7**, 630 (2012)
[2] G. Széchenyi and A. Pályi, Phys. Rev. B **91**, 045431 (2015)
[3] O. N. Jouravlev and Y. V. Nazarov, Phys. Rev. Lett. **96**, 176804 (2006)

Efficient readout of a coherent single spin in diamond

Daniel Riedel[1], Dominik Rohner[1], Marc Ganzhorn[1], Timo Kaldewey[1], Patrick Appel[1], Elke Neu[2], Richard J. Warburton[1] and Patrick Maletinsky[1]

[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*

[2]*Department of Physics, Saarland University, Campus E2 6, 66123 Saarbrücken*

Single spins in the solid-state find applications in various fields ranging from nanoscale sensing to quantum information processing. The electron spin associated with the nitrogen vacancy (NV) center in diamond fulfills key requirements for these applications, such as long coherence times (up to a ms) and overall robustness. In addition, the NV spin can be readily initialized and read out by optical means and deterministically manipulated using microwaves. However, an obstacle to practical applications is the poor photon extraction from single-crystalline diamond due to total internal reflection at the diamond-air interface. This represents a major limit to the efficiency of spin readout.

To address this issue, we embed NV centers into a nanostructured dielectric antenna [1]. In principle, a dielectric antenna yields highly directional emission as a result of self-interference of NV photoluminescence photons in a thin diamond layer. Our antenna design is based on a diamond membrane attached to a gallium phosphide (GaP) solid-immersion lens (SIL) [Fig. 1(a)]. We fabricate diamond membranes from high-quality, single-crystalline diamond substrates and fix them to a GaP SIL using van der Waals wafer-bonding. Subsequent etching steps allow the diamond layer thickness to be controlled precisely.

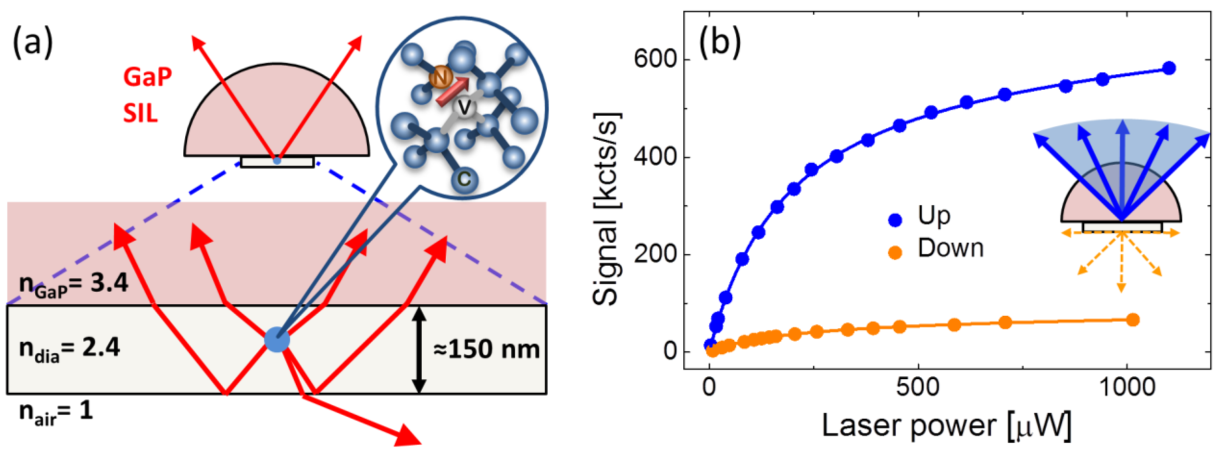


Figure 3 (a) Structure of dielectric antenna. (b) Directional emission caused by antenna structure.

As a first step, we confirm the functionality of our design by characterizing the emission profile of antennas with different diamond layer thicknesses and find quantitative agreement between experiment and calculations. We then isolate single NV centers in a very thin diamond layer (≈150 nm) and find an improved single NV photon detection rate by one order of magnitude compared to NVs in unstructured bulk diamond. The directionality of the emission is pronounced, 10:1 [Fig. 1(b)]. Finally, we show that the coherence properties of our NV spins are preserved in the antenna.

Optimization of our antenna will pave the way for ultra-sensitive magnetometry and unsurpassed photon detection rates, and thereby find applications in spintronics.

[1] D. Riedel, D. Rohner, M. Ganzhorn, T. Kaldewey, P. Appel, E. Neu, R. J. Warburton and P. Maletinsky, Phys. Rev. Applied **6**, 064011 (2014).

Hybrid Qubit in a GaAs/AlGaAs Double Quantum Dot

Ming Xiao
Key Laboratory of Quantum Information, CAS
University of Science and Technology of China
Hefei, Anhui 230026, China

Hybrid qubit has been proposed [1,2] and experimentally demonstrated [3,4] in silicon double-quantum-dot. It consists of the spin singlet and triplet in a doubly occupied dot and a single spin in a singly occupied dot. A hybrid qubit can be manipulated using high-frequency electrical pulses (in 10 GHz range) like a traditional charge qubit. Meanwhile, the spin states of a hybrid qubit are insensitive to charge noise and its dephasing rate is much slower than a traditional charge qubit.

However, a valley splitting is possibly within the energy scale of a silicon-based hybrid qubit. Here we present our research on a hybrid qubit in a GaAs/AlGaAs double quantum dot. One side of the double dot is singly occupied and the other side is possibly split into two closely coupled dots. Owing to the small spin singlet-triplet splitting of two electrons in the split dots, the whole system behaves as a hybrid qubit. We performed Larmor, Ramsey, and echo manipulations. An exceptionally long relaxing time, as well as a long dephasing time, is observed (T1 ~ 100 ns and T2 ~ 20ns). Therefore, we demonstrated the feasibility of hybrid qubit without the ambiguity of valley states in a semiconductor double quantum dot.

[1] Zhan Shi, C. B. Simmons, J. R. Prance, John King Gamble, Teck Seng Koh, Yun-Pil Shim, Xuedong Hu, D. E. Savage, M. G. Lagally, M. A. Eriksson, Mark Friesen, and S. N. Coppersmith, Fast Hybrid Silicon Double-Quantum-Dot Qubit , PRL 108, 140503 (2012).
[2] Teck Seng Koh, John King Gamble, Mark Friesen, M. A. Eriksson, and S. N. Coppersmith, Pulse-Gated Quantum-Dot Hybrid Qubit, PRL 109, 250503 (2012).
[3] Dohun Kim, Zhan Shi, C. B. Simmons, D. R. Ward, J. R. Prance, Teck Seng Koh, John King Gamble, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith & Mark A. Eriksson, Quantum control and process tomography of a semiconductor quantum dot hybrid qubit, Nature 511, 70 (2014).
[4] Dohun Kim, D. R. Ward, C. B. Simmons, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson, High fidelity resonant gating of a silicon based quantum dot hybrid qubit, arXiv:1502.03156v1 (2015).

Long-range two-qubit gate between nuclear spins in diamond mediated via an optical cavity

Adrian Auer and Guido Burkard
Department of Physics, University of Konstanz, Germany

Nitrogen-vacancy (NV) centers in diamond represent a promising possibility for a solid-state based realization of a qubit due to their excellent electron- and nuclear-spin coherence properties [1]. Fast single-qubit gates for the nitrogen nuclear spin have been successfully implemented [2]. For the use in quantum information processing, it is furthermore indispensable to deterministically entangle two distant nuclear spin qubits.

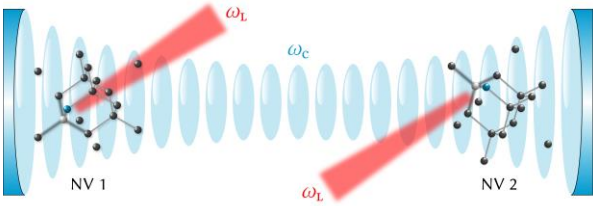


Figure 1 – Two NV centers (NV 1 and NV 2) are coupled to a common mode ω_c of an optical cavity. Photons from the external lasers of frequency ω_L can be scattered into the cavity. This mechanism effectively couples the two nitrogen nuclear spins intrinsic to each NV center, which can be harnessed to implement a two-qubit quantum gate.

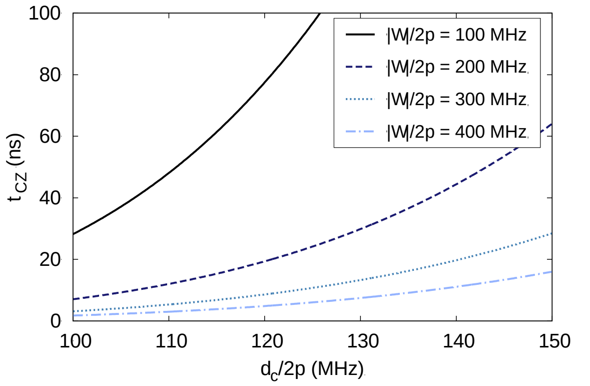


Figure 2 – Time τ_{CZ} to generate a CZ gate between two ^{14}N nuclear spin qubits as a function of the cavity detuning δ_c for different values of the laser Rabi frequencies Ω.

In our work, we extend an earlier proposal [3] for cavity-mediated coupling between NV electron spins and develop a scheme to implement a universal two-qubit gate between distant ^{14}N or ^{15}N nuclear spins. The coupling between the nuclear spins is achieved by virtual excitation of an optical cavity, to which both NV centers are coupled (Fig. 1). External laser photons incident on each NV center can be scattered into the cavity mode by exciting electronic Raman-type transitions between the NV center orbital ground and excited state, and thereby mediating an effective interaction between the two NV centers. We find that the scattering process depends on the nitrogen nuclear-spin state. The scattering can be completely suppressed for a specific nuclear spin configuration by properly tuning the laser frequency ω_L, which eventually leads to the implementation of a controlled-*Z* (CZ) gate. Quantitative analysis of our proposed mechanism yields fast gate operation times below 100 nanoseconds (Fig. 2), which is a few orders of magnitude faster than the decoherence time of about a millisecond for the nitrogen nuclear spin [4].

[1] V. Dobrovitski *et al.*, Annu. Rev. Condens. Matter Phys. **4**, 23 (2013).
[2] S. Sangtawesin *et al.*, Phys. Rev. Lett. **113**, 020506 (2014).
[3] G. Burkard and D. D. Awschalom, arXiv:1402.6351.
[4] G. D. Fuchs *et al.*, Nature Phys. **7**, 789 (2011).

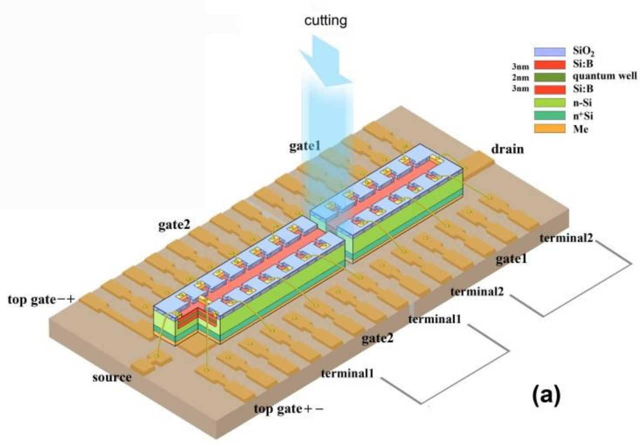
Negative U centers for qubit architecture

N. Bagraev[1,2], A. Kaveev[1], L. Klyachkin[1], A. Malyarenko[1], V. Mashkov[2], I. Vinerov[1] and V. Zaborovskii[2]

[1]*Ioffe Physical Technical Institute, Polytekhnicheskaya 26, 194021 St. Petersburg, Russia*

[2]*Peter the Great Saint Petersburg Polytechnic University, 195251, St. Petersburg, Russia*

We present the first findings that the strata consisting of the negative U centers which surround the edge channels of quantum wells are steadily gaining attention as promising candidates for the realization of different versions of a qubit. The planar silicon nanosandwich device represents the high mobility p-type silicon quantum well of 2 nm wide, Si-QW, confined by the δ-barriers heavily doped with boron, 5×10^{21} cm^{-3}, on the n-type Si (100) surface (Fig. 1a). The δ -barriers have been shown to contain the negative-U trigonal dipole boron centers, B^{+}+B^{-}, between which the topological edge channels appeared to be created. This multi-terminal device seems to carry out the operations of a quantum register because of the GHz and THz transitions between excited states of the negative U dipole boron center. Firstly, the GHz and THz Rabi oscillations were found by measuring the electroluminescence spectra with the Bruker-Physik VERTEX 70 FT-IR spectrometer under the stabilized drain-source current along the Si-QW plane at room temperature (Fig. 1b). Secondly, the phase shifts of the 9 GHz and 120 GHz emission (Figs. 1c and d) selected by changing the microcavity modes were revealed by varying the values of the lateral voltage applied in the Si-QW plane (Fig. 1a and b). Finally, the GHz and THz emission appears to be controlled by measuring the CV characteristics thereby defining prospects of qubit operations with multi-terminal silicon sandwich devices (Figs. 1e and f).



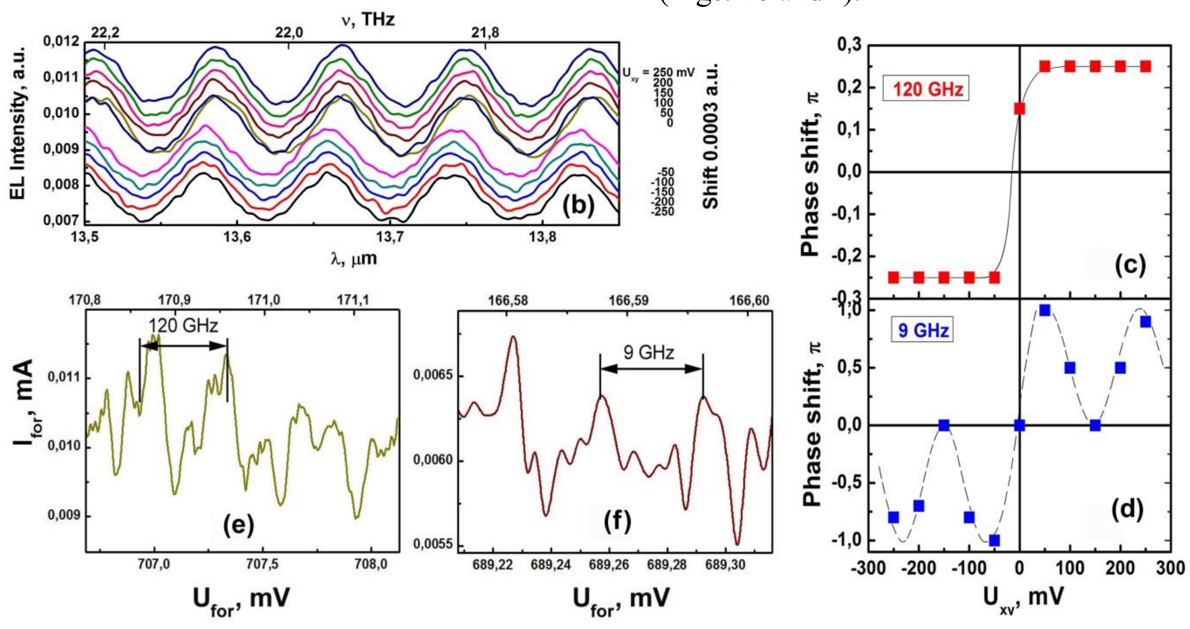


Fig.1. The Si-nanosandwich device (a) reveals the Rabi oscillations (b) found by measuring the electroluminescence spectra reveal the phase shifts of the 9 GHz and 120 GHz emission (c, d) that results from the optical transitions between excited states of the negative U dipole boron centers. (e, f) – The same GHz – THz emission controlled by measuring the CV characteristics.

Exchange-bias measured in single permalloy nanotubes using a hybrid nanoscale magnetometer

A. Buchter[1]*, R. Woelbing[2]*, M. Wyss[1], O.F. Kieler[4], T. Weimann[4], J. Kohlmann[4], A.B. Zorin[4], A. Farhan[7,8], A. Kleibert, D[9]. Rueffer[3], F. Matteini[3], G. Tutuncuoglu[3], F. Heimbach[5], A. Fontcuberta i Morral[3], D. Grundler[5,6], R. Kleiner[2], D. Koelle[2], M. Poggio[1]

[1]*Department of Physics, University of Basel, CH-4056 Basel*
[2]*Physikalisches Institut and Center for Collective Quantum Phenomena in LISA⁺, Universitaet Tuebingen, D-72076 Tuebingen*
[3]*Laboratoire des Matériaux Semiconducteurs, Institut des Matériaux, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne*
[4]*Fachbereich „Quantenelektronik“, Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig*
[5]*Lehrstuhl fuer Physik funktionaler Schichtsysteme, Physik Department E10, Technische Universitaet Muenchen, D-85747 Garching*
[6]*Institut des Matériaux, Faculté Sciences et Technique de l' Ingenieur, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne*
[7]*Laboratory for Micro- and Nanotechnology, Paul Scherrer Institute, CH-5232 Villigen*
[8]*Laboratory for Mesoscopic Systems, Department of Materials, ETH Zuerich, CH-8093 Zuerich*
[9]*Swiss Light Source, Paul Scherrer Institute, CH-5232 Villigen*

We investigate exchange-bias in single Permalloy (Py) nanotubes using a hybrid magnetometer consisting of a nanometer-scale Nb SQUID and a Si cantilever [1]. The Py nanotube is affixed to the tip of the cantilever and positioned in order to optimally couple its stray flux into the nanoSQUID [2]. In this configuration we are able to simultaneously measure the nanotube's volume magnetization by cantilever magnetometry and its stray flux using the nanoSQUID. By measuring single nano-magnets, we avoid ensemble effects such as size and orientation distribution, which obscure the interpretation of conventional techniques. In the Py nanotubes, we observe the characteristic features of exchange-bias. The small measured blocking temperature points to the presence of a thin antiferromagnetic native oxide, as confirmed by X-ray absorption spectroscopy. Furthermore, we find not only shifts of the hysteresis loop along the field-axis, as expected for such an antiferromagnetic-ferromagnetic bilayer, but we also measure changes in the shape of the magnetic hysteresis and find differences in comparing reversal of stray field and volume magnetization. These observations hint at alterations in the magnetic reversal process as a function of temperature and increased training of the system.

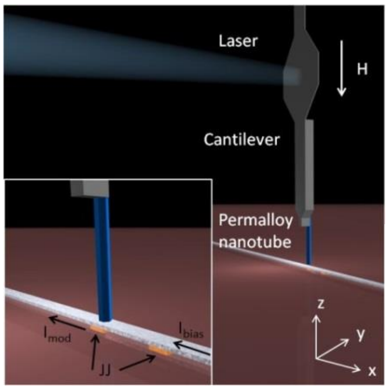


Figure 1: Shown is the setup of the hybrid nanoscale magnetometer. It consists of an ultrasoft Si cantilever with a Py nanotube sample glued to its tip and a Nb/HfTi/Nb nanoSQUID.

[1] A. Buchter, et al, Phys. Rev. Lett. **111**, 067202 (2013).
[2] J. Nagel, et al, Phys. Rev. B **88**, 064425 (2013).

Feedback-tuned gates for GaAs based two-electron spin qubits near the error correction threshold

Pascal Cerfontaine[1], Tim Botzem[1], Dominique Bougeard[2] and Hendrik Bluhm[1]
[1]*JARA-Institute for Quantum Information, RWTH Aachen University, D-52074 Aachen, Germany*
[2]*Department of Physics, University of Regensburg, D-93040 Regensburg, Germany*

High fidelity gate operations for manipulating individual and multiple qubits in the presence of decoherence are a prerequisite for fault-tolerant quantum information processing. Coherence measurements on two-electron spin qubits indicate a good potential for high fidelity in spite of the presence of nuclear spins. However, the baseband control methods commonly used are based on unrealistic approximations which lead to large systematic gate errors. Furthermore, great care must be taken to minimize decoherence.

An attractive solution is to use control pulses found in numerical simulations that minimize the infidelity from decoherence and take the experimentally important imperfections and constraints into account [1]. We show that the experimental implementation of these numerically optimized control pulses is possible by using a self-consistent calibration routine we proposed earlier [1]. In our experiment, this calibration routine succeeds in removing systematic gate errors to a high degree without increasing the pulses' decoherence.

We characterize the resulting gates using randomized benchmarking and self-consistent state tomography and find an average gate fidelity of 98.5% and 0.4% leakage out of the computational subspace. Simulations show good agreement with experimental data, as shown in Fig. 1, and indicate that straightforward material improvements should readily allow for fidelities in excess of 99%.

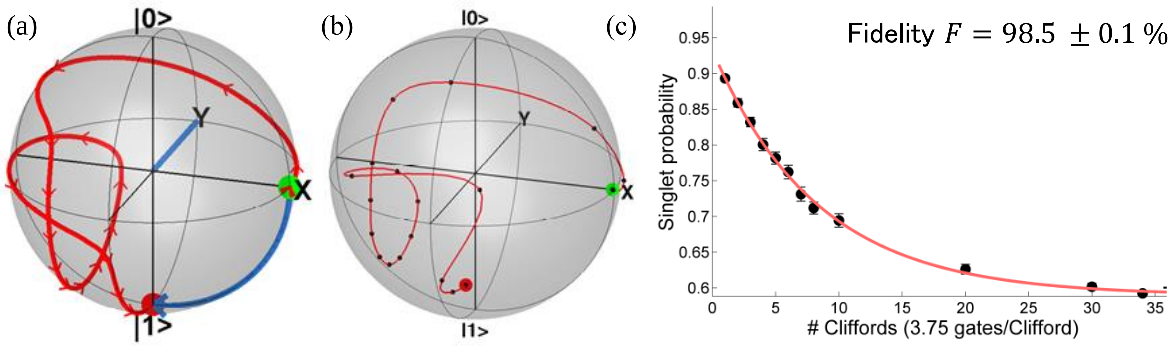


Fig. 1: Bloch sphere trajectories for a $\boldsymbol{y_{\pi/2}}$ gate. The initial state on the x-axis is rotated to $|\mathbf{1}\rangle$. While (a) shows the simulated trajectory, (b) illustrates the experimental trajectory, which was determined using self-consistent state tomography [2]. Panel (c) shows randomized benchmarking data [3], which yields an average gate fidelity of 98.5%.

[1] P. Cerfontaine, T. Botzem, D. P. DiVincenzo, and H. Bluhm, Physical Review Letters **113** (2014)
[2] M. Takahashi, S. D. Bartlett and A. C. Doherty, Physical Review A **88**(2) (2013)
[3] E. Magesan, J. M. Gambetta, and J. Emerson, Physical Review Letters **106** (2011)

Magnetotransport measurements in topological insulators

André Dankert,[1] P. Bhaskar,[1] J. Geurs,[1] M. V. Kamalakar,[1] and Saroj P. Dash[1]
[1]*Department of Microtechnology and Nanoscience, Chalmers University of Technology, Quantum Device Laboratory; Göteborg, Sweden*

Topological insulators (TIs) are a new class of quantum materials that exhibit an insulating band structure in the bulk, but possess Dirac like topological surface states (TSS). These TSS have only one spin state per momentum state in contrast to two spin states in conventional materials. Furthermore, the TSS are extremely robust against most perturbations from defects or impurities and allow the propagation of dissipationless spin currents making them highly interesting for spintronic devices. So far, spin-resolved photoemission spectroscopy measurements probed the helical spin polarization in the surface states of three-dimensional (3D) TIs up to room temperatures [1]. Only recently, spin polarized surface currents in 3D TIs were detected by electrical methods using ferromagnetic (FM) contacts in a lateral spin-valve measurement geometry [2]. However, next to being limited to low temperatures, such electrical approaches can be significantly affected by other magnetoresistive contributions, such as the Rashba, anomalous and spin Hall effect.

Here we investigate magnetotransport measurements over a large temperature range up to room temperature in Bi_2Se_3 [3] and $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ by employing spin sensitive FM tunnel contacts. The different bulk doping concentration of these materials combined with angle dependent quantum interference measurements, flake thickness dependence studies and several control experiments provide a better understanding of the origin of the detected magnetoresistance switching. We discuss those different mechanisms which can affect the electrical detection of a spin polarization in 3D TIs due to spin-momentum locking in the surface states. These results could lead to innovative spintronic information technology based on spin sources without ferromagnetic components.

[1] Hsieh, D. et al. Nature 460, 1101 (2009).
[2] Li, C. et al. Nat. Nanotechnol. 9, 218 (2014).
[3] Dankert et al. arXiv:1410.8038.

Mixing of crystal field levels of individual erbium ions in silicon

Gabriele de Boo,[1] Qi Zhang[1], Chunming Yin,[1] Milos Rancic,[2] Brett Johnson,[2] Jeffrey C. McCallum,[3] Matthew J. Sellars,[2] and Sven Rogge[1]

[1] *CQC2T, School of Physics, University of New South Wales, Sydney,Australia*

[2] *CQC2T, RSPE, Australian National University, Canberra, Australia*

[3] *CQC2T, School of Physics, University of Melbourne, Melbourne, Australia*

We have developed a method that allows for the electrical read-out of the electron and nuclear spin states of individual erbium ions in silicon using optical transitions [1]. The electrical read-out provides a high detection efficiency, while the narrow line width of the optical transitions provides a high energy resolution. Using this combination we aim to create single spin qubits that can be initialized and read-out with high fidelity. The long lifetime of nuclear spins of rare earth ions also provides possibilities to create quantum memories [2].

In our experiment we use a silicon field effect transistor that is cooled down to 4 K. By operating it as a single electron transistor we can sense charge transitions inside the transistor. The transistor has been implanted with erbium atoms that can be photo-ionized by exciting the $^4I_{15/2}$ to $^4I_{13/2}$ transition. Because of the narrow homogeneous line width and the different erbium ions having slightly different transition energies, we can distinguish between them by scanning the laser wavelength. By applying a magnetic field we observe the splitting of different electron spin states and the mixing of different crystal field levels. The site symmetry is determined using a vector magnetic field. Understanding the crystal field induced level splitting and site symmetry is key to creating long-lived electron and nuclear spin states.

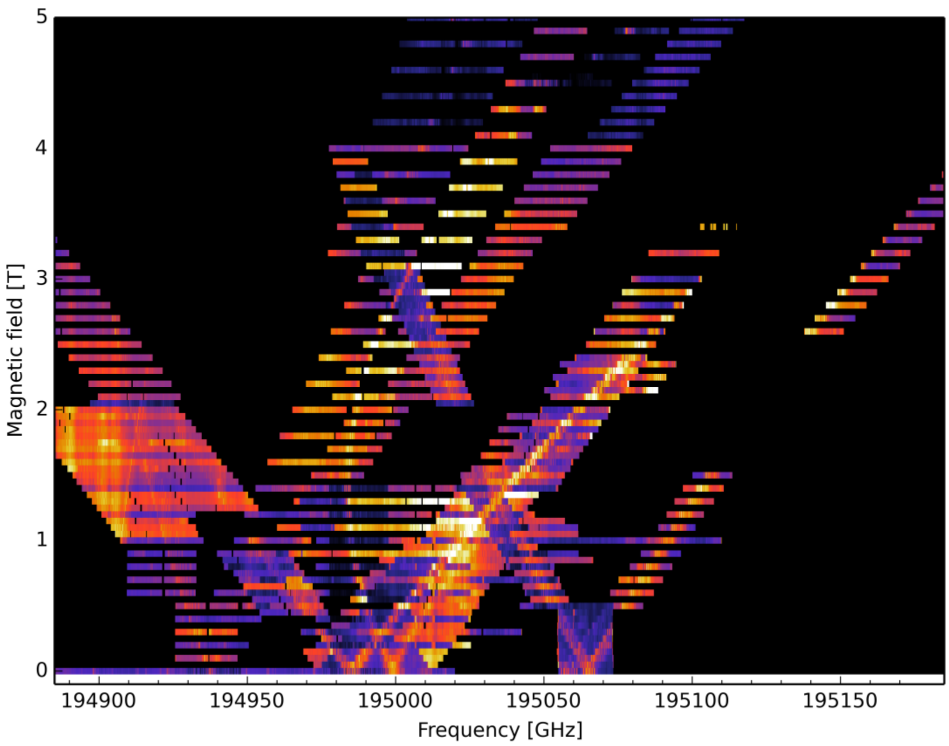


Figure 4 Optical resonances of several individual erbium ions inside a silicon field effect transistor in an applied magnetic field.

[1] C. Yin, Nature **497**, 91-94 (2013).
[2] M. Zhong, Nature **517,** 177-180 (2015).

Single Rare Earth Ions as a New Platform for Solid State Quantum Optics

Emanuel Eichhammer, Tobias Utikal, Stephan Götzinger and Vahid Sandoghdar
Max Planck Institute for the Science of Light, 91058 Erlangen, Germany
Friedrich-Alexander University (FAU), Erlangen

In recent experiments we have shown the first high-resolution spectroscopy and manipulation of single ions in the solid state using rare earth doped crystals [1, 2]. Due to weak interaction with the host crystal, the 4f-intrashell transitions of rare-earth ions are only weakly allowed. They exhibit very narrow Fourier-limited linewidths on the order of tens of kHz, which makes spectral selection of single ions from an inhomogeneously broadened ensemble feasible. Figure 1a shows a simplified excitation scheme of the Pr^{3+} ions used in this experiment. The hyperfine interaction between the 4f electrons and the nucleus splits the electronic ground state into a long-lived set of sublevels with exceptionally long coherence times on the order of minutes [3], even up to hours [4], at cryogenic temperatures. This ground state splitting can serve as a lambda level scheme, a key ingredient for many prospective applications in quantum optics, in particular, qubit storage and manipulation.

We present our latest results in the ongoing investigation of Praseodymium doped Yttrium orthosilicate (Pr:YSO) on the single-ion level. With a highly stabilized laser and a high-NA cryogenic microscope, we record single ion resonances with a linewidth of 1 MHz (fig. 1b). In preliminary experiments, we demonstrated state initialization via an optical pulse sequence. Continuing from there we target direct coherent spin manipulation via the microwave frequencies of 10.19 and 17.3 MHz, acting on the ground state multiplet.

Finally, we address current challenges, such as reducing spectral diffusion and line broadening down to the expected natural linewidth of 82 kHz. Due to the compactness and easy handling of the solid state system, future improvements such as combination with micro cavities or plasmonic nano-antennas become feasible and can enhance the photon yield by orders of magnitude. Furthermore, the system lends itself to on-chip integration for the realization of photonic quantum networks.

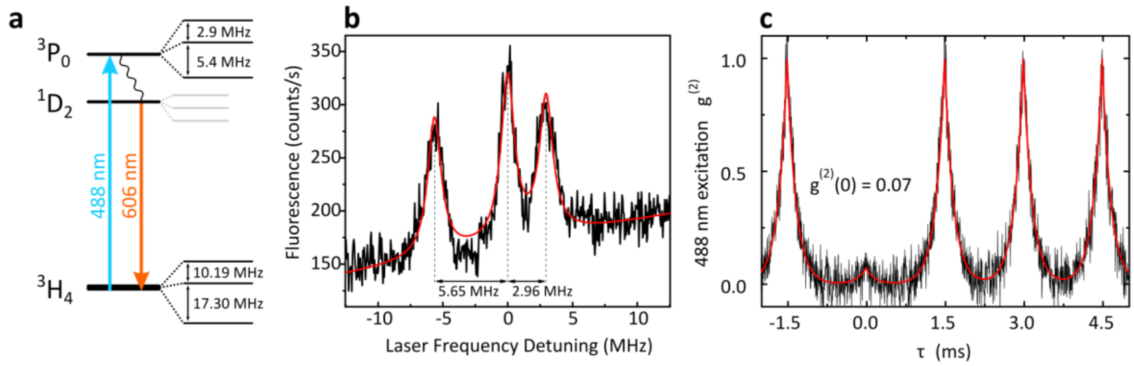


Figure 5: (a) Levels of Pr^{3+} relevant for single ion detection and manipulation. The hyperfine splitting of the ground state provides the lambda scheme. (b) The excitation spectrum of a single ion. Due to very narrow linewidths of about 1 MHz, the hyperfine splitting of the excited state is resolved. (c) A photon auto-correlation measurement acquired while addressing a single ion by pulsed excitation. The missing central peak demonstrates strong single-emitter antibunching with $g^{(2)}(0) = 0.07$.

[1] T. Utikal, E. Eichhammer, L. Petersen, A. Renn, S. Götzinger, and V. Sandoghdar, Nature Communications **5**, 3627 (2014).
[2] E. Eichhammer, T. Utikal, S. Götzinger, and V. Sandoghdar, *submitted*, arXiv:1504.00857
[3] G. Heinze, C. Hubrich, and T. Halfmann, Phys. Rev. Lett. **111**, 033601 (2013).
[4] M. Zhong, M. P. Hedges, R. L. Ahlefeldt, J. G. Bartholomew, S. E. Beavan, S. M. Wittig, J. J. Longdell, and M. J. Sellars, Nature **517**, 177 (2015).

Device-size scaling of frequency and oscillation power in nano-contact spin torque oscillators

Anders Eklund,[1] Randy K. Dumas,[2] Johan Åkerman,[1,2] and B. Gunnar Malm[1]
[1]*School of Information and Communication Technology, KTH Royal Institute of Technology, Stockholm, Sweden*
[2]*Department of Physics, University of Gothenburg, Gothenburg, Sweden*

The spin torque oscillator (STO) is an emerging spintronic device for generation of radio frequencies (RF) in the microwave band 0.1 – 65 GHz. Apart from the electrical RF signal generation, the local generation of large-amplitude spin wave modes is also of great interest within the field of magnonics. We present an experimental study of the dependence of the frequency and oscillation power on the lateral device size, defined as the radius of the circular nano-contact (NC) used to inject the electrical current into the extended ferromagnetic film stack with materials and thicknesses Co(8 nm)/Cu(8 nm)/NiFe(4.5 nm). Electrical spectral measurements have been performed on 58 devices from the same chip, with nano-contact radii, r, ranging from 25 - 125 nm.

Despite the substantial device-to-device variation (a well-known but not extensively studied problem), the averaged behavior shows clear trends as a function of the NC radius. First, the maximum oscillating magnetoresistance signal amplitude, ΔR, falls off as $1/r^2$ similarly to the DC resistance, R. This indicates that the magnetization is precessing with the same average precession cone opening independently of the NC radius. Second, the frequency (Figure 1) scales approximately linearly as $C_1 + C_2 * I_{DC}/r$ (C_1 and C_2 are positive constants).

Following previous reports [1,2], we calculate the Oersted magnetic field generated by I_{DC} and find that along the perimeter of the NC, the local ferromagnetic resonance frequency (FMR) varies by as much as +/- 40 % for the highest current levels. The high-frequency section of the NC perimeter exhibits a local FMR frequency which is linear in I_{DC}/r and coincides approximately with the experimental result. Another mechanism for the STO frequency tunability is the amplitude/frequency nonlinearity of the magnetization dynamics [3], which predicts an increase in the frequency as a function of increasing I_{DC}, but with a more nonlinear behavior. The final spin wave frequency selection is likely governed by the complex interplay between the oscillation nonlinearity and the FMR frequency landscape.

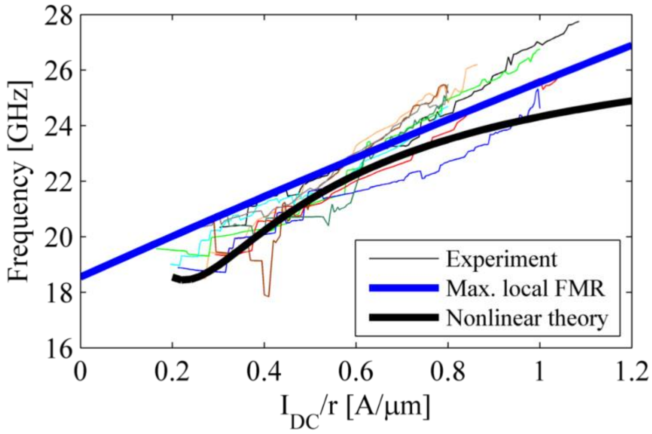


Figure 1. Each experimental line represents one device size. B = 1.0 T directed 70° out-of-plane.

[1] Hoefer *et al.*, Physical Review B **77**, 144401 (2008).
[2] Dumas *et al.*, Physical Review Letters **110**, 257202 (2013).
[3] Slavin and Kabos, IEEE Transactions on Magnetics **41**, 1264 (2005).

dc-bias dependence of ferromagnetic resonance spectra of a CoFeB-MgO based magnetic tunnel junction

Shun Kanai,[1,2] Martin Gajek,[3] D.C. Worledge,[3] Fumihiro Matsukura,[1,2,4] and Hideo Ohno[1,2,4]

[1]*Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University,*

[2]*Center for Spintronics Integrated Systems, Tohoku University*

[3]*IBM TJ Watson Research Center*

[4]*WPI-Advanced Institute for Materials Research (WPI-AIMR), Tohoku University*

Magnetic anisotropy in CoFeB/MgO systems can be modulated by applying the bias voltage [1]. In this work, we investigate the bias voltage dependence of the magnetic anisotropy in a CoFeB free layer in a magnetic tunnel junction (MTJ) by ferromagnetic resonance (FMR).

A stack structure, Ta/Ru/Ta/$Co_{0.2}Fe_{0.6}B_{0.2}$ (0.9 nm)/MgO (1.4 nm)/$Co_{0.2}Fe_{0.6}B_{0.2}$ (1.8 nm)/ Ta/Ru, is deposited by rf magnetron sputtering, and is processed into a 40-nm-diameter MTJ by electron beam lithography and Ar ion milling. The stack is annealed at 300^{o}C in a perpendicular magnetic field of 0.4 T. The two CoFeB layers have perpendicular magnetic easy axis, and the resistance-area product is 34 $\Omega\mu m^2$. rf voltage is applied to the MTJ to excite FMR, and FMR spectra as a function of dc bias voltage V_{bias} and in-plane magnetic field $H_{||}$ are measured by homodyne detection technique [2].

Figure shows the FMR spectra at three V_{bias}'s under $\mu_0 H_{||}$ = 44 mT. The resonant frequencies f_r are different at different V_{bias} because of the bias dependent magnetic anisotropy. The bias dependence of first- and second- order perpendicular magnetic anisotropy is determined from the fitting of the resonant condition to the magnetic-field dependence of f_r. The modulation ratio of the first-order anisotropy is evaluated to be 64 $\mu J/m^2$ per 1 V/nm, while the second-order anisotropy is almost independent of V_{bias}. The result is consistent with the previous one obtained from a cavity FMR measurements [3]. Anti-symmetric lineshape at V_{bias} = 0 indicates that FMR is induced by the rf voltage through the electric field-modulation of the magnetic anisotropy [4]. At $V_{bias} \neq 0$, the lineshape becomes more symmetric due to the reflected dc bias voltage from the MTJ, and the behavior can be reproduced by the simulation based on the macrospin model.

The authors thank D. Abraham, J. Z. Sun, K. Mizunuma, M. Yamanouchi, S.Ikeda, I. Morita, T. Hirata, and H. Iwanuma for their technical supports and discussions. This work was supported in part by JSPS through FIRST program, R&D for ICT Key Technology of MEXT, Grants-in-Aid for Scientific Research from JSPS (No. 26889007), MEXT (No. 26103002), and the GCOE Super-Internship.

[1] M. Endo *et al.*, Appl. Phys. Lett. **96**, 212503 (2010).
[2] A. A. Tulapurkar *et al.*, Nature **438**, 339 (2005).
[3] A. Okada *et al.*, Appl. Phys. Lett. **105**, 052415 (2014).
[4] T. Nozaki *et al.*, Nature Phys. **8**, 492 (2012).

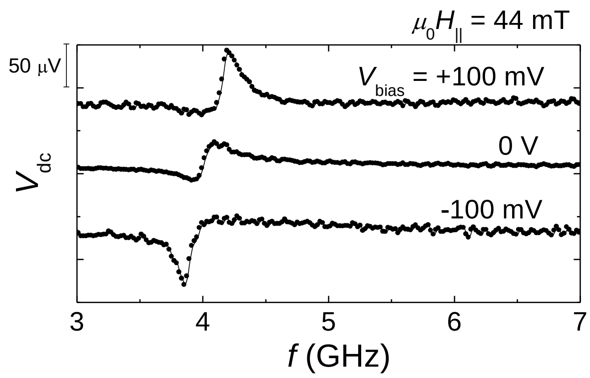


Figure: Ferromagnetic resonance spectra at three dc bias voltages under an in-plane external magnetic field of 44 mT.

Magnetic ground state of an individual Fe^{2+} ion in a strained semiconductor quantum dot

T. Smoleński, T. Kazimierczuk, J. Kobak, M. Goryca, A. Golnik, P. Kossacki, and W. Pacuski
Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Poland

Spin manipulation of individual impurities have attracted a lot of research attention over the last years [1-5]. Important contribution to this field can be done using quantum dots (QDs) containing various single transition metal ions, as was recently shown by the measurements of Mn^{2+} and Co^{2+} spin relaxation dynamics in different QD systems [3,4] or by our observation of coherent precession of a single Mn^{2+} spin [5].

One of the strongest motivations for the research in this area is a possibility to obtain long spin coherence time of an individual magnetic moment. From that perspective the Fe^{2+} ion embedded in a semiconductor QD seems a promising system, since it can be grown nuclear-spin free (e.g., in CdSe matrix), and due to a strong localization it is protected from itinerant carriers. However, such a system was not considered as a candidate for quantum information applications, since the Fe^{2+} ion in bulk zinc-blende or wurtzite II-VI semiconductors was found to inherently exhibit a single non-degenerate ground state and thus unable to store any quantum information.

In this work we demonstrate that by using the strain of a semiconductor QD it is possible to tailor the energy spectrum of the Fe^{2+} ion to exhibit doubly degenerate (i.e., magnetic) ground state. Moreover, this ground state is composed of states corresponding to ion spin projections $S_z = \pm 2$, which makes those two states less prone to decoherence, e.g., by residual in-plane magnetic field. Our concept is evidenced both theoretically and experimentally. From the theoretical side, we find that strong structural strain of a QD alters the spectrum of the ion orbital states, which in turn induces a distinctive changes in the ordering of the ion spin levels due to the spin-orbit coupling. The experimental proof is based on the results of photoluminescence (PL) studies of a novel QD system: self-assembled CdSe/ZnSe quantum dots doped with individual Fe^{2+} ions. A direct fingerprint of a nonzero spin of the Fe^{2+} ion ground state is a pronounced twofold splitting of the emission lines visible in a PL spectrum of a single QD, which is observed for all three excitonic complexes (as shown in Fig. 1). In each case, the splitting originates from the *s,p-d* exchange interaction between the ion and confined carriers, which leads to two different energies of the optical transitions depending on the actual spin projection of the Fe^{2+} ion. Our analysis is complemented by the measurements of a QD PL spectrum evolution in magnetic field, which allow us to determine the character and strength of the *s,p-d* exchange and to obtain the ion g-factor of 2.0, exactly as expected for the Fe^{2+}.

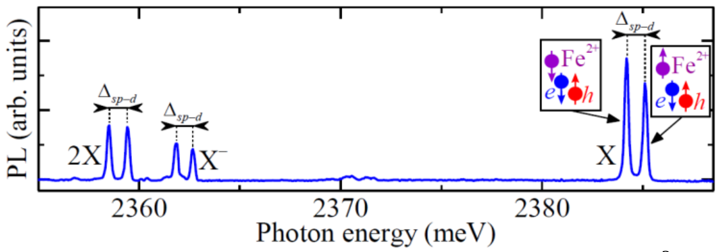


Fig.1: PL spectrum of a CdSe/ZnSe QD witha single Fe^{2+} ion

An excellent agreement between our model and experimental results unequivocally confirms the strain-induced magnetic character of a single Fe^{2+} ion in a CdSe/ZnSe QD. Such a novel QD system is thus a prominent candidate for quantum information processing, since both the CdSe lattice and Fe^{2+} ion can be free of any nuclear spin fluctuations.

[1] C. Yin et al., Nature 497, 91 (2013).
[2] T. Smoleński et al., Phys. Rev. B 91, 045306 (2015).
[3] J. Kobak, T. Smoleński et al., Nat. Commun. 5, 3191 (2014).
[4] B. Varghese et al., Phys. Rev. B 90, 115307 (2014).
[5] M. Goryca et al., Phys. Rev. Lett. 113, 227202 (2014).

Single-shot readout of electron spin states in a quantum dot using spin filtering by quantum Hall edge states

Haruki Kiyama,[1] Akira Oiwa,[1] and Seigo Tarucha[2,3]

[1] *The Institute of Scientific and Industrial Research, Osaka University, 8-1, Mihogaoka, Ibaraki-shi, Osaka 567-0047, Japan*

[2] *Department of Applied Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku 113-8656, Japan*

[3] *Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan, 361-0198*

Preparation and detection of electron spins in quantum dots (QDs) are prerequisite technologies for spintronics and quantum information processing. For these purposes, spin-resolved quantum Hall edge states may be useful since their spatial separation provides spin-dependent tunnel couplings to the QD [1]. However, the spin filtering by edge states has not yet been applied to the spin preparation and detection because of its poor efficiency. Recently, we have improved the spin-filtering efficiency high enough for spin injection and detection by the electrical tuning of the local filling factor near the QD [2].

In this work, we demonstrate the single-shot readout of electron spins using the improved spin filtering in a gate-defined GaAs QD (Fig. 1). We discriminate two-electron spin states with a spin angular momentum of $S_z = 0$ and $S_z = 1$. When $S_z = 0$ and $S_z = 1$ states transit to three-electron ground spin state $S_z = +1/2$, a spin-up and spin-down electrons tunnel into the QD, respectively. Because of the highly efficient spin filtering, the tunnel rate for the spin-up electron is much higher than that for the spin-down electron. Thus, the two-electron spin states are discriminated by monitoring such a tunnel-rate difference. The maximum readout visibility reaches 94% (Fig. 2), the highest ever reported for GaAs-based QDs.

Moreover, we apply this spin readout scheme to measure the spin relaxation rates of multi-electron high-spin states, three-electron $S_z = +3/2$ and four-electron $S_z = +2$. We prepare these high-spin states by loading spin-up electrons into the two-electron $S_z = +1$ ground state. For the readout of these states, first they are converted into two-electron spin states by removing one or two electrons. Because spin-up electrons are predominantly removed from the QD due to the spin filtering, the two-electron spin states after the removal have one-to-one correspondence to the initial multi-electron spin states. Then, the high-spin states are detected via the two-electron spin readout described above. As the result, we find that the spin relaxation rates of the high-spin states are approximately 10 times higher than that of $S_z = 0$

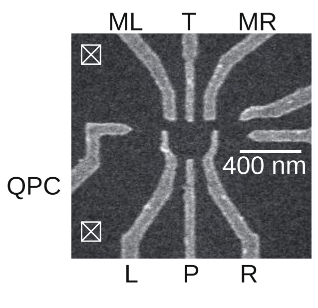


Figure 1: Scanning electron micrograph of the device

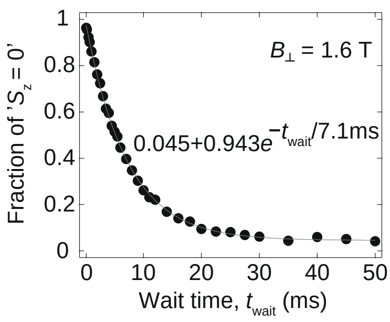


Figure 2: Fraction of the `S_z = 0' count as a function of wait time

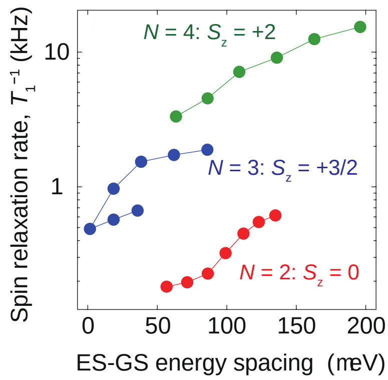


Figure 3: Spin relaxation rates of N = 2, 3 and 4 spin states

state (Fig. 3).

[1] M. Ciorga, A. S. Sachrajda, P. Hawrylak, C. Gould, P. Zawadzki, S. Jullian, Y. Feng and Z. Wasilewski, Phys. Rev. B 61, R16315 (2000).
[2] H. Kiyama, T. Fujita, S. Teraoka, A. Oiwa, and S. Tarucha, Appl. Phys. Lett. 104, 263101 (2014).

Magnetospectroscopy of CdTe and CdSe QDs with individual cobalt, and manganese

J. Kobak, T. Smoleński, M. Goryca, M. Papaj, K. Gietka, A. Bogucki, M. Koperski, J.-G. Rousset, J. Suffczyński, E. Janik, M. Nawrocki, A. Golnik, P. Kossacki, W. Pacuski
Institute of Experimental Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warsaw, Poland

This work presents molecular beam epitaxy and time resolved magnetooptical spectroscopy of novel semiconductor structures with single magnetic ions [1]. For the first time individual cobalt ion and individual manganese ion is optically observed in CdTe/ZnTe quantum dot (QD) and CdSe/ZnSe QD respectively (Fig. 1).

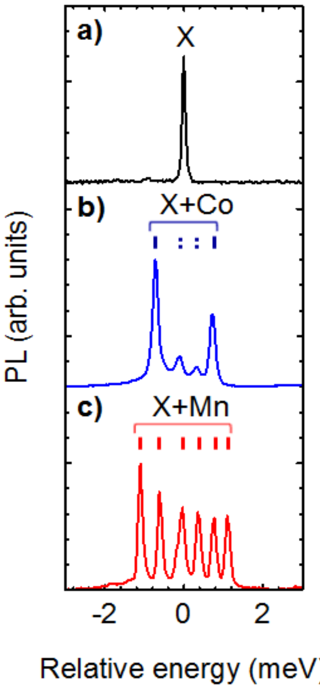


Fig. 1. Exciton line of a QD without magnetic ion (a), with single Co^{2+} (b), and with single Mn^{2+} ion (c).

The low temperature magneto – photoluminescence (PL) measurements and modelling allow us to identify PL lines related to QDs containing exactly one cobalt ion. QDs containing exactly one magnetic ion exhibit characteristic photoluminescence (PL) spectrum modified by s,p-d exchange interaction. Exciton and biexction lines are split by 4 due to 4 spin possible projection of Co^{2+}: ±3/2, ±1/2 [1], similarly to QDs with single Mn^{2+} where exciton and biexciton are split by 6 due to 6 spin projection of Mn^{2+}: ±5/2, ±3/2, ±1/2 [2,3]. However, the intensity of the lines related to Co^{2+} spin projections ±3/2 (outer lines) can be significantly different from those related to the spin projections ±1/2 (inner lines). In contrast to Mn^{2+} the Co^{2+} ion has non-zero orbital momentum and Co^{2+} incorporated to the crystal is very sensitive to a local anisotropy and the strain, which lead to the splitting of ±3/2 and ±1/2 states and a difference in their occupancy [1]. Moreover, we have found experimentally that the sign of Co^{2+} strain can be positive and negative. Therefore, depending on strain both ±3/2 and ±1/2 spin state can be the ground state of Co^{2+} in QD. In order to obtain a deeper understanding of the impact of local strain on the ground state of cobalt ion we performed theoretical simulations. We were able to achieve perfect agreement between experiment and simulation when we took into account that the quantization direction of the cobalt ion ground state does not have to be parallel to the quantization axis of the quantum dot which is the ion environment. Through the simulations, we are able to determine parameters not only related to the cobalt ion, but also many interesting parameters of quantum dots such as exchange integrals and local strain. During the exciton PL decay measurement for QDs with and without single magnetic ions, we did not observe any impact of single dopants on exciton decay time, which implies that the nonradiative channel is slower than the radiative channel. By on/off modulated non-resonant laser excitation we determined spin relaxation time of individual magnetic ions and we found longer relaxation times for single Mn^{2+} in CdSe QDs [1]. We interpret this results as related to weaker spin orbit interaction in selenidies than in tellurides, and more favorable electronic configuration of Mn^{2+}.

[1] J. Kobak et al., Nature Communications **5**, 3191 (2014).
[2] L. Besombes et al., Phys. Rev. Lett. **93**, 207403 (2004).
[3] M. Goryca et al., Phys. Rev. Lett. **103**, 087401 (2009).

Spin-orbit interaction in hydrogenated graphene

Taketomo Nakamura,[1] Yoshiaki Hashimoto,[1] Junji Haruyama,[2] Yasuhiro Iye,[1] and Shingo Katsumoto[1]

[1]*Institute for Solid State Physics, The University of Tokyo*

[2]*Graduate school of Science & Engeneering, Aoyama Gakuin University*

Graphene is a candidate material for spintronics due to its long spin coherence length coming from weak spin-orbit interaction (SOI) of a few tens of microelectronvolts. On the other hand, the weak SOI at the same time leads to the difficulty in spin-charge conversion *e.g.*, with spin Hall effects. A key in graphene spintronics is thus the introduction of the SOI, which process cannot be accomplished by applying the gate voltage unlike the case of two-dimensional systems in semiconductor heterostructures [1]. Recently, Balakrishnan *et al*. reported that weak hydrogenation greatly enhances SOI in graphene [2]. They discovered anomalous increase of non-local resistance attributable to the enhancement of SOI up to 2.5 meV for 0.05% hydrogenated graphene (H-graphene). But there is also a skeptical view about the enhancement because of the lightness of the composition elements. In order to confirm the enhancement, we have investigated transport in H-graphene, which is safer to say that they are really spin-related.

The configuration of the fabricated devices is displayed in the inset of Fig.1. The devices consisted of an exfoliated graphene, $Ni_{0.78}Fe_{0.22}$ ferromagnetic electrodes and gold nonmagnetic electrodes, the latter two of which were formed with standard lithography method. The graphene was hydrogenated just before measurements using hydrogen silsesquioxane and electron beam irradiation [3]. Figure 1(a) shows a conventional lateral spin-valve signal, which guarantees successful spin injection into H-graphene. In different terminal configuration, the magnetic field dependence of the voltage between nonmagnetic electrodes exhibits Hanle-like signal as shown in Fig.1(b). This signal originates from the spin current in H-graphene and also supports the emergence of the inverse spin Hall effect. The present experiment doubtlessly demonstrates the enhancement of SOI in H-graphene.

[1] S. Konschuh, M. Gmitra, and J. Fabian, Phys. Rev. B 82, 245412 (2010).
[2] J. Balakrishnan, G. K. W. Koon, M. Jaiswal, A. H. Castro Neto, and B. özyilmazm, Nat. Phys. 9, 284 (2013).
[3] S. Ryu, M. Y. Han, J. Maultzsch, T. F. Heinz, P. Kim, M. L. Steigerwald, and L. E. Brus, Nano Lett. 8, 4597 (2008).

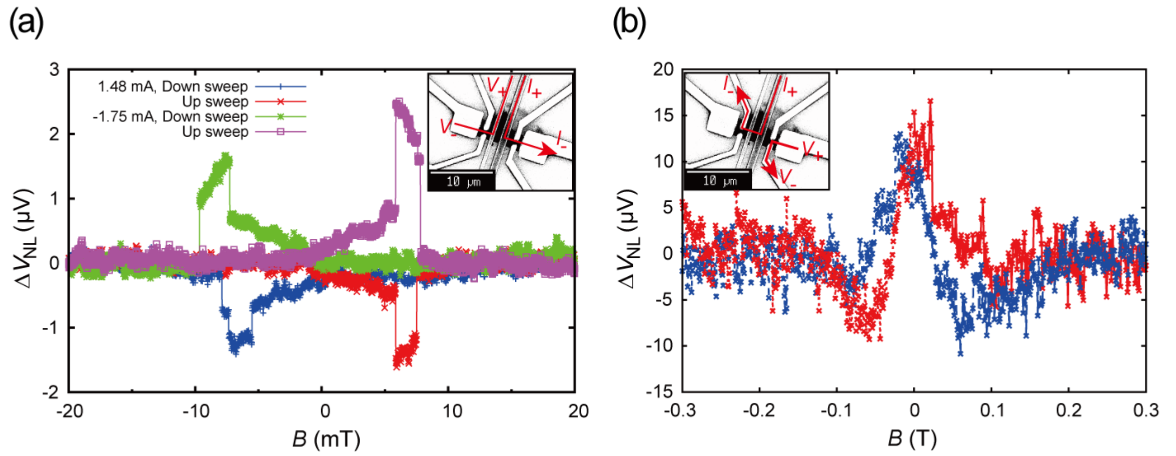


Fig. 1. Non-local voltages with the terminal configurations displayed in inset SEM images. The white, gray and black figures indicate gold, permalloy, and graphene. The magnetic fields are parallel and perpendicular to the permalloy electrodes in (a) and (b), respectively.

Efficiency of ferromagnet/semiconductor spin valve structures: Influence of ferromagnetic band structure and electrical contact characteristic

Manfred Ramsteiner,[1] Pawel Bruski,[1] Yori Manzke,[1] Steven C. Erwin,[2] and Jens Herfort[1]
[1]*Paul-Drude-Institut für Festkörperelektronik, Berlin, Germany*
[2]*Center for Computational Materials Science, Naval Research Laboratory, Washington DC, USA*

Numerous spintronic device concepts rely on the efficient electrical generation of a spin accumulation inside a semiconductor (SC) using the interface with a ferromagnetic metal (FM). Frequently employed lateral transport structures include the non-local and the three-terminal (3T) geometries. However, the results obtained in the 3T geometry are often found to be inconsistent with the expectations derived from the established detection of spin signals in the non-local spin valve (NLSV) configuration. Unambiguous reports on spin transport in the technologically more relevant two-terminal arrangement of the local spin valve (LSV) are scarce due to the difficulty to fulfill the specific requirements on the device parameters.

Regarding the efficiency of spin generation, the spin-polarized band structure of the FM is of crucial importance. The Heusler alloy Co_2FeSi in the fully ordered $L2_1$ phase is considered to be half-metallic and, hence, an ideal candidate for electrical spin injection. Disorder drastically modifies the electronic band structure. The partially disordered $B2$ phase not only lacks half-metallicity, but also exhibits an opposite spin polarization at the Fermi level. In this work, we investigate the bias-current dependence of spin generation in Co_2FeSi/GaAs NLSVs and compare our experimental results with the expections derived from the bulk band structures obtained by first-principles calculations for the two different Co_2FeSi phases. We demonstrate that the specific characteristics of the electronic band structures in the FM contacts indeed manifest themselves in the current dependences of the spin generation processes (cf. Fig. 1). With this knowledge, we have a tool at hand to probe details of the spin-polarized electronic band structure of ferromagnetic materials. In this way, our experimental findings confirm the results of the first-principles calculations reported previously. In particular for the $L2_1$ phase of Co_2FeSi, the prediction of a half-metallic character is strongly supported, an important material property which is otherwise very difficult to access experimentally.

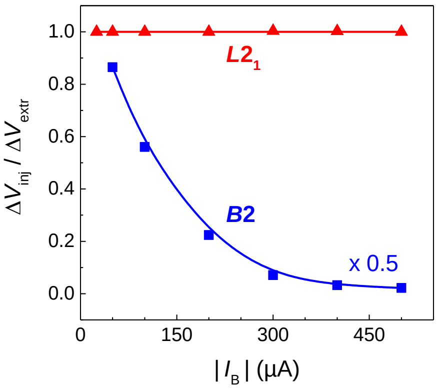


FIG. 1 Ratio of the NLSV signals obtained under spin injection and spin extraction conditions as a function of the bias current.

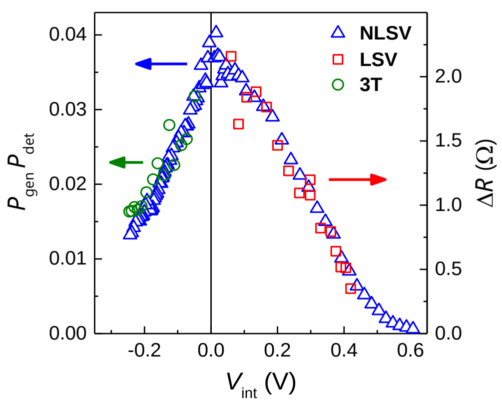


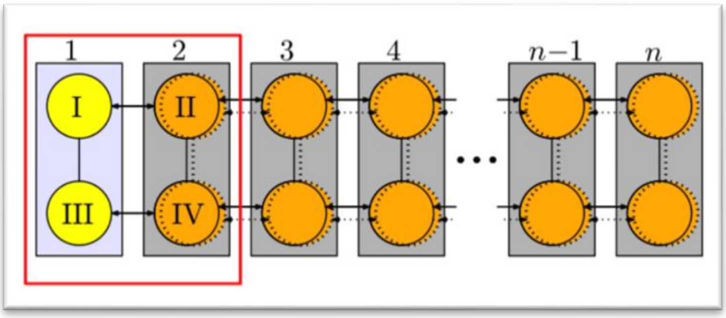
FIG. 2 Spin efficiency product as a function of the interface voltage for the NLSV and 3T configurations together with magnetoresistance of the LSV structure.

Besides the choice of a FM with an appropriate band structure, the current-voltage (I-V) characteristic also has an essential influence on the spin generation of a FM/SC contact. In this work, we demonstrate spin transport for a FM/SC system with a particularly favorable I-V characteristic in both the NLSV and LSV configurations. In addition, our results obtained in the 3T configuration are consistent with the spin-transport characteristics in NLSV and LSV structures (cf. Fig. 2).

Hybrid Spin and Valley Quantum Computing with Singlet-Triplet Qubits

Niklas Rohling, Maximilian Russ, and Guido Burkard
Department of Physics, University of Konstanz

The valley degree of freedom in the electronic band structure of silicon, graphene, and other materials is often considered to be an obstacle for quantum computing based on electron spins in quantum dots. Here we show that control over the valley state opens new possibilities for quantum information processing. Combining qubits encoded in the singlet-triplet subspace of spin and valley states allows for universal quantum computing using a universal two-qubit gate directly provided by the exchange interaction [1]. We show how spin and valley qubits can be separated in order to allow for single-qubit rotations [2]. These single-qubit operations are available when the qubits are stored in different double quantum dots and the exchange interaction and control over the spin or valley splittings provide arbitrary rotation on the respective Bloch sphere. The universal two-qubit gate and the single-qubit operations, together, provide universal quantum computing with both spin and valley degree of freedom used as qubits in the same quantum register.



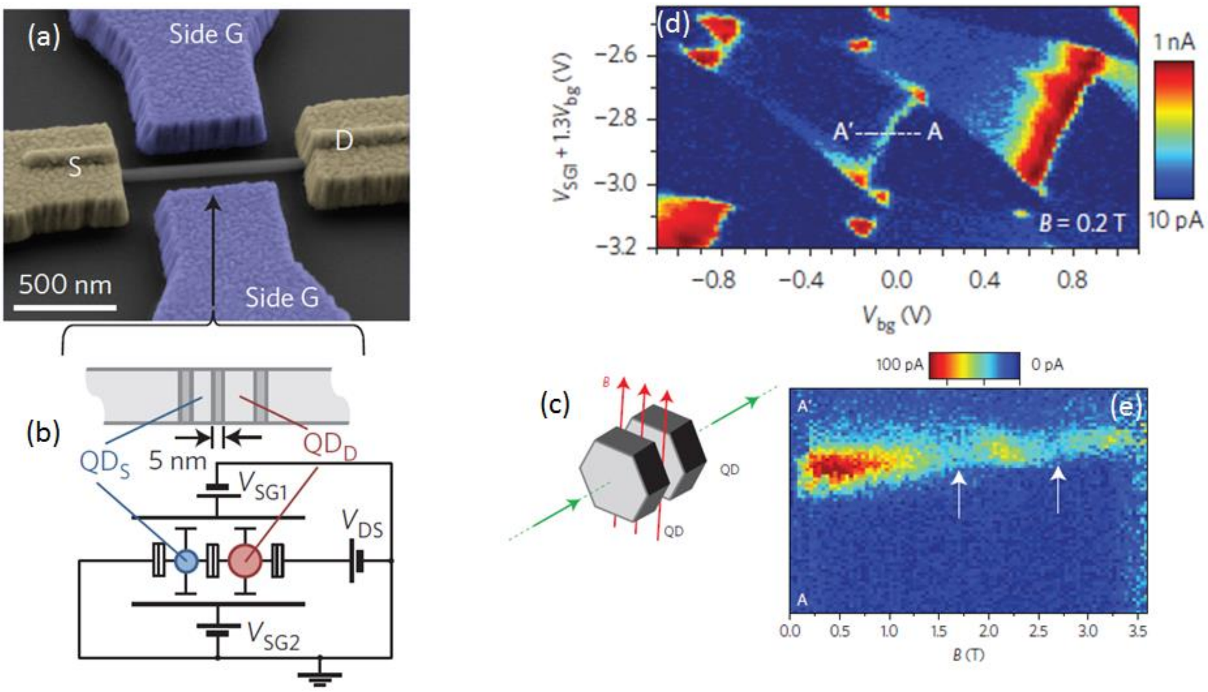
Quantum register combining quantum dots with spin degree of freedom only (yellow) and those containing spin and valley degrees of freedom (orange). Each of the double dots 2 to *n* stores two singlet-triplet qubits, one for the spin and one for the valley. For single-qubit operations the qubits from any double dot are first transferred to double dot 2 (arrows with solid and with dotted lines). Then, the spin qubit is interchanged with polarized spins in double dot 1 (solid line arrows) separating spin and valley qubits.

[1] N. Rohling and G. Burkard, New J. Phys. **14**, 083008 (2012).
[2] N. Rohling, M. Russ, and G. Burkard, Phys. Rev. Lett. **113**, 176801 (2014).

Stark effect controlled nanoscale spin rectifier

Francesco Rossella,[1] Andrea Bertoni,[2] Daniele Ercolani,[1] Massimo Rontani,[2] Lucia Sorba,[1] Fabio Beltram,[1] and Stefano Roddaro[1]
[1]NEST, Scuola Normale Superiore & Istituto Nanoscienze-CNR, Pisa, Italy
[2]S3, Istituto Nanoscienze-CNR, Modena, Italy

We demonstrate a novel technique to electrostatically control the spin configurations of single- and multi-dot systems implemented in heterostructured (InAs/InP) nanowires, using a method exploiting the Stark effect [1-3]. This allows us to independently address the filling of two dots separated by only few nanometers, thus achieving a fully-functional device without the need of implementing any challenging nanoscale gating architecture [4]. The full control of the double-dot configurations and a strong spin blockade up to about 10 K are demonstrated, and a novel re-entrant spin blockade lifting as a function of the magnetic field is highlighted. The latter oscillatory evolution is related to the modulation of interdot coupling with the field and is explained invoking Fraunhofer-like interference effects on a finite-size tunnel barrier.



(a) SEM image of one of the investigated NW transistors. A multiple gating technique is used to control quantum states in a one-dimensional InAs/InP heterostructure. (b) Sketch of the device structure: two quantum dots are subject to the same gating action. (c) Magnetic field configuration during measurements. (d) Bias triangles in spin blockade configuration (1,1)→(2.0) at B=0.2 T, V_{DS} = –10 mV. (e) Sweeping B as a function of the detuning along the dashed white segment crossing the base of the triangle indicated in the middle colourplot of (b), an unexpected oscillatory pattern is observed in the spin relaxation, with re-entrant spin blockade (arrows).

[1] S.Roddaro et al. 2011 Nano Lett. 11, 1695
[2] L.Romeo et al. 2012 Nano Lett. 12, 4490
[3] F.Rossella et al 2014 J. Phys. D: Appl. Phys. 47 394015
[4] F.Rossella et al. 2014 Nat. Nanotech. 9, 997

Spin relaxation mechanism and gate controlled magneto conductance in an epitaxial Pt thin film

Jeongchun Ryu, Shoichi Takasuna, Kohei Yoshizumi, Makoto Kohda and Junsaku Nitta
Department of Materials Science, Tohoku University, Sendai 980-8579, Japan

For realization of functional spintronic devices, electrical spin manipulation is one of the essential technologies. Even though the D'yakonov-Perel' (DP) mechanism originated from the Rashba spin orbit interaction (SOI) has been well established in Ⅲ – Ⅴ semiconductors [1, 2], there are disadvantages, for example, the long spin precession length and limitation of operating temperature. To overcome those problems, spin manipulation in metals has been raised. However, further understanding of spin relaxation mechanism in thin metal films is required. Here, we report that in epitaxial Pt thin films, the spin relaxation is induced by the DP mechanism and magneto conductance can be manipulated by an external gate voltage.

Each epitaxial Pt layer was deposited on MgO (111) substrates by Radio-Frequency sputtering with a different thickness: d = 3 nm, 4 nm, and 6 nm. All samples were covered with an AlO layer (0.6 nm) in order to induce the Rashba SOI. We made an electric double layer for applying electric field to Pt. To evaluate the SOI in thin Pt films, we focus on quantum correction of the conductance, i.e. weak antilocalization (WAL). If strong SOI exists, negative magneto-conductance is observed around zero magnetic fields. As a result, we can obtain the spin relaxation time τ_{so} which reflects the strength of SOI.

Figure 1 shows the relationship between momentum scattering time τ_p and τ_{so}, depending on Pt thickness. The inversely proportional relationship indicates that the dominant spin relaxation in epitaxial Pt films is induced by the DP mechanism, whereas it has been known as the Elliott-Yafet (EY) mechanism associated with the momentum scattering in normal metallic systems [3, 4]. As the reason for appearing the DP mechanism, we consider that crystal orientation along [111] direction in epitaxial Pt films suppresses the EY mechanism a lot, thus it enhances the effect of Rashba SOI at the MgO / Pt and Pt / AlO interfaces remarkably. Since the Rashba SOI is tunable by an electric field, we applied gate voltage on a 3 nm - thick epitaxial film and measured its WAL. As shown in Fig. 2, the signals of WAL are manipulated depending on gate voltage, which suggests possibility of voltage - controlled spin relaxation time.

In conclusion, we demonstrated the DP mechanism induced by Rashba SOI appears dominantly in epitaxial Pt thin films. Moreover we succeeded to manipulate WAL by applying an external gate voltage. The quantitative analysis correlated to manipulation of spin relaxation time will be discussed in the conference.

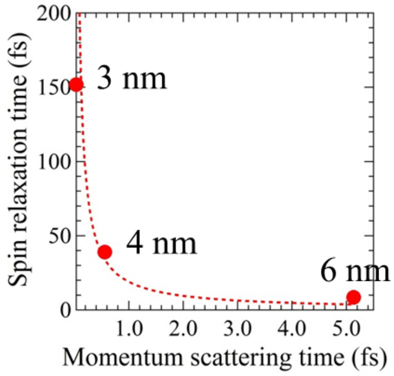


Fig. 1. Relationship between τ_p and τ_{so}. Dotted line shows the DP mechanism in thick Pt films.

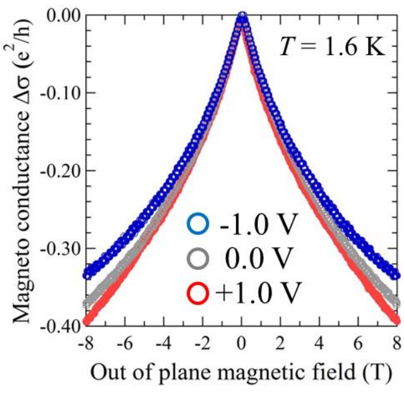


Fig. 2. WAL in 3 nm thickness of epitaxial Pt film depending on gate voltage.

[1] J. Nitta *et al.*, Phys. Rev. Lett. **78**, 1335 (1997).
[2] E. I. Rashba, Fiz. Tver. Tela (Soviet Physics-solid state), **2**, 1224 (1960).
[3] R. J. Elliott, Phys, Rev. **96**, 266 (1954).
[4] Y. Niimi *et al.*, Phys. Rev. Lett. **110**, 02685 (2013).

Spin-dependent Trap-assisted Tunneling Including Spin Relaxation at Room Temperature

Viktor Sverdlov and Siegfried Selberherr
Institute for Microelectronics, TU Wien
Gußhausstraße 27-29, A-1040 Wien, Austria

In order to realize spin-driven devices in semiconductors, efficient spin injection and detection must be possible. Two schemes to analyze spin injection into a semiconductor are available [1]. A signal obtained with the three-terminal scheme at room temperature was documented for both n- and p-doped silicon in 2009 [2]. Electric signals believed to be corresponding to spin injection through silicon dioxide at 500K have also been reported [3]. However, the discrepancy between the signal measured and the theoretical value [1] is several orders of magnitude. It turns out that the signal is stronger in three-terminal measurements, while it is weaker in the non-local scheme. The reasons for these discrepancies are heavily debated [4]–[7]. Recently, the large amplitude of the signal observed in the three-terminal injection method was attributed to resonant tunneling through deep impurities [4]. The large contribution to the magnetoresistance is due to a spin blockade at trap-assisted tunneling. The spin at a trap has an equal probability for being parallel or anti-parallel to the magnetization of the ferromagnetic contact. When being anti-parallel, it cannot escape to the ferromagnet and blocks the current flow from the semiconductor to the ferromagnet. The blockade is lifted, when an external magnetic field orthogonal to the magnetization is applied. The coherent spin precession in such a field was only considered in [4].

Here we include spin decoherence and spin relaxation described by the times T_2 and T_1. At room temperature and weak field these times are expected to be almost equal [8], while typically $T_2<T_1$. We solve the equations for the density matrix describing the spin dynamics including dephasing and relaxation. The trap coupling is described by the rate Γ_N of tunneling from a semiconductor and the rate Γ_F of tunneling to a ferromagnet. The current I for spin injection due to tunneling via a trap, with the spin quantization axis forming an angle Θ with the magnetization direction, is:

$$I = \frac{\Gamma_F(\Theta)\,\Gamma_N}{\Gamma_F(\Theta)+\Gamma_N} ,$$

where

$$\Gamma_F(\Theta) = \Gamma_F\left(1 - p^2\,\Gamma_F T_1\left\{\frac{\cos^2\Theta}{\Gamma_F T_1+1} + \frac{T_2}{T_1}\frac{\sin^2\Theta(\Gamma_F T_2+1)}{\omega_c^2 T_2^2+(\Gamma_F T_2+1)^2}\right\}\right) .$$

Here ω_c is the cyclotron frequency and p is the interface current polarization. In the case $T_1 = T_2 \to \infty$ the corresponding expression in [4] is recovered. The obtained expression allows to investigate the dependence of the current on temperature through the temperature dependences of spin dephasing and relaxation as well as of the tunneling rates.

This work is supported by the European Research Council
through the grant #247056 MOSILSPIN

[1] R. Jansen, Nature Materials 11, pp. 400–408 (2012).
[2] S. P. Dash, S. Sharma, R. S. Patel, M. P. de Jong, and R. Jansen, Nature, 462, pp. 491–494 (2009).
[3] C. Li, O. van ’t Erve, and B. Jonker, Nature Communications 2, p. 245 (2011).
[4] Y. Song and H. Dery, Phys. Rev. Lett. 113, 047205 (2014).
[5] R. Jansen, A. M. Deac, H. Saito, and S. Yuasa, Phys. Rev. B 85, 134420 (2012).
[6] A. Spiesser, H. Saito, R. Jansen, S. Yuasa, and K. Ando, Phys. Rev. B 90, 205213 (2014).
[7] K.-R. Jeon, H. Saito, S. Yuasa, and R. Jansen, Phys. Rev. B, 91, 155305 (2015).
[8] A. Kawabata, Progress Theor. Phys. 48, pp. 2237-2251 (1972).

All-electrically controlled long distance entanglement of mobile electron soliton spin qubits in gated nanodevices

Paweł Szumniak,[1,2] Stanisław Bednarek,[2] and Daniel Loss[1]
[1] Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland
[2]AGH University of Science and Technology, Faculty of Physics and Applied Computer Science al. Mickiewicza 30, 30-059 Kraków, Poland

The ability to couple and entangle solid state spin qubits over long distances is crucial for realization of scalable quantum computer architecture and for applications of fault-tolerant quantum error correction codes. However it is still one of the key challenges to overcome [1].

Here we propose a novel technique for generating maximally entangled spin states of distant electrons by all-electrical means within sub-nanoseconds [2]. The proposed scheme is based on the interplay between the exchange interaction and theoretically proposed on-demand coherent transport of self-trapped electron solitons [3, 4] confined in the gated semiconductor nanowires. The electrostatic coupling between electrons in the nanowire and the induced charge on the metal electrodes can lead to a lateral self-confinement of the electrons which results in soliton-like properties. In our scheme self-trapping allows for transporting spatially separated initially not entangled electrons to the region where they can entangle their spins due to the exchange interaction and finally be separated and transported back to remote regions as an entangled entity.

Presented entanglement scheme can be straightforwardly integrated with recently proposed all-electrically controlled nanodevices acting as an ultrafast (sub nanoseconds) single quantum logic gates on the electron [5] and hole spin qubits [6,7]. This allows for realization of 2D scalable architecture of spin qubits which can be individually and selectively manipulated and coupled over long distances.

We present the results for InAs nanowires and discuss feasibility of proposed scheme for different materials and for various system parameters. Furthermore we show how presence of the nuclear spins of the host material and the exchange noise can affect spin entanglement process.

[1] C. Kloeffel and D. Loss, Annual Review of Condensed Matter Physics 4, 51 (2013).
[2] P. Szumniak, J. Pawłowski, S. Bednarek and Daniel Loss Arxiv:1501.01932 (2015)
[3] S. Bednarek, B. Szafran, and K. Lis, Phys. Rev. B **72**, 075319 (2005).
[4] S. Bednarek, B. Szafran, R. J. Dudek, and K. Lis, Phys. Rev. Lett. **100**, 126805 (2008).
[5] S. Bednarek and B. Szafran, Phys. Rev. Lett. **101**, 216805 (2008).
[6] P. Szumniak, S. Bednarek, B. Partoens, and F. M. Peeters, Phys. Rev. Lett. **109**, 107201 (2012).
[7] P. Szumniak, S. Bednarek, J. Pawłowski, and B. Partoens, Phys. Rev. B **87**, 195307 (2013).

Spatio-temporal spin fluctuations in two-dimensional electron gas

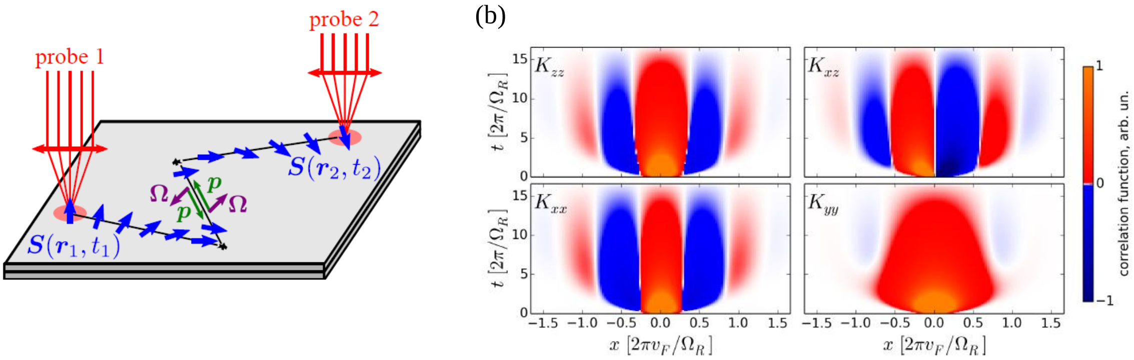
A.V. Poshakinskiy and S.A. Tarasenko
Ioffe Institute, 194021 St. Petersburg, Russia

The spectroscopy of spin noise is an efficient state-of-the-art tool for the study of spin dynamics in conditions close to thermal equilibrium [1]. So far, the spin-noise studies in conducting structures have been focused on the evolution of spin fluctuations in time (or the spectral density of fluctuations) while the general analysis shows that the temporal and spatial correlations of spin fluctuations emerging in an electron gas are coupled due to Brownian motion of electrons and spin-orbit interaction.

Here, we develop a theory of propagating thermal spin fluctuations in a two-dimensional electron gas confined in a quantum well. We calculate the spatio-temporal correlation functions of the spin density for both diffusive and ballistic electron transport and analyze them for different types of spin-orbit coupling including the isotropic Rashba model and the persistent spin helix regime. We show that the correlations of spin fluctuations at large delay times are determined by the long-lived waves of spin density and drastically increase in the regime of persistent spin helix [2]. The measurements of spatio-temporal spin fluctuations provide a direct noninvasive access to spin-orbit coupling and spin transport parameters.

We consider a two-dimensional electron gas in thermal equilibrium. The gas is spin-unpolarized, however there are incessant fluctuations of the spin density. The spin fluctuations propagate in the QW plane due to Brownian motion of electrons and precess in the effective momentum-dependent magnetic field $\mathbf{\Omega}(\mathbf{p})$ caused by spin-orbit interaction, see Fig. 1a. The fluctuations are described by the correlation functions of the spin-density components in real space and time, $K_{\alpha\beta}(\mathbf{r}_1-\mathbf{r}_2,t_1-t_2)=\langle S_\alpha(\mathbf{r}_1,t_1)S_\beta(\mathbf{r}_2,t_2)\rangle$. Figure 1b shows the calculated spatial and temporal dependence of the correlation functions $K_{\alpha\beta}(\mathbf{r},t)$ for diffusive transport of electrons between the spots where the fluctuations are probed. The correlations survive at rather long distances. Despite the diffusive transport, where electrons can travel along many different trajectories, the correlation functions contain oscillations as a function of the distance. Such an oscillatory behavior is caused by the precession of spin fluctuations in the effective magnetic field.

(b)



(a)

(a) Sketch of a possible probe-probe experiment on the measurements of spatio-temporal spin fluctuations. (b) Spin density correlation functions $K_{\alpha\beta}(\mathbf{r},t)$ for Rashba spin-orbit interaction and $\mathbf{r} \parallel x$.

[1] J. Hübner, F. Berski, R. Dahbashi, and M. Oestreich, physica status solidi (b) 251, 1824 (2014).
[2] A.V. Poshakinskiy and S.A. Tarasenko, arXiv:1505.03826.

Magnetic tunnel junction's with highly magnetostrictive layers

B. Gobaut[1], G. Vinai[2], H. Rafaqat[2,3], S. Roddaro[2,4], G. Rossi[2,5], G. Panaccione[2], M. Eddrief[6,7], M. Marangolo[6,7] and P. Torelli[2]

[1]*Sincrotrone Trieste S.C.p.A., S.S. 14 Km 163.5, Area Science Park, 34149 Trieste, Italy*
[2]*Laboratorio TASC, IOM-CNR, S.S. 14km 163.5, Basovizza, 34149 Trieste, Italy*
[3]*ICTP, Trieste, Italy*
[4]*NEST, CNR-NANO, Piazza S. Silvestro 12, 56127 Pisa, Italy*
[5]*Dipartimento di Fisica, Università di Milano, via Celoria 16, 20133 Milano, Italy*
[6]*Sorbonne Universites, UPMC Paris 06, UMR 7588, INSP, 4 place Jussieu, F-75005, Paris, France*
[7]*CNRS, UMR 7588, Institut des NanoSciences de Paris, 4 place Jussieu, F-75005, Paris, France*

Much effort is devoted to learn how to control magnetization of ferromagnetic layers through application of electric pulses, as potential applications for sensors, magnetic memories or spintronic devices are expected [1]. The strategy for obtaining an high magnetoelectric coupling consists in the fabrication of artificial interfaces combining piezoelectric and magnetostrictive materials [2] or ferroelectric and ferromagnetic layers [3].
Here we present novel results on a magnetic tunnel junction (MTJ) involving one ferromagnetic layer displaying one of the highest magnetostrictive coefficient values known as of today: galfenol ($Fe_{1-x}Ga_x$). Replacing one of the Fe electrode into the prototypical Fe/MgO/Fe stack with galfenol we can obtain a MTJ with high magnetoresistance in which the magnetization of one layer can be controlled by mechanical stress. We thus designed and grew the $Fe_{1-x}Ga_x$/MgO/Fe stack on a GaAs substrate.

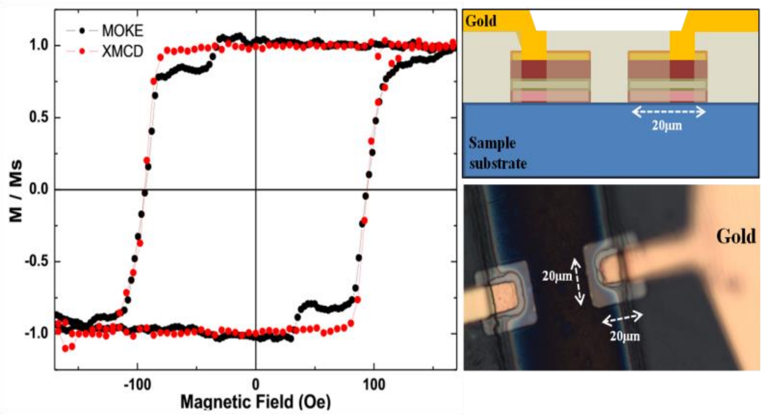


Figure: Hysteresis Curves of FeGa/MgO/Fe heterostructure by MOKE and XMCD; Scheme and Picture of the patterned pillars for electric characterisations.

The magnetic properties of the heterostructure have been studied by element specific synchrotron x-ray absorption spectroscopy and magnetic circular dichroism as well as with magneto-optical kerr effect measurements [3]. Columnar structures with 20x20 μm^2 size were prepared by lithography and electrically characterized. These devices show a magnetoresistive response demonstrating the success of our strategy for the development of new prototypes of future possible devices.
Magnetic and electric characterisation has been performed at the NFFA-Trieste facility.[5].

[1] F. Matsukura, Y. Tokura, H. Ohno, Nat. Nanotechnol. 10 (2015) 209.
[2] M. Overby et al. APL 92, 192501 (2008)
[3] G. Radaelli et al., Nat. Commun. 5 (2014) 3404.
[4] B. Gobaut et al., J. Magn. Magn. Mater. 383 (2015) 56
[5] http://nffa.promoscience.com/

All-optical coherent population trapping with divacancy spin ensembles in silicon carbide

Caspar H. van der Wal[1], Olger V. Zwier[1], Xu Yang[1], Danny O'Shea[1], Alexander R. Onur[1], Erik Janzén[2], and Nguyen T. Son[2]

[1] *Zernike Institute for Advanced Materials, University of Groningen, The Netherlands*
[2] *Department of Physics, Chemistry and Biology, Linköping University, Sweden*

Divacancy defects in silicon carbide have long-lived electronic spin states and sharp optical transitions, with properties that are similar to the nitrogen-vacancy defect in diamond. If ensembles of such spins can be all-optically manipulated, they make compelling candidate systems for quantum-enhanced memory, communication, and sensing applications.

We report experiments on 4H-SiC that investigate all-optical addressing of divacancy spin states with the zero-phonon-line transitions. Our magneto-spectroscopy results fully identify the spin S=1 structure of the ground and excited state (Fig. 1a), and we use this for tuning of transition dipole moments between particular spin levels. We also identify a role for relaxation via intersystem crossing. Building on these results, we demonstrate coherent population trapping (CPT, a key effect for quantum state transfer between spins and photons) for divacancy sub-ensembles along particular crystal axes [1]. Notably, weak-magnetic-field tuning of the spin states allows for controlling CPT with two lasers, without using a third laser for avoiding optical pumping into one of the three S=1 spin levels.

Our initial results used photo-luminescence signals from samples with low divacancy concentration [1]. In more recent work we studied samples with 1000 times higher divacancy concentration (after electron irradiation and subsequent annealing). This allowed for CPT studies via optical transmission signals, thus directly testing electromagnetically induced transparency (EIT) in this medium (Fig. 1b). These results, combined with the availability of mature device processing technology, put SiC at the forefront of quantum information science in the solid state.

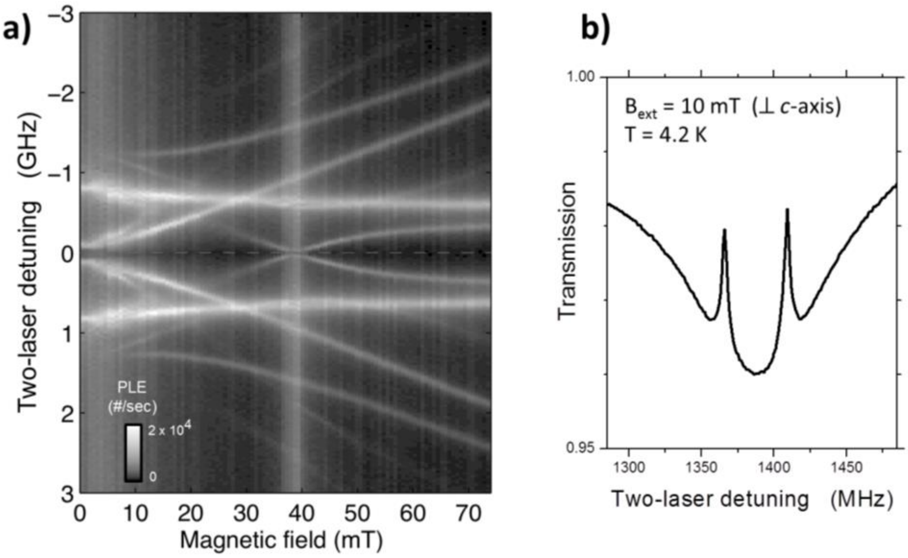


Figure 1: **a)** Photo-luminescence signals from two-laser magneto-spectroscopy reveal the homogeneous optical linewidth of spin-selective transitions and the structure of the spin S=1 Hamiltonians. **b)** Two EIT peaks (from two different combinations of ground-state spin levels) observed in the transmission of a probe laser in two-laser spectroscopy. Tuning of the strength and direction of the weak magnetic field can give a single EIT peak with near unity transmission.

[1] O.V. Zwier, D. O'Shea, A.R. Onur, and C.H. van der Wal, *Scientific Reports (NPG)* **5**, 10931 (2015); doi:10.1038/srep10931; arXiv:1411.1366.

Spatially resolving coupled donors quantum states in silicon

B.Voisin[1*], J. Bocquel[1], J. Salfi[1], M. Usman[2], A. Tankasala[3], R. Rahman[3], G. Klimeck[3], M. Y. Simmons[1], L. C. L. Hollenberg[2] and S. Rogge[1]

[1] Centre for Quantum Computation and Communication Technology, School of Physics, The University of New South Wales, Sydney, NSW 2052, Australia

[2] Centre for Quantum Computation and Communication Technology, School of Physics, University of Melbourne, Parkville, VIC 3010, Australia

[3] Purdue University, West Lafayette, Indiana 47906, USA

[*]e-mail: benoit.voisin@unsw.edu.au

The control of interactions between two-level systems is a key requirement towards reliable quantum computation schemes in the solid-state. Theory predicts that the exchange interaction between donors in silicon, which are now demonstrated as robust qubits, is governed by the presence of valleys and drastically oscillates with atomic variations in the donors' placement [1]. In this work few-dopant correlated systems are addressed using scanning tunneling microscopy and spectroscopy (STM/STS), tools of choice to probe quantum systems properties at this scale.

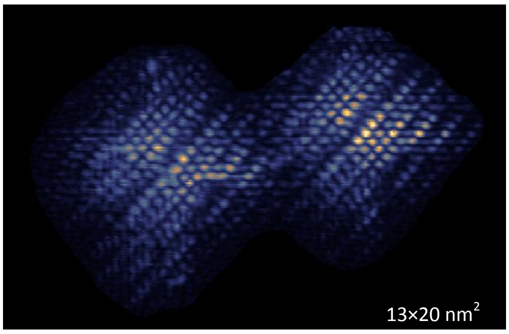


Fig. 1: Two coupled phosphorus donors in silicon probed by STM.

In the presented experiments, subsurface donors are decoupled from the substrate, acting as an electron reservoir, to directly image probability densities in the single electron resonant tunneling regime [2]. The energy scale and electric field at the donor site are obtained from tip-height dependent spectroscopy. For single donors, the quantum mechanical valley interferences are deduced [3]. The valley population distribution in the donor ground state is quantified as function of donor depth and electric field, in agreement with tight-binding calculations, which include tip orbitals. Furthermore, the atomically precise in-situ fabrication achieved by STM lithography has opened the way to the investigation of interactions in few-donor systems by STS [4]. Molecular states of two electrons bound to a donor pair have been spatially resolved, which, supported by full configuration interaction calculations, gives unprecedented insights into charging energies and the role of valleys on couplings. Notably a change in the excited states valley composition is expected when the donor-donor distance becomes less than about 5 nm, regime experimentally accessible, causing a saturation of the exchange energy. The analysis of the wave-functions in real (Fig. 1) and reciprocal spaces allows direct access to quantum correlations in dopant-based systems in silicon.

References

[1] B. Koiller *et al.*, PRL **88**, 027903 (2001).

[2] B. Voisin *et al.*, J. Phys.: Condens. Matter **27**, 154203 (2015).

[3] J. Salfi *et al.*, Nature Materials **13**, 605-610 (2014).

[4] M. Fuechsle *et al.*, Nature Nanotechnology **7**, 242−246 (2012).

Long spin lifetimes and high fidelity readout of electrons bound to single and few-donor dots in silicon

T. F. Watson,[1] B. Weber,[1,2] M. House[1], H. Büch[1,3], and M. Y. Simmons[1]

[1]Australian Research Council Centre of Excellence for Quantum Computation and Communication Technology, School of Physics, University of New South Wales, Sydney, NSW 2052, Australia
[2]Present address: School of Physics, Monash University, Melbourne, VIC 3800 Australia
[3]Present address: Center for Nanotechnology Innovation@ NEST, Istituto Italiano di Tecnologia, Piazza San Silvestro 12, 56127 Pisa, Italy

Electron spins bound to donors in silicon are attractive qubits due to their millisecond coherence times [1] and the ability to store quantum information in the donor nuclear spin [2]. The next major step towards a scalable donor-based architecture is to perform a two qubit gate between a pair of exchange-coupled donor-bound electron spins which requires the ability to readout the individual electron spin states [3]. Readout of a single electron spin has been achieved via spin selective tunnelling to an electron reservoir [4, 5] with fidelities as high as 97% [1]. However, robust quantum error correction protocols such as the surface code require fidelities of ∼ 99% with the measurement of parity operators to detect and correct errors faster than qubit coherence times [6]. For electron spin qubits, these fidelities are determined by a number of factors which include the signal to noise ratio of the charge sensor, thermal excitation of electrons, and the electron tunnel times from the donor to an electron reservoir. The latter is extremely challenging to control due to the stochastic nature of most doping techniques.

We address these issues by using the atomic precision accuracy of STM-lithography [7,8,9] to fabricate a single donor device which incorporates a single electron transistor with an extremely high signal to noise ratio. The ability to accurately position the donor with respect to an electron reservoir allows us to tailor the tunnel rates to achieve a record fidelity of 99.6%. Importantly, we show that we can decrease the tunnel times by nearly two orders of magnitude by selecting the doubly occupied charge state of the donor for spin readout while still maintaining high fidelities of 98%. We use these techniques to demonstrate the electron spin readout of two weakly-coupled few-donor dots with equally high fidelities (99.8%) where we measure extremely long spin lifetimes (~30s) due to the tight Coulomb confinement in these dots.

[1] J. T. Muhonen *et. al.*, Nature Nanotechnology, **9**, 986 (2014).
[2] J. J. Pla *et. al.*, Nature **496**, 334 (2013).
[3] K. C. Nowack *et. al.*, Science **333**, 1269 (2011)
[4] J. M. Elzerman *et. al.*, Nature **430**, 431 (2004)
[5] A. Morello *et. al.*, Nature **467**, 687 (2010)
[6] A. G. Fowler *et. al.*, Physical Review Letters, **108**, 180501 (2012)
[7] M. Fuechsle *et. al*, Nature Nanotechnology **7**, 242 (2012)
[8] B. Weber *et. al.*, Science, **335**, 64 (2012)
[9] B. Weber *et. al.*, Nature Nanotechnology, **9**, 430 (2014)

The Andreev spectrum in multi-terminal Josephson junction: singularities and topological properties

Tomohiro Yokoyama[1,2] and Yuli V. Nazarov[1]
[1]*Kavli Institute of Nanoscience, Delft University of Technology, The Netherlands*
[2]*Center for Emergent Matter Science, RIKEN institute, Japan*

We study theoretically short multi-terminal Josephson junction. Such junctions have been realized with crossed InSb/As nanowires [1], where spin-orbit (SO) interaction is strong. In short Josephson junctions, the Andreev bound states with discrete energy-levels are formed in the superconducting gap region, $|E| < \Delta$. The Andreev levels depend on the phase differences between superconductors. The levels are 2π periodic in all pahses. We consider a four-terminal junction, where three phase differences are defined. The Andreev levels are regarded as a “band structure”. We investigate the Andreev spectrum and the singular points in the spectrum at $E = 0$ and $|E| = \Delta$, which are associated with the Weyl physics in a 3D solid [2].

The Andreev levels are calculated from the Beenakker's determinant equation [3]. By the time-reversal symmetry, the change of sign of all phases gives the same energy level. The Andreev levels come in pair of positive and negative energies. For some junctions, conical band touching is found at $E = 0$ in the absence of SO interaction. The levels are doubly degenerate. The conical points come in groups of four, as shown in Fig. 1(a). The SO interaction splits the conical points to upward and downward energetically [Fig. 1(b)]. When the S-matrix in the determinant equation is changed continuously, the conical points move but keep the groups of four. If the points meet each other, we find a pair annihilation. These indicate topological protection of the Weyl fermion.

The Andreev level touches the gap edge in the absence of SO interaction. The gap edge touching point forms a 2D surface in the 3D phase space. The SO interaction generally removes the levels from $|E| = \Delta$. We establish the effective Hamiltonian from the determinant equation and find the conditions of the gap edge touching in the presence of SO interaction.

[1] S. R. Plissard *et al.*, Nature Nanotech. **8**, 859 (2013).
[2] X. Wan *et al.*, Phys. Rev. B **83**, 205101 (2011).
[3] C. W. J. Beenakker, Phys. Rev. Lett. **67**, 3836 (1991)

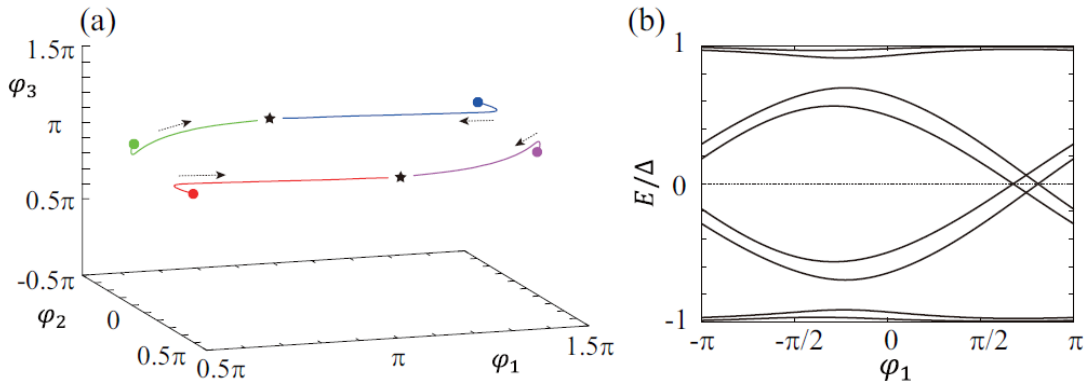


Figure 1: (a)Position of Weyl points in 3D phase space. Dots mean no SO interaction. Lines are the trajectory when the SO interaction is tuned continuously. The pair annihilation takes place at star marks. (b)Andreev level with conical point, which is split by the SO interaction to upward ($E > 0$) and downward ($E < 0$).

Photon-controlled Berry phase in a solid-state spin qubit

Brian B. Zhou,[1] Christopher G. Yale,[1,2] and F. Joseph Heremans,[1] Adrian Auer,[3] Guido Burkard,[3] and David D. Awschalom[1]

[1]*Institute for Molecular Engineering, University of Chicago, Chicago, Illinois 60637, USA*
[2]*Department of Physics, University of California, Santa Barbara, California 93106, USA*
[3]*Department of Physics, University of Konstanz, D-78457 Konstanz, Germany*

Geometric phases, which arise when a quantum state is evolved due to nonlocal properties of the path travelled, represent one of the surprising features of quantum physics. Besides their fundamental role in physical phenomena such as molecular distortions and the quantum Hall effect, the intrinsic noise resiliency of geometric phases has motivated their application as an alternative approach for realizing high fidelity quantum gates. This potential would be advanced by implementations of geometric phase in solid state platforms, with robust, independent control over individual qubits. Here, we demonstrate Berry phase in an exemplary solid-state qubit, the nitrogen-vacancy (NV) center in diamond, through controlling the amplitude and phase of the incident light [1]. In comparison to microwave techniques that lack spatial resolution, our optical realization presents a framework for site-selective geometric manipulation in arrays of qubits and enables integration with the toolkit of existing photonic techniques for quantum control.

The method we employ is based on stimulated Raman adiabatic passage to manipulate a dark state of a lambda system [2] within the NV center's low temperature electronic structure ($T < 20$ K). Through evolving the relative amplitude and phase of two optical fields adiabatically, we guide the dark state along the surface of the Bloch sphere, accumulating a Berry phase proportional to the enclosed solid angle. We investigate the resiliency of this Berry phase to the limits set by the loss of adiabaticity and decoherence at short and long time scales, respectively, and to stochastic noise introduced into the control parameters. We find that dephasing of our Berry phase is independent of geometric factors, a condition conducive to practical protocols. The prevalence of lambda energy structures makes possible the extension of our techniques to other optically-active defects in solid state materials, whereby specific material advantages may be combined with the benefits of optical geometric control.

This work is supported by the AFOSR and NSF.

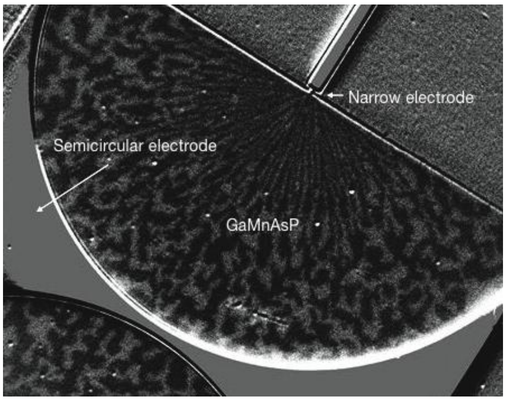
[1] C. G. Yale*, F. J. Heremans*, B. B. Zhou*, A. Auer, G. Burkard, D. D. Awschalom, *submitted* (2015).
[2] D. Møller, L. B. Madsen, K. Mølmer, *Phys. Rev. A* 74, 062302 (2007).

Current Induced Instability in Magnetic Domain Walls

J. Gorchon,[1] J. Curiale,[2,1,3] A. Cebers,[4] A. Lemaître,[2] N. Vernier,[5] M. Plapp,[6] and V. Jeudy[1,7]
[1] *Laboratoire de Physique des Solides, Université Paris-Sud, CNRS, 91405 Orsay, France*
[2] *Laboratoire de Photonique et de Nanostructures, CNRS, 91460 Marcoussis, France*
[3] *CONICET, Centro Atomico Bariloche-CNEA, , 8400 San Carlos de Bariloche, Argentina*
[4] *University of Latvia, Zellu-8, Riga, LV-1002, Latvia*
[5] *Institut d'électronique fondamentale, Université Paris-Sud, CNRS, UMR8622, 91405 Orsay, France*
[6] *Physique de la Matière Condensée, Ecole Polytechnique, CNRS, 91128 Palaiseau, France*
[7] *Université Cergy-Pontoise, 95000 Cergy-Pontoise, France*

Domain wall (DW) shape instabilities originate from the competition between surface tension, which tends to favor flat interfaces, and destabilizing interactions. A well-know destabilizing mechanism results from the long-range dipolar interactions. Yet other mechanisms can contribute, when a gradient of an external driving force is present, such as magnetic field or temperature. Here, we studied the effect of a current gradient in the context of spin transfer torque (STT), when a polarized current induces DW motion. We show that this gradient can either stabilize or destabilize DW shape.

To that end we investigated current induced DW motion in wide geometries where instabilities produced by current and/or dipolar interactions can develop and be visualized. We used a (Ga,Mn)(As,P) thin film with perpendicular magnetization. We introduced, on purpose, a progressive current density gradient by patterning our device in a semi-circular geometry (see left fig.) with a narrow electrode and a large semi-circular electrode.



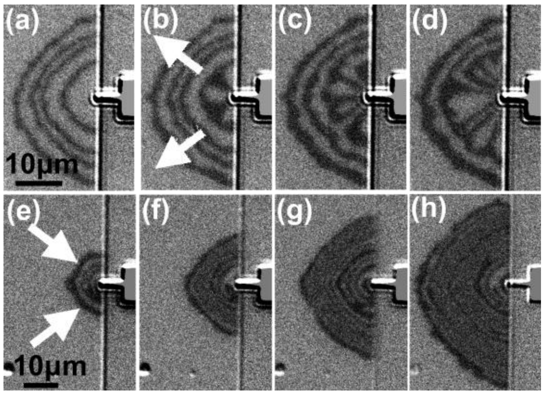


Fig.: (left) Magnetic Kerr image of the device. Magnetic domains in the GaMnAsP layer with opposite magnetization directions appear with two different grey levels. (right) Zoom of the region close to the narrow electrode. Images b to d were acquired after positive current pulses, f to h after negative pulses.

The initial magnetic state was prepared using current induced stochastic domain nucleation and DW propagation [1] as seen close to the narrow electrode (right figure, images a and e). Then a sequence of current pulses with increasing amplitude was injected with positive (top row, right fig.) or negative polarity (bottom row). The DW shape exhibits very distinct behaviors, remaining stable for negative pulses, and being destabilize for positive pulses. The current density gradient acts as a stabilization or destabilization mechanisms for the DW shape depending on the DW motion direction with respect to the gradient. We analyzed these results in details, and developed a model. We show in particular that this mechanism is controlled by the non-adiabatic contribution of the spin transfer torque.

[1] J. Gorchon et al., Phys. Rev. Lett. **112**, 026601 (2014).

Protecting a Quantum Dot Spin Qubit from its Environment

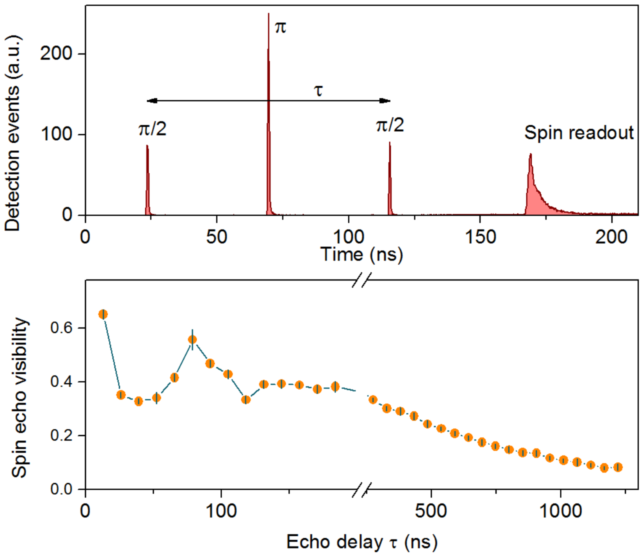
Clemens Matthiesen,[1] Robert Stockill,[1] Claire Le Gall,[1] Lukas Huthmacher,[1] Megan Stanley,[1] and Mete Atature[1]

[1] *Cavendish Laboratory, Department of Physics, University of Cambridge, JJ Thomson Avenue, CB3 0HE Cambridge, UK*

Spin carriers confined in single self-assembled InAs quantum dots provide optically accessible quantum bits. Thanks to the quantum dot's strong oscillator strength and favourable level structure spins can be coherently manipulated on picosecond timescales [1]. Compared to other qubit implementations, such as with trapped ions, NV centres, or gate-defined quantum dots, which rely on microwave fields, this timescale is orders of magnitude shorter.

The qubit coherence, however, is limited in ensemble-averaged measurements by the hyperfine interaction with the bath of 10^5 nuclear spins, giving rise to a T_2*-time of 1-2 ns. Previous seminal research used a Hahn spin-echo sequence to measure a coherence time of a few microseconds for a single electron spin [2]. Given electron spin lifetimes and nuclear bath coherence times have been found to be in the millisecond range [3,4], it is not yet clear what the limiting mechanism for electron spin coherence is, and indeed, what the limit is.

Here, we extend previous work on optical control of single quantum dot spins to show how the qubit coherence is modulated by the coherent evolution of the nuclear spin bath. The figure below displays the experimental sequence for a Hahn spin-echo (top) which provides the tool to observe environment noise at different timescales. Contrary to naïve expectation we observe loss and revival of spin coherence (bottom, data taken at 3T external field) at short echo delays, while the visibility decays exponentially at longer pulse delays. We further implement dynamical decoupling with picosecond optical pulses and observe electron spin coherence extending beyond the Hahn spin-echo limit. Combining the fast manipulation capabilities, long coherence times, and the ability to map the stationary electron spin qubit into a flying qubit [5], we aim to create a quantum optical network where remote spins are entangled by photonic interference.



[1] D. Press, T. D. Ladd, B. Zhang, and Y. Yamamoto, Nature. 456, 218 (2008).
[2] D. Press et al., Nature Phot. 4, 367 (2010).
[3] C.-Y. Lu et al., Phys. Rev. B 81, 035332 (2010).
[4] E.A. Chekhovich, M. Hopkinson, M.S. Skolnick, and A.I. Tartakovskii, Nature Comms. 6, 6348 (2015).
[5] K. de Greeve et al., Nature 491, 421 (2012); W. B. Gao, P. Fallahi, E. Togan, J. Miguel-Sanchez, and A. Imamoglu, Nature 491, 421 (2012)

Spin-dependent thermoelectric effects in Fano-Kondo T-shaped double quantum dots

Krzysztof P. Wójcik and Ireneusz Weymann
Faculty of Physics, Adam Mickiewicz University, Poznań, Poland

In the contribution, the thermoelectric properties of T-shaped double quantum dots coupled to ferromagnetic leads will be presented. We calculate spin-dependent quantities in the linear-response regime: electric and thermal conductance, Seebeck coefficient, spin thermopower, and thermoelectric figure of merit. This is done with the aid of numerical renormalization group technique.

We focus on the strong coupling regime, where the two-stage Kondo effect occurs. In a nonmagnetic case, in the first stage, when the temperature of the system is decreased, the usual Kondo effect appears, *i.e.* below the Kondo temperature T_K the magnetic moment of the quantum dot connected to the leads is screened collectively by conduction electrons; however, in the second stage, at even lower temperatures (below T^*) the singlet is formed inside the double-dot subsystem. The magnetism of the leads can change the ground state of the double-dot subsystem to a triplet, suppressing the second stage of screening. This restores the usual Kondo effect. Nonetheless, strongly polarized leads can suppress also the first-stage Kondo effect, because they induce the effective exchange field in the dots, removing the necessary spin-degeneracy (except for the particle-hole-symmetric case) [1].

The linear conductance G of the system reveals the two-stage Kondo effect: in the (first stage) Kondo regime it is enhanced to $2e^2/h$, while at the second stage of screening the conductance vanishes. When at least one of the quantum dots' energy levels ε_i is shifted from the particle-hole symmetric point, the temperatures T_K and T^* change, which at very low temperatures (lower then T^* at the particle-hole symmetric point) gives rise to the formation of strong anti-resonance in $G(\varepsilon_i)$, which become asymmetric when energy levels of both quantum dots are tuned out of particle-hole symmetry. This is sometimes referred to as the Fano-Kondo effect. The ferromagnetism of electrodes leads to the mismatch of the anti-resonance conditions in respective spin channels, which results in perfect spin polarization of a linear conductance even for a finite polarization of the leads [2].

The interference effects in general enhance the termoelectric efficiency. Indeed, we show that the thermopower S as a function of ε_i exhibits a peaks in the vicinity of the anti-resonance. Moreover, in the temperature dependence of S there is also a peak, at the temperature corresponding to T^*, when the inter-dot interaction is the most relevant. In the magnetic system, as a consequence of spin-dependent shift of the anti-resonances in respective spin channels, the spin thermopower emerges and exhibits peaks similar to S.

[1] K. P. Wójcik, I. Weymann, Phys. Rev. B **91**, 134422 (2015).
[2] K. P. Wójcik, I. Weymann, Phys. Rev. B **90**, 115308 (2014).

Fast nanoscale addressability of individual NV spins via coupling to driven ferromagnetic vortices

Michael Wolf,[1] Robert Badea,[1] and Jesse Berezovsky[1]
[1]*Case Western Reserve University, Cleveland OH, 44106 USA*

Proposed quantum information schemes based on dipole-coupled nitrogen-vacancy (NV) qubits require fast, nanoscale addressability of NV spins in a scalable platform. We present recent progress towards this goal using driven ferromagnetic vortices coupled to NV centers. Vortex magnetization can be realized in thin, micron-scale ferromagnetic disks or in vortex domain walls in a ferromagnetic nanowire. The core of these vortices produces a strong, local magnetic field (falling off like r^{-3}, with a maximum approaching 1 T). Further, the vortex core can be translated on timescales of tens of ns using a small bias magnetic field. The extremely large field gradient produced by the vortex core can be used to bring NV spins into resonance with a driving field (or with each other) with very high spatial resolution.

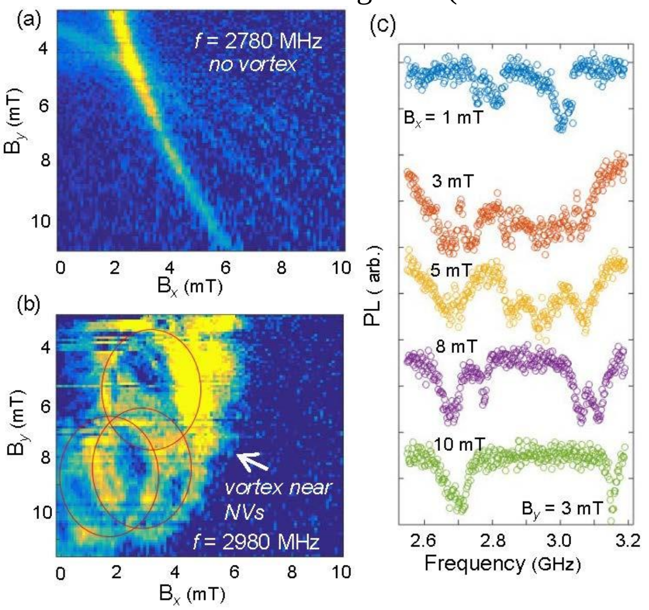


Figure 1. (a) and (b) ODMR map of several NVs in a nanoparticle without and with a proximal vortex core. (c) ODMR as the vortex core is swept past the NVs.

We fabricate 2-μm-diameter, 40-nm-thick Permalloy disks atop a coplanar waveguide (CPW), and disperse NV-containing, ~25-nm-diameter diamond nanoparticles over the surface. We then use a scanning microscopy setup to simultaneously (1) initialize and detect NV spins (via optically-detected magnetic resonance, ODMR), and (2) track the dynamics of the vortex core (via differential Kerr microscopy [1]). The CPW is used both to drive magnetic resonance of the NV spins and to manipulate the vortex position.

We find that coupling between NVs contained within a single nanoparticle and the vortex core permits a large and tunable differentiation of the spin transitions of the individual NVs. For example, Figs. 1(a) and (b) show photoluminescence (PL) maps vs. in-plane magnetic field from two different diamond nanoparticles each containing several NVs. The dips in PL (yellow) indicate magnetic fields at which an NV spin transition is in resonance with the RF field. When the NVs are *not* near a vortex (Fig. 1(a)) the map displays straightforward Zeeman-split resonances. In contrast, when the vortex core is swept beneath the NVs (Fig. 1(b)) a complex pattern of resonances emerges. When the vortex is far from a nanoparticle containing several NVs in the same orientation (Fig. 1(c), top and bottom traces) a single pair of resonances is seen. At intermediate fields, the vortex approaches the NVs and the ODMR dips split into a manifold, arising from the different NVs within the nanoparticle with separations ~10 nm.

The ability to tune NV resonances with nanoscale spatial resolution in a fast, integrated platform opens up new pathways towards implementing solid state, room temperature quantum information processing.

[1] Badea, R., J. A. Frey, and J. Berezovsky. "Magneto-optical imaging of vortex domain deformation in pinning sites." *JMMM* (2015).

Boson-assisted and resonant Andreev tunneling observed on a carbon nanotube quantum dot

J. Gramich, A. Baumgartner and C. Schönenberger
Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland

In quantum dots (QDs) with superconducting and normal metal contacts electronic transport is mediated by both Cooper pairs from the superconductor and single electrons in the QD. This leads to a variety of exotic bound states, e.g. Andreev bound states [1,2] and Majorana fermions [3], or to nonlocal processes like Cooper pair splitting [4,5], a potential source of spin-entangled electrons. However, the most fundamental process in such a system is resonant Andreev tunneling (AT), in which the two electrons of a Cooper pair tunnel coherently through the QD level. This process results in a characteristic subgap resonance [6,7], which has not been identified experimentally, yet. In addition, phonons [8] or other bosons [9] can theoretically lead to replicas of AT resonances at finite bias.

Here we report the observation of two distinct subgap transport features within the large energy gap of 1.2 meV in experiments on a carbon nanotube (CNT) QD contacted by a superconducting Nb and a normal metal contact. The first feature is a resonance line with position, shape and amplitude consistent with the theoretically predicted resonant AT through a single QD level [6]. Second, this resonance exhibits replicas at a separation on the order of 145 μeV with a gate, bias and temperature dependence consistent with phonon-assisted AT [8]. Specifically, we find the predicted negative differential conductance accompanying each resonance and temperature-induced side-bands at lower energies. Also consistent with theory, the broadening of the lines is not determined by the temperature. In addition, we report the peculiar dependence of these features on an external magnetic field. As the origin of the replicas we discuss length-quantized longitudinal acoustic vibration modes in the CNT, but also electromagnetic and plasma modes in the superconducting contact.

[1] J-D. Pillet *et al.*, Nat. Phys. **6**, 965 (2010)
[2] J. Schindele *et al.*, Phys. Rev. B **89**, 045422 (2014)
[3] V. Mourik *et al.*, Science **336**, 1003 (2012)
[4] L. Hofstetter *et al.*, Nature **461**, 960 (2009)
[5] J. Schindele *et al.*, Phys. Rev. Lett. **109**, 157002 (2012)
[6] C. W. J. Beenakker, Phys. Rev. B **46**, 12841(R) (1992)
[7] Q.-F. Sun *et al.*, Phys. Rev. B **59**, 3831 (1999)
[8] S-N. Zhang *et al.*, Phys. Rev. B **86**, 104513 (2012)
[9] J. Barański *et al.*, arXiv:1503.07119 (2015)

Light control of the lattice magnetism in EuTe

F. C. D. Moraes, A. F. Morais, A. Henriques, and G. D. Galgano
Instituto de Física, Universidade de São Paulo, São Paulo, Brazil

EuTe is an exciting magnetic semiconductor with an energy gap in the visible region of the light spectrum. The source of magnetism is related to the large spin (S=7/2) of the Eu atoms. The combination of intrinsic magnetism and light transparency would make EuTe highly useful for application in magneto-optical devices, if only it was possible to control the magnetization of EuTe using an electrical or optical stimulus. Recently it was demonstrated that at helium temperatures, when EuTe is antiferromagnetic, light resonant with the EuTe gap can photoexcite magnetic polarons [1]. These magnetic polarons consist of a spherical region of canted Eu spins with a total magnetic moment of 610 Bohr magnetons and a binding energy of 27 meV [1]. The Eu polarization is brought about by the exchange interaction between the photoexcited electron and the lattice spins. By applying a small magnetic field, the spin of photogenerated polarons can be aligned in a common direction, to give a net magnetization that can be optically controlled in the ultrafast time scale.

In this work we investigate up to which temperature control of magnetic order, seen in EuTe at helium temperatures, is possible. The starting point is a Schrödinger equation we formulated for the polaron, which was resolved using the self-consistent method to give the minimum energy state of the system, as well as the magnetic moment of the polaron at T=0K. To describe the system at non-zero temperatures, two approaches were used: (1) Monte-Carlo simulations of the spin structure to yield the most probable state; (2) analytical modeling to obtain the magnetic moment of the polaron deduced from the minimum free energy of the system. In the latter case, approximations were required, whose validity could be checked from a confrontation with the "exact" Monte Carlo results.

We find that the large binding energy for T=0K decreases when the temperature increases, which is explained by thermal fluctuations of the spins within the polaron region reducing the electron's self-energy. Nevertheless, a substantial polaron magnetic moment can still be induced at temperatures well above the EuTe Néel temperature. The predicted magnetic moment of the polaron as a function of temperature is compared to the experimental data obtained from measurements of photoinduced linear birefringence as a function of temperature and magnetic field of 0-8 Teslas.

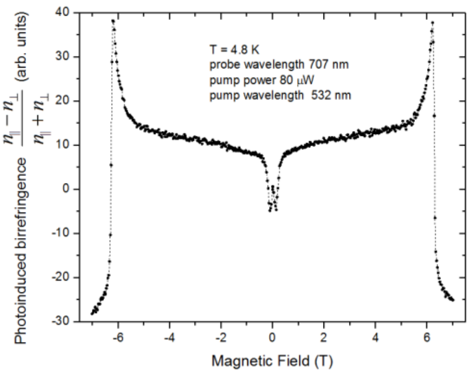


Fig. 1: Magnetic field dependence of the photoinduced birefringence in EuTe at 4.8 K. From the sharp resonance seen around 6.2 T the polaron magnetic moment could be deduced, and followed as a function of temperature.

A.B.H. acknowledges financial support provided by CNPq (Projects 401694/2012-7 and 304685/2010-0) and FAPESP (Project 2012/23406-0).

[1] A. B. Henriques, F. C. D. Moraes, G. D. Galgano, A. J. Meaney, P. C. M. Christianen, and J. C. Maan, E. Abramof and P. H. O. Rappl, Phys. Rev. B **90**, 165202 (2014).

Nuclear magnetic resonance on the nuclear spins inside a self-assembled quantum dot

Mathieu Munsch[1], Gunter Wüst[1], Franziska Maier[1], Arne Ludwig[2], Andreas D. Wieck[2], Martino Poggio[1], Daniel Loss[1], and Richard J. Warburton[1]

1. Department of Physics, University of Basel, Basel, Switzerland

2. Ruhr-Universität, Bochum, Germany

mathieu.munsch@unibas.ch

The nuclear spins in a semiconductor quantum dot represent a key source of noise not just for an electron spin qubit but also for an optical qubit [1,2]. In a self-assembled quantum dot, an electron spin interacts with ~100,000 nuclear spins. In a strong magnetic field, these spins are largely decoupled from the other nuclear spins in the host material. These are ideal conditions to explore the complex central spin problem. We report here nuclear magnetic resonance (NMR) on the nuclear spins inside a single InGaAs self-assembled quantum dot. Our key result is that the nuclear spin decoherence time reduces considerably on occupying the quantum dot with a single electron but recovers on occupying the quantum dot with two electrons.

We establish a protocol to determine the nuclear spin energy levels and their populations (specifically, the nuclear spin temperature following polarization, indium concentration, isotope-specific quadrupole frequency distributions). In this protocol we initialize and read-out the nuclear spin polarization with high resolution laser spectroscopy: via resonance fluorescence detection we perform NMR with sensitivity to just 1,000 nuclear spins. Nuclear spin manipulation is carried out using an on-chip microwire which generates ac magnetic fields up to several mT. At its heart, the NMR protocol exploits frequency-swept pulses, sweeping the frequency from a low value to a high value, addressing every nuclear spin at some point along the way. A remarkable feature is a plateau in the dependence of NMR signal on NMR sweep rate: it arises as a consequence of the quadrupole interaction and survives the ensemble averaging even though there are four different isotopes, each isotope with atom-dependent shifts. We show that this plateau represents the key to unlocking the key nuclear spin parameters from the NMR signal [3].

Based on the frequency-swept NMR, we develop a scheme to enhance the population difference of the -1/2 and +1/2 nuclear spin levels. This allows us to determine the coherence of the isotope-specific -1/2 to +1/2 NMR using a Hahn echo. The quantum dot operates in the Coulomb blockade regime: the charge state is controlled precisely. For an empty quantum dot, the nuclear spin decoherence time is about 5 ms, probably limited by the nuclear dipole-dipole interaction. On occupying the quantum dot with a single electron, the decoherence time decreases by about a factor of 100. On occupying the quantum dot with two electrons, the decoherence time increases back to 5 ms. These results demonstrate the key role of an unpaired electron in determining the nuclear spin coherence. We propose that the underlying mechanism is RKKY-like: the nuclear spins all couple to each other via a common interaction with the electron spin. A calculation backs up this assertion by accounting quantitatively for the measured decoherence time. The consequences for a spin qubit are discussed.

[1] R. J. Warburton *et al*, Nature Materials **12**, 483 (2013)
[2] E. Chekhovich *et al*, Nature Materials **12**, 494 (2013)
[3] M. Munsch *et al*, Nature Nanotechnology **9**, 671 (2014)

Non-Abelian parafermions in time-reversal-invariant interacting helical systems

Rakesh P Tiwari,[1] C. Orth,[1] T. Meng,[2] and T. L. Schmidt[3]
[1]*Department of Physics, University of Basel, Switzerland*
[2]*Institute of Theoretical Physics, TU Dresden, Germany*
[3]*Physics and Materials Science Research Unit, University of Luxembourg, Luxembourg*

We discuss the zero-energy bound states associated with the interfaces on the edge states of a two-dimensional topological insulator. We show that at the interfaces between a section of the edge states, which is gapped out by the superconducting proximity effect and a section gapped out by umklapp scattering can give rise to **Z4** parafermions. We show that these interfaces pin charges, which are multiples of e/2, giving rise to a Josephson current with 8\pi periodicity. [1,2].

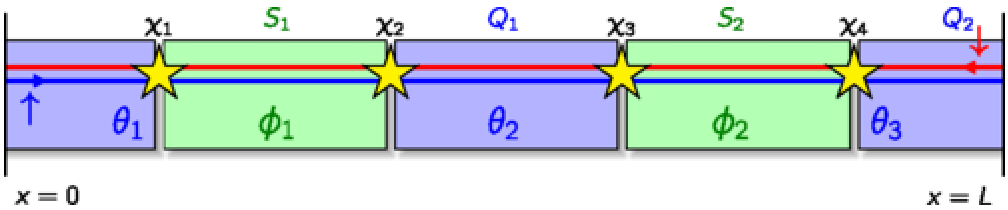


Figure 1: Alternating superconducting and Mott insulating junctions with periodic boundary conditions. Different fields are pinned in the blue superconducting and green Mott insulating regions. Bound states emerge at the interfaces (shown by yellow stars) .

[1] C. Orth, Rakesh P. Tiwari, T. Meng, and T. L. Schmidt, Phys. Rev. B **91**, 081406 (2015).
[2] F. Zhang and C. L. Kane, Phys. Rev. Lett. **113**, 036401 (2014).

Spin-orbit mediated spin relaxation in a single-electron quantum dot

L. C. Camenzind,[1] L. Yu,[1] D. E. F. Biesinger,[1] J. Zimmerman,[2] A. C. Gossard,[2] and D. M. Zumbühl[1]

[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2]*Materials Department, University of California, Santa Barbara, CA93106, USA*

Spins in quantum dots are promising candidates for the realization of qubits – the elementary units of a quantum computer – and hold the potential for scaling to a large number of qubits. Stable qubits with long coherence times are of crucial importance to execute numerous coherent quantum gates. Great progress was recently made to decouple the electron spins from the nuclear spins of the host material. A fundamental limit to the spin coherence is set by the spin relaxation time T_1. In a magnetic field, spins relax predominantly by phonon-emission mediated by the spin-orbit (SO) coupling [1,2]. Since the SO coupling in GaAs is weak, very long T_1 times have been measured, reaching 1 s at 1T [3].

Here, we present measurements of the spin relaxation rate in a gate-defined single-electron quantum dot formed in a GaAs 2D electron gas. An adjacent quantum dot in the tunnel-broadened regime is used as a sensitive charge detector with a bandwidth of ~30 kHz, similar to the setup described in [4]. This allows real-time single-shot read-out of the spin state via spin-to-charge conversion using energy selection. The device is mounted on a piezo-electric rotator placed inside a 14 T magnet, making it possible to accurately control the angle ϕ of the applied magnetic field $B_{||}$ in the plane of the 2D electron gas, while the out-of-plane component is kept small (<5º). To measure T_1, three-step pulse sequences with microsecond resolution are applied to one of the dot gates. Identical pulses of reverse polarity and reduced amplitude are applied to a sensor gate to compensate the cross capacitance. The experiment is performed in a dilution refrigerator with an electron temperature of 100 mK.

The spin relaxation rate W, measured at 4 T, exhibits a sinusoidal dependence on the B-field angle ϕ with a period of 180°, as similarly reported recently [5]. The extrema are seen when the field is pointing nearly along the [110] and [1-10] crystal axes, changing by a factor of about 20 from minimum to maximum. When the field is oriented along the [1-10] direction – where maximal spin relaxation times are observed – T_1 reaches ~5 s at B = 1 T, extending the previous record [3] by a factor of five. Upon increasing the field to 12 T, the T_1 time is reduced by approximately five orders of magnitude, close to the expected B^5 dependence [1]. For a comparison to theory, the quantum dot orbitals are playing a major role. Therefore, we perform pulsed-gate spectroscopy to extract orbital excited-state energies, and obtain very good agreement with theory also for the angle dependence $W(\phi)$, indicating that Rashba and Dresselhaus SO strengths have the same relative sign and are within ~20% of each other.

In the future, we intend to manipulate the dot orbitals with gate voltages, implement electrical control of the Rashba SO interaction using top- and back gates [6], and also investigate the B-field angle dependence of the spin tunnelling asymmetry. Finally, we plan to study alternate spin relaxation mechanisms, e.g. 2-phonon processes in double dots.

[1] V.N.Golovach, A. Khaetskii, and D. Loss, Phys. Rev. Lett. **93**, 016601 (2004).
[2] P. Stano and J. Fabian, Phys. Rev. B **74**, 045320 (2006).
[3] S. Amasha, K. MacLean, I. Radu, D. M. Zumbuhl, M. A. Kastner, M. P. Hanson, and A. C. Gossard, Phys. Rev. Lett. **100**, 046803 (2008).
[4] D. E. F. Biesinger, C. P. Scheller, B. Braunecker, J. Zimmerman, A. C. Gossard, and D. M. Zumbuhl, arXiv:1505.03195 (2015).
[5] P. Scarlino, E. Kawakami, P. Stano, M. Shafiei, C. Reichl, W. Wegscheider, and L. M. K. Vandersypen, Phys. Rev. Lett. **113**, 256802 (2014).
[6] F. Dettwiler, J. Fu, S. Mack, P. J. Weigele, J. C. Egues, D. D. Awschalom, and D. M. Zumbuhl, arXiv:1403.3518 (2014).

Increment of Spin Lifetime by Spin Injection Orientation in Stressed Thin SOI Films

Joydeep Ghosh, Viktor Sverdlov, and Siegfried Selberherr
Institute for Microelectronics, TU Wien
Gußhausstraße 27-29/E360, A-1040 Wien, Austria
{ghosh|sverdlov|selberherr}@iue.tuwien.ac.at

The scaling of CMOS devices is about to reach fundamental limits, and this prompts the development of new technologies in semiconductor industry. Spin-based electronics or spintronics is considered as one of the alternatives in 'beyond CMOS' research. Silicon, the main element of microelectronics, appears to be the perfect material for spin-driven applications. Purely electrical spin injection in silicon from a ferromagnetic contact at room temperature has been successfully demonstrated [1]. However, a large spin relaxation in electrically-gated silicon structures as experimentally observed [2] could become an obstacle in realizing spin driven devices. Therefore, a deeper understanding of the fundamental spin relaxation mechanism in SOI MOSFETs is urgently needed. Stress has been traditionally used to enhance the electron mobility, and it has been demonstrated that, when spin is injected perpendicular to the film, shear strain due to tensile stress in [110] direction is also extremely efficient in boosting the spin lifetime (τ) in advanced (001) SOI MOSFETs with ultra-thin body [3]. It has also been mentioned that spin flip scattering processes between the two unprimed [001] valleys are primarily responsible for spin relaxation in the film [4]. The physical reason for the enhancement of τ by shear strain lies in an ability to lift completely the degeneracy between the remaining two valleys in a confined electron systems by uniaxial stress. This significantly suppresses the main component of spin relaxation due to intervalley scattering (Figure 1). We demonstrate a further reduction of the spin relaxation at any fixed stress, when the spin injection direction (denoted by polar angle θ) is gradually drawn towards in-plane ($\theta=\pi/2$), given by $\frac{1}{\tau(\theta)} \propto 1+\cos^2\theta$. This allows to further increase τ by a factor of two for the in-plane injection orientation as shown in Figure 2 at any stress value.

This research is supported by the European Research Council through the Grant #247056 MOSILSPIN.

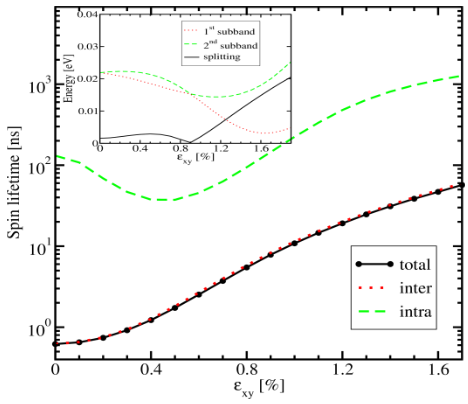


Figure 6 Variation of the spin lifetime with stress with its components. Thickness t=4.34nm, T=300K, electron conc. N_S=1.29x10^{12} cm^{-2}.

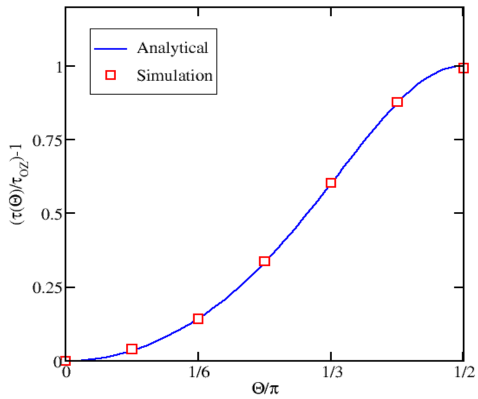


Figure 2 Dependence of the spin lifetime τ with spin injection orientation θ at any fixed stress point. τ_{OZ}: $\tau(\theta=0)$.

[1] R. Jansen, *Nature Materials* **11**, p. 400, 2012.
[2] J. Li, I. Appelbaum, *Appl. Phys. Lett.* **100**, 162408, 2012.
[3] D. Osintsev *et al.*, *Solid-State Electronics*, 2015.
[4] J. Ghosh *et al.*, *Microelectronic Engineering* **147**, 2015.

Interactions in Electronic Mach-Zehnder Interferometers with spin-resolved edge channels

L. Chirolli,[1] F. Taddei,[2] R. Fazio[2],V. Giovannetti,[2]
Imdea Nanoscience, Calle Faraday 9, ES-28049 Madrid, Spain
[2]Scuola Normale Superiore, Piazza dei Cavalieri 7, IT-56126 Pisa, Italy

We study Coulomb interactions in the finite bias response of Mach-Zehnder interferometers, which exploit copropagating spin-resolved edge states in the integer quantum Hall effect. Here, interactions are particularly important since the coherent coupling of edge channels is due to a resonant mechanism that is spoiled by inelastic processes. We find that interactions yield a saturation, as a function of bias voltage, of the period-averaged interferometer current, which gives rise to unusual features, such as negative differential conductance, enhancement of the visibility of the current, and nonbounded or even diverging visibility of the differential conductance.

[1] L. Chirolli, F. Taddei, R. Fazio, V. Giovannetti, Phys. Rev. Lett. 111, 036801 (2013).

Stroboscopic coherent population trapping of a single nuclear spin under ambient conditions

P. Jamonneau, G. Hétet, A. Dréau, J.-F. Roch, and V. Jacques
Laboratoire Aimée Coton, CNRS, Université Paris-Sud and Ecole Normale Supérieure de Cachan, 91405 Orsay, France

Coherent control of quantum systems has far-reaching implications in quantum engineering. In this context, coherent population trapping (CPT) to dark states is a well-established technique which already enabled a large range of applications from laser cooling of atoms [1] to metrology [2]. Extending these methods to solid-state quantum systems has only been achieved at cryogenic temperature for electron spin impurities [3, 4] and superconducting circuits [5].

In this work, we demonstrate CPT of a single nuclear spin in a room temperature solid. To this end, we make use of a three-level system with a Λ-configuration in the microwave domain, which involves electron spin transitions of a single nitrogen-vacancy defect in diamond coupled by hyperfine interaction with a nearby nuclear spin impurity. Importantly, the dark state preparation is performed in a pulsed regime for which the coherent driving of the spin system is decoupled from relaxation that is externally triggered. This new stroboscopic regime enables to investigate step-by-step accumulation of population in the dark state and to reach an unusual regime of CPT for which a periodic array of dark resonances can be observed [6].

This mechanism can find applications for quantum state preparation, information storage with hybrid quantum systems [7] and atomic clocks.

[1] A.Aspect, *et al*, Phys. Rev. Lett. **69** 1360 (1992).
[2] J. Vanier, Appl. Phys. B **81**, 421 (2005).
[3] X.Xu, *et al*, Nat. Phys. **4**, 692 (2008).
[4] E. Togan, *et al*, Nature **478**, 497 (2011).
[5] M. A. Sillanpää, Phys. Rev. Lett. **103**, 193601 (2009).
[6] P. Jamonneau, *et al*, submitted
[7] Y. Kubo, *et al*, Phys. Rev. Lett. **107**, 220501 (2011).

Nanoscale magnetic imaging using Single Nitrogen Vacancy Centers in diamond

Marc Ganzhorn[1], Patrick Appel[1], Lucas Thiel[1], Brendan Shields[1], Elke Neu[2] and Patrick Maletinsky[1]

[1]Departement Physik, Universität Basel, 4056 Basel Switzerland
[2]Universität des Saarlandes, 66123 Saarbrücken Germany

Recent developments in magnetic imaging have led to important advances in material science, mesoscopic physics or life science [1]. In particular, scanning probe based approaches such as magnetic resonance force microscopy [2] or SQUID based detection schemes [3] have proven to play a pioneering role as they enable nanoscale spatial resolution, combined with a high sensitivity for small magnetic fields. However, the performance of these magnetometers is still limited by factors such as detector size and operation at cryogenic temperature only [1].
In this context, magnetic imaging with the isolated electronic spin of a nitrogen vacancy (NV) center in diamond offers a promising alternative. The NV center's atomic size and exceptionally long spin coherence time, even at room temperature, enables magnetic imaging with spatial resolution of tens of nanometers and a magnetic field sensitivity in the nanotesla range over a broad range of temperatures [4].
Here we report on our approach to such a high performance NV center based magnetometer. We will give an overview of the quantitatively imaging of magnetic stray fields in various nanoscale magnetic systems, for instance in ferromagnetic nanorods. Quantitative probing the stray fields of nanomagnetic structures will in the future allow us to study and image the dynamics of domain walls [5], spin waves [6] or high frequency magnetic fields.

References

1. L. Rondin et al., Rep. Prog. Phys. 77, 056503 (2014)
2. Y. Martin et al., Appl. Phys. Lett. 50, 1455 (1987)
3. D. Vasyukov et al., Nature Nano 8, 639 (2013)
4. Maletinsky et al., Nature Nano 7, 320 (2012)
5. J.-P. Tetienne, Science 344, 1366 (2014)
6. van der Sar et al., Arxiv 1410.6123 (2014)

Observation of anomalous current in InSb nanowire quantum dots

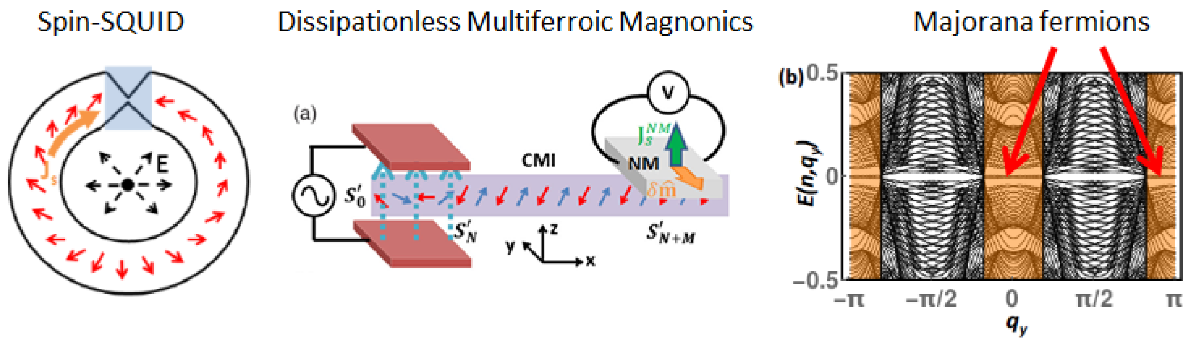
Daniel Szombati,[1] Stevan Nadj-Perge,[1] Diana Car,[2] Erik Bakkers[1,2] and Leo Kouwenhoven[1]
[1]*Delft University of Technology*
[2]*Eindhoven University of Technology*

We consider supercurrent transport through InSb nanowires contacted with NbTiN leads. We study both current and phase bias measurements in the so created superconductor-nanowire-superconductor (S-NW-S) Josephson junction (JJ). Due to the strong Zeeman interaction and large spin orbing coupling in our nanowire, the JJ exhibits an anomalous supercurrent flowing at zero phase difference, equivalent to a phi0 shift in the current phase relation, when changing the magnetic field or the electrostatic potential around the junction. Our results provide useful insights into superconductor/semiconductor hybrid systems capable of hosting Majorana fermions, future building blocks for topological quantum computing.

Multiferroic Magnonics: Quantum Interference, Energy Transport, and Majorana Fermions

Wei Chen[1], Manfred Sigrist[1], Andreas P. Schnyder[2], Peter Horsch[2], and Dirk Manske[2]
[1]*Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland*
[2]*Max Planck Institute for Solid State Research, 70569 Stuttgart, Germany*

We demonstrate the broad applications of multiferroic materials based on their noncollinear magnetic order and magnetoelectric effect. Upon mapping the noncollinear magnetic order into a spin superfluid, the magnetoelectric effect enables the electrically controlled quantum interference of spin superfluid[1], indicating the possibility of a room temperature SQUID-like quantum interferometer that manifests the flux quantization of electric field[2]. Because the magnetoelectric effect enables changing the noncollinear magnetic order by electric field, we propose that applying an oscillating electric field with frequency as low as household frequency can generate a fast, coherent rotation of the magnetic order that is free from energy loss due to Gilbert damping, and can be used to deliver electricity up to the distance of long range order[3]. At a superconductor/multiferroic interface, the noncollinear magnetic order imprints into the superconductor via s-d coupling, which can produce Majorana fermions at the edge of the superconductor without the need to adjust chemical potential[4].



[1] W. Chen and M. Sigrist, Phys. Rev. B 89, 024511 (2014).
[2] W. Chen, P. Horsch, and D. Manske, Phys. Rev. B 87, 214502 (2013).
[3] W. Chen and M. Sigrist, Phys. Rev. Lett. 114, 157203 (2015).
[4] W. Chen and A. P. Schnyder, arXiv:1504.02322

Anti-ferromagnetic nuclear spin helix and topological superconductivity in interacting ^{13}C carbon nanotubes

Chen-Hsuan Hsu,[1] Peter Stano,[1] Jelena Klinovaja,[2] and Daniel Loss[1,2]
[1] *RIKEN Center for Emergent Matter Science (CEMS), Japan*
[2] *Department of Physics, University of Basel, Switzerland*

We investigate the RKKY interaction arising from the hyperfine coupling between localized nuclear spins and conduction electrons in interacting ^{13}C carbon nanotubes. Using the Luttinger liquid formalism [1,2], we show that the RKKY interaction is sublattice dependent, consistent with the spin susceptibility calculation in non-interacting systems [3]. The RKKY interaction forms $q=\pm 2k_F$ peaks with the Fermi wave number, k_F (Fig. 1), and induces anti-ferromagnetic nuclear spin helix with a spatial period π/k_F (Fig. 2). The transition temperature reaches up to millikelvins, due to the feedback effect through the Overhauser field from the ordered nuclear spins. The nuclear spin helix, combining spin and charge degrees of freedom, results in synthetic spin-orbit interaction, which is crucial for non-trivial topology [4]. In the presence of proximity-induced superconductivity, this system has a potential to realize Majorana fermions without the need of fine tuning chemical potential.

[1] B. Braunecker, P. Simon, and D. Loss, Phys. Rev. Lett. 102, 116403 (2009).
[2] B. Braunecker, P. Simon, and D. Loss, Phys. Rev. B 80, 165119 (2009).
[3] J. Klinovaja and D. Loss, Phys. Rev. B 87, 045422 (2013).
[4] J. Klinovaja, P. Stano, A. Yazdani, and D. Loss, Phys. Rev. Lett. 111, 186805 (2013).

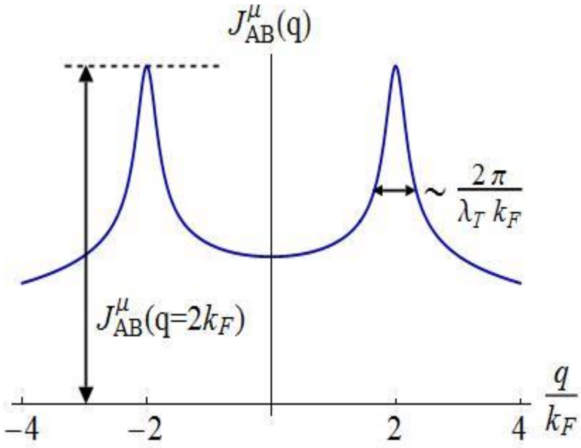


Fig. 1 RKKY interaction between nuclear spins on different sublatice sites. λ_T is the thermal wavelength.

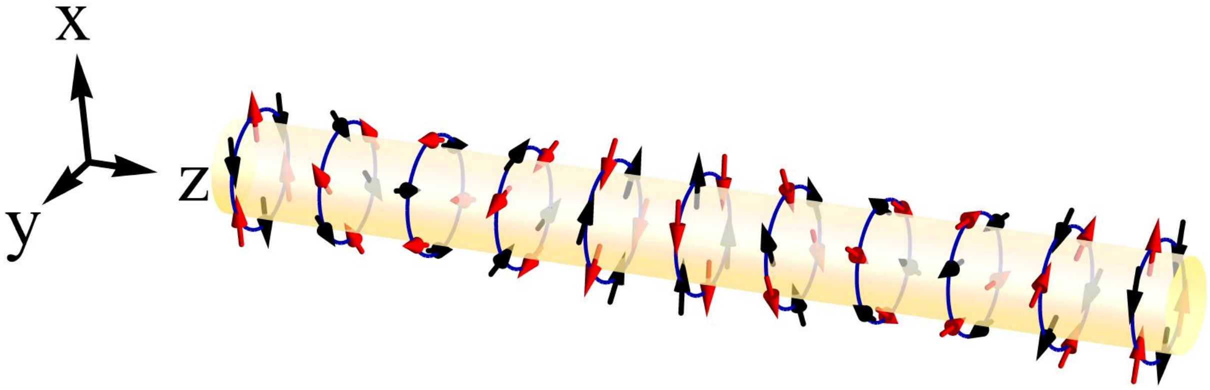


Fig. 2 Illustration of anti-ferromagnetic nuclear spin helix. For simplicity, the actual carbon lattice is not plotted.

Long-distance entanglement of spin qubits via quantum Hall edge states

Guang Yang,[1] Chen-Hsuan Hsu,[1] Peter Stano,[1] Jelena Klinovaja,[2] and Daniel Loss[1,2]
[1]*RIKEN Center for Emergent Matter Science, Wako, Saitama 351-0198, Japan*
[2]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*

The implementation of a functional quantum computer involves entangling and coherent manipulation of a large number of qubits. For qubits based on electron spins confined in quantum dots, which are among the most investigated solid-state qubits at present, architectural difficulties are usually encountered in the practical design of quantum circuits attempting to assemble the qubits within the very limited space available. In this work, we propose a mechanism to achieve long-distance entanglement of spin qubits, based on Ruderman–Kittel–Kasuya–Yosida exchange coupling mediated by quantum Hall edge states, which creates extra wiring space for the quantum circuits and helps overcome the architectural difficulties. We show that the established coupling between qubits can be mutual or "one-way" and is strong anisotropic, depending on the chirality and spin polarization of the quantum Hall edge states. Such features, conversely, provide valuable insights into the topological nature of the quantum Hall states at various filling factors.

Spin and magnetothermal transport in the S=1/2 XXZ chain

C. Psaroudaki[1] and X. Zotos[2,3]
[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2]*Department of Physics, University of Crete, 71003 Heraklion, Greece*
[3]*Department Foundation for Research and Technology - Hellas, 71110 Heraklion, Greece*

We present a temperature and magnetic field dependence study of spin transport and magnetothermal corrections to the thermal conductivity in the spin S=1/2 integrable easy-plane regime Heisenberg chain. We critically discuss the low temperature, weak magnetic field behavior, the effect of magnetothermal corrections in the vicinity of the critical field and their role in recent thermal conductivity experiments in 1D quantum magnets. Finally, magnetothermal effects such as the magnetic Seebeck coefficient are also explored.

[1] C. Psaroudaki and X. Zotos, arXiv:1502.05557 (2015).

Angle Resolved Photoelectron Spectroscopy Instrument development for ARPES and spin resolved ARPES

J. Boettcher, J. Åhlund, H. Bergersen and M. Lundwall
Scienta Omicron GmbH

Here we present results from development of the next generation of electron spectroscopy analyzers, the Scienta DA30 hemispherical analyser. Using this analyser the parallel angle detection angle resolved photoemission (ARPES) capabilities extends to record ARPES and spin resolved ARPES (SARPES) spectra even off slit axis without moving the sample, which ensures e.g. a constant matrix element and ease of alignment during measurement.

ARPES is an excellent tool in surface science due to the possibility to probe electronic and geometric structure. Angle resolved valence band photoemission is a direct measurement of the band structure of a material. Geometric structure could be acquired using ARPES to detect variations in intensity due to the forward focusing effect (X-ray photoelectron diffraction). The intensity variations in a peak with respect to angle is also used for depth profiling of a material.

In the mid 1990's Scienta Omicron revolutionized ARPES with the introduction of the parallel angle-resolving analysers, thereby allowing for simultaneous measurements of electrons with different emission angles (along the slit axis) without having to tilt the sample [1]. The function of this analyzer was later [2] extended to being able to measure 2D ARPES and Mott spin in parallel using the same setup. Here we present results from the next generation of analyser, the Scienta DA30.

This novel analyser represents yet another breakthrough in ARPES instrumentation, since it enables ARPES measurements of slit axis. This feature can be used e.g. for Fermi surface mapping or Spin measurements. As its predecessors the DA30 can be equipped with a spin transfer lens, allowing for ARPES as well as spin detection using Mott or VLEED, as for example with the FERRUM detector. Here we will demonstrate the capabilities of this analyser and show some test results.

[1] A very high resolution electron spectrometer, N. Mårtensson, P. Baltzer, P. A. Brühwiler, J. -O. Forsell, A. Nilsson, A. Stenborg, and B. Wannberg. Electron Spectrosc. Relat. Phenom, 70, 117 (1994).

[2] M. H. Berntsen, P. Palmgren, M. Leandersson, A. Hahlin, J. Åhlund, B. Wannberg, M. Mansson, and O. Tjernberg, A spin- and angle-resolving photoelectron spectrometer. Review of Scientific Instruments 81, 035104 (2010).

Majorana braiding and thermal noise

Fabio L. Pedrocchi and David P. DiVincenzo
JARA Institute for Quantum Information, RWTH Aachen, Germany

We investigate the self-correcting properties of a network of Majorana wires, in the form of a trijunction, in contact with a parity-preserving thermal environment. As opposed to the case where Majorana bound states (MBSs) are immobile, braiding MBSs within a trijunction introduces dangerous error processes that we identify. Such errors prevent the lifetime of the memory from increasing with the size of the system. We confirm our predictions with Monte Carlo simulations. Our findings put a restriction on the degree of self-correction of this specific quantum computing architecture.

NiMnSb-based spin valves for application in spin torque devices

Felicitas Gerhard, Martin Baussenwein, Charles Gould, Laurens W. Molenkamp
Experimentelle Physik 3, Physikalisches Institut, Universität Würzburg, Germany

The Half-Heusler alloy NiMnSb is an attractive material for application in spintronic devices due to its high spin polarization [1], tunable magnetic anisotropy [2] and extremely low magnetic damping [3]. Here we present the growth and characterization of a spin-valve based on two high crystal quality NiMnSb layers with two nominally orthogonal anisotropies, grown fully epitaxial by means of molecular beam epitaxy (MBE).

Fig. 1 (a) shows a sketch of the entire stack: The first NiMnSb layer is grown on top of an InP substrate (001) and (In,Ga)As buffer. It is followed by a very thin ZnTe layer grown in-situ by an atomic layer epitaxy process and then the top NiMnSb layer. The two NiMnSb layers have different Mn concentration to achieve different anisotropies [2]. Finally, the stack is capped with a metal (usually Ru), deposited in-situ for protection against oxidation and strain relaxation.

High resolution x-ray diffraction measurement of such a stack together with a simulation (Fig. 1 (b)) confirm the existence of the ZnTe layer, and the very narrow ω-scans of the NiMnSb peak (inset) represent extremely high crystalline quality.
The room temperature magnetization curves of the sample, as measured by SQUID for two orthogonal crystal directions [110] and [$1\bar{1}0$] are shown in Fig. 1 (c). The two NiMnSb layers clearly respond separately to the external magnetic field. In each crystal direction, the two layers show complementary behavior, one showing easy axis like behavior, the other hard axis like behavior and vice versa.
Such layer stacks are therefore a promising basis for spin torque devices such as spin torque oscillators.

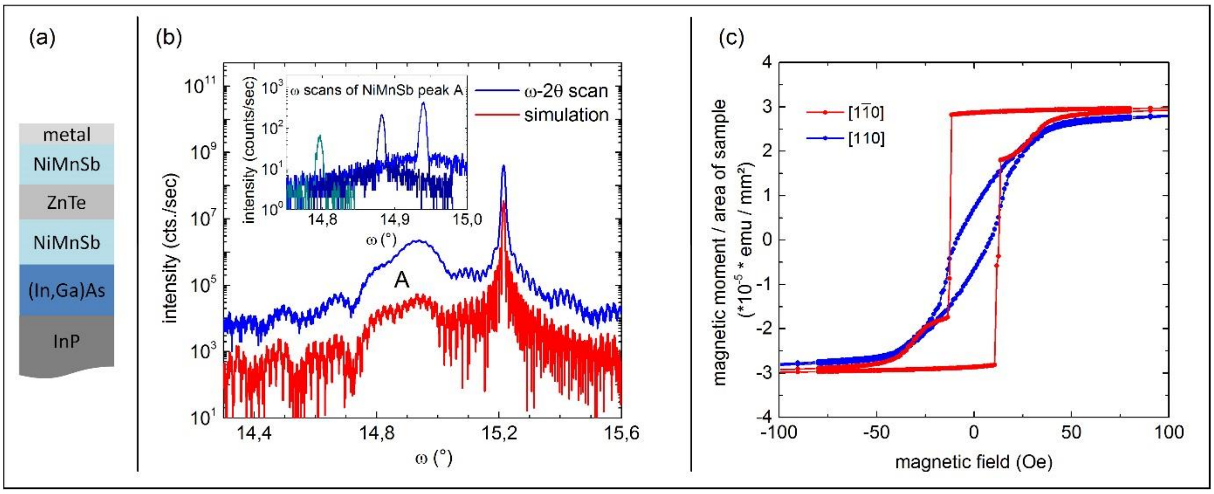


Figure 7a) Sketch of the spin valve. b) HRXRD measurements confirming the nominal layer stack by comparison to a simulation (red) and the high crystalline quality by very narrow ω-scans (inset) c) hysteresis curves at room temperature, showing individual behavior of the two NiMnSb layers.

[1] R. J. Soulen, et al. Science, 282(5386):85-88, 1998
[2] F. Gerhard et al. Journal of Applied Physics, 115(9):094505-094505-4, Mar 2014
[3] A. Riegler. PhD thesis, Universitaet Wuerzburg, 2011

POSTERS
B

Application of hydrogen lithography using Co-doped ZnO thin film and gate voltage control of AHE

Seunghun Lee,[1,4] Yong Chan Cho,[2] Won-Kyung Kim,[3] Miyeon Cheon,[4] Chul Hong Park,[5] Chae Ryong Cho,[6] and Se-Young Jeong[4,7]

[1] *Materials and Science Engineering, University of Maryland, College Park, Maryland 20742, USA*
[2] *Korea Research Institute of Standards and Science, Daejon 305-340, Republic of Korea.*
[3] *R&D Center, LG Display Co., Ltd., Paju, Republic of Korea*
[4] *Department of Cogno-Mechatronics Engineering, Pusan National University, Miryang 627-706, Republic of Korea*
[5] *Department of Physics Education, Pusan National University, Busan 609–735, Republic of Korea*
[6] *Department of Nanoenergy Engineering, Pusan National University, Busan 609-735, Republic of Korea*
[7] *Department of Optics and Mechatronics Engineering, Pusan National University, Busan 609-735, Republic of Korea*

Based on hydrogen-mediated ferromagnetism and a selective hydrogen exposure technique, i.e., hydrogen lithography, we attempted to produce magnetic domains in a paramagnetic host. A possible magneto-optic application of hydrogen lithography is exploited at hydrogen-injected Co-doped ZnO thin film by using the design of magnetic circular dichroism (MCD). Band structure and MCD of Co-doped ZnO are changed by hydrogen injection under different conditions with hard masking, resulting in different degrees of MCD near the band-gap of Co-doped ZnO.
The hydrogen-injected Co-doped ZnO thin films show an anomalous Hall effect (AHE) which is persisted up to room temperature and is assumed to be originated from the asymmetric scattering of carrier hopping between the localized states driven by ferromagnetic Co-H-Co complexes. We also discuss about the gate voltage dependence of the AHE.

[1] Applied Physics Letters **104**, 052405 (2014)
[2] Applied Physics Letters 104, 052412 (2014)
[3] New J. Phys. **16** 073030 (2014)

Interface effects on acceptor levels in Si and Ge

José Carlos García-Abadillo Uriel, María José Calderón
Instituto de Ciencia de Materiales de Madrid, CSIC, Sor Juan Inés de la Cruz, 3, 28049 Madrid, Spain
E-mail jcgau@icmm.csic.es

Substitutional impurities in Si, such as donors and acceptors, have attracted considerable attention in the last few years because of their promising applications in solid state quantum computing [1,2]. Group III acceptors in silicon can bind holes at low temperatures. The hole has a four-fold degenerate ground state reflecting the degeneracy of the silicon valence band. This four-fold degeneracy can be completely lifted with a magnetic field and two of these levels can be used as the two states of a qubit [2], so understanding the splitting of these levels is crucial for quantum computing.

In this work we study theoretically the effect of a nearby interface in the energy spectrum of a group III acceptor in Si or Ge. Interfaces can significantly change the acceptor binding energy and their wave-function symmetry due to quantum confinement and to the dielectric mismatch between the semiconductor, the surrounding insulators and the metallic gates. To model the acceptor-bound hole we use an effective mass approximation for the top of the valence band [3]. The results are relevant for transport and quantum control measurements performed in Si (or Ge) nanodevices with single acceptors [4,5].

References

[1] B. E. Kane, *Nature* **393**, 133-137 (1998)
[2] Rusko Ruskov and Charles Tahan, Phys. Rev. B **88**, 064308 (2013)
[3] Lipari and Baldereschi. Solid State Communications **33**, 277-279 (1980)
[4] Van der Heijden et al., *Nano Lett.*, 2014, 14 (3), pp 1492–1496 (2014)
[5] J.A. Mol et al., Phys. Rev. B 87, 245417 (2013)

Scattering of high-energy magnons off a magnetic skyrmion

Sarah Schroeter and Markus Garst
Institute for Theoretical Physics, University of Cologne

Magnetic skyrmions are topologically protected smooth magnetic whirl textures, which are energetically stabilized in chiral magnets by the Dzyaloshinskii-Moriya interaction. Skyrmions can be manipulated by ultra-low current densities, which makes them promising candidates for novel spintronic applications. Here, we study the scattering of magnons off a single magnetic skyrmion in the background of a field-polarised two-dimensional chiral magnet [1,2]. In the limit of high energies, the skyrmion-magnon interaction is dominated by an effective magnetic flux density, which leads to skew and rainbow scattering reflected in a asymmetric differential cross section with multiple peaks. Using the conservation law for the energy-momentum tensor, we further demonstrate that the magnons also transfer momentum to the skyrmion. As a consequence, a magnon current leads to magnon pressure reflected in a momentum-transfer force in the Thiele equation of motion for the skyrmion. This force is reactive and governed by the transport scattering cross sections; it causes not only a finite skyrmion velocity but also a large skyrmion Hall effect. While at small energies the transversal momentum transfer is negligible resulting in a large skyrmion Hall angle, we demonstrate that it dominates in the limit of high-energies leading to a universal relation between the magnon current and the skyrmion velocity.

[1] C. Schütte and M. Garst, Phys. Rev. B 90, 094423 (2014).
[2] preprint arXiv:1504.02108 [cond-mat.str-el]

Spin-dependent direct gap emission in tensile-strained Ge-on-Si heterostructures

E.Vitiello,[1] A. Giorgioni,[1] J. Frigerio,[2] E.Gatti,[1] S. De Cesari,[1] E. Grilli,[1] G. Isella[2] and F.Pezzoli[1]

[1] *LNESS-Dipartimento di Scienza dei Materiali, Università degli Studi di Milano-Bicocca, via Cozzi 55, I-20125 Milano, Italy*

[2] *LNESS-Dipartimento di Fisica del Politecnico di Milano, Polo di Como, via Anzani 42, I-22100 Como, Italy*

Ge films can be epitaxially grown on Si substrates, introducing biaxial tensile strain. This opens up applications of Ge in photonic [1], as strain contributes to enhance direct-gap emission, eventually yielding lasing action at room temperature [2].
Noticeably, the optical access to the direct gap transitions in Ge provides the possibility of spin-injection by optical orientation [3]. As a result, spectroscopic access to the very rich spin-physic of this semiconductor can be achieved.

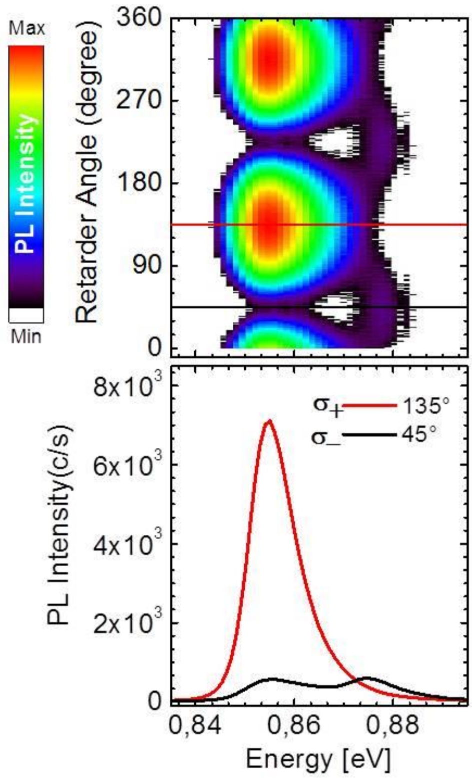


Figure 8: Low temperature (4K) PL of a Ge-on-Si epilayer resolved for left (σ-) and right-handed (σ+) helicity. The upper panel provides the full polarimetric analysis reporting the colour-coded PL intensity map as a function of the angle between an optical retarder and a linear polarizer placed along the emission path.

In this work we thus study the effect of tensile strain on the spin-properties of Ge by measuring, upon optical orientation of the carrier spin, the polarization of the radiative recombination across the direct-gap [4]. Polarization-resolved photoluminescence (PL) technique provides an ideal tool to observe emission due to optical transitions involving spin-polarized conduction band electrons with strain-splitted valence band light (cΓ-LH) and heavy holes (cΓ-HH).
Figure 1 shows that the two cΓ-LH and cΓ-HH spectral features are counter-circularly polarized and separated by about 19 meV. Surprisingly, for the fundamental cΓ-LH transition and for an off-resonance excitation of more than 300 meV, we measure a low temperature polarization degree as high as 85%. This is the highest value reported so far for Ge-based structures.
We will demonstrate that these findings can be explained in terms of the ultrafast-dynamics of hot conduction band electrons [2] and of the strain-induced change in the density of states of the valence band due to splitting and anticrossing between the LH and HH subbands.
Finally, our results provide a step forward in the investigation of the dynamics of non-equilibrium spin populations in group IV materials, and confirm Ge as a promising candidate for the development of next-generation CMOS-compatible devices featuring spintronics and photonics functionalities [5].

[1] D. Liang and J. E. Bowers *Nature Photon.* **4**, 511 (2010)
[2] Liu et al. *Opt. Lett.* **35,** 679 (2010).
[3] Pezzoli et al. *Phys. Rev. Lett.* **108**, 156603 (2012)
[4] Pezzoli et al. *Phys. Rev. B* **88**, 045204 (2013).
[5] F. Bottegoni et al. *Nature Mater.* **13**, 790 (2014)

Theory of copper induced spin-orbit coupling in graphene: substrate and adatoms

Tobias Frank,[1] Susanne Irmer,[1] Denis Kochan,[1] Martin Gmitra,[1] and Jaroslav Fabian[1]
[1]*Universität Regensburg*

We present a DFT study of graphene functionalized by copper adatoms as well as of graphene on the (111) Cu surface, focussing on spin-orbit coupling effects. In the single copper adatom limit we study two energetically favored adsorption positions: the top and bridge positions. Based on symmetry arguments (as in Ref. [1]) we propose an effective tight-binding model Hamiltonian to describe low energy electronic states and determine realistic orbital and spin-orbit coupling parameters to be in the order of 40 meV. We determine the mechanism of how spin-orbit coupling is introduced in the system by means of a DFT+U study and identify copper p and d orbitals as main contributors. We consider also graphene physisorbed on the Cu (111) surface, showing how well DFT can reproduce the electronic structure in comparison with ARPES measurements. Also for this system we fit to a model Hamiltonian to extract Rashba and intrinsic spin-orbit coupling strengths for varing graphene-copper distances. This work is supported by the DFG GRK 1570, SFB 689, and European Union Seventh Framework Programme under Grant Agreement No. 604391 Graphene Flagship.

[1] S. Irmer, T. Frank, S. Putz, M. Gmitra, D. Kochan, and J. Fabian, PRB 91 115141 (2015).

Magnetoanisotropic Andreev reflection in ferromagnet/superconductor junctions

Petra Högl
University of Regensburg

Andreev reflection spectroscopy of ferromagnet/superconductor (F/S) junctions is a sensitive probe of the junction interface as well as the spin polarization. We theoretically investigate spin-polarized transport in F/S junctions in the presence of Rashba and Dresselhaus interfacial spin-orbit fields and show that Andreev reflection can be controlled by changing the magnetization orientation. This suggests a similar control of the superconducting proximity effect and Majorana states. We predict a giant in- and out-of-plane magnetoanisotropy of the junction conductance. If the ferromagnet is highly spin polarized - in the half-metal limit - the magnetoanisotropic Andreev reflection depends universally on the spin-orbit fields only. Our results show that Andreev reflection spectroscopy can be used for sensitive probing of interfacial spin-orbit fields in F/S junction. This work has been supported by DFG SFB 689 and the International Doctorate Program Topological Insulators of the Elite Network of Bavaria.

Spin-orbit coupling in fluorinated Graphene

Susanne Irmer, Tobias Frank, Sebastian Putz, Martin Gmitra,
Denis Kochan, and Jaroslav Fabian
Institute for Theoretical Physics, University of Regensburg, 93040 Regensburg, Germany

We theoretically study spin-orbit coupling effects of fluorine chemisorbed on graphene. Both dense and dilute limit reveal a giant local enhancement of spin-orbit coupling by a factor of 1000 in the vicinity of the adatom corresponding to a spin-orbit strength of about 10 meV [1].

Our results are based on fully converged first-principles calculations which are analyzed by a tight-binding Hamiltonian based on symmetry arguments. We cover different fluorine concentrations from dense to intermediate to dilute coverage. In contrast to the case of hydrogenated graphene with a local spin-orbit enhancement of 0.1 to 1 meV [2], fluorine's native spin-orbit coupling exceeds the effect of the adatom-induced sp^3 distortion of the lattice. Moreover, we identify fluorine as a weak resonant scatterer giving rise to resonant signatures in the band structure off the Dirac point by about 0.3 eV. Our findings are important for studies on relaxation and transport.

This work was supported by the DFG SFB Grant No. 689 and GRK Grant No. 1570, and by the European Union Seventh Framework Programme under Grant Agreement No. 604391 Graphene Flagship.

[1] S. Irmer, T. Frank, S. Putz, M. Gmitra, D. Kochan, and J. Fabian, Phys. Rev. B 91, 115141 (2015).
[2] M. Gmitra, D. Kochan, and J. Fabian, Phys. Rev. Lett. 110, 246602 (2013).

Long-lived spin coherence of a two-dimensional electron gas in double and triple quantum wells

Saeed Ullah,[1] Gennady Gusev,[1] Felix G. G. Hernandez,[1] and Askhat Bakarov[2]

[1]*Institute of Physics, University of São Paulo, 05508-090 São Paulo – SP- Brazil*

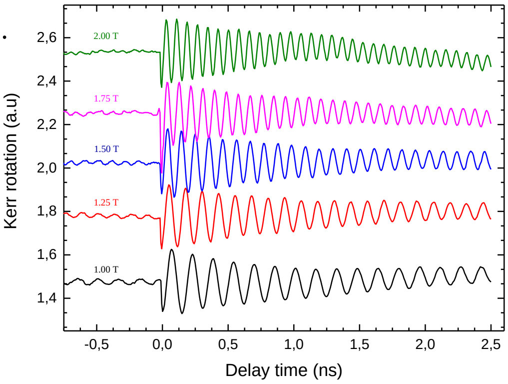
[2]*Institute of Semiconductor physics & Novosibirsk state University – Novosibirsk 630090, Russia*

Spintronics [1] or spin based electronic is of great importance in condensed matter physics. It has been attracted a lot of interest in the last few decades for possible applications in electronic devices [2]. Long-lived spin coherence of electronic states is one of the key features required for practical applications to store and manipulate spin information without loss [3]. It has been widely studied in different dimensionally semiconductor structures like quantum well (QWs) [4], quantum dots (QDs) [5] and layered structures [6].

In this work we report on the generation of spin dynamics in GaAs quantum wells containing a two-dimensional electron gas 2DEG. We investigate the spin coherence in double and triple (QWs). As reported previously in [7,8], such structures are suitable for long spin coherence time. The double QW sample (RC447) studied here consist of a 45 nm wide quantum well with high density $n_s = 9.2 \times 10^{11}$ cm^{-2} and electron mobility $\mu = 1.9 \times 10^6$ cm^2 / Vs assembling a bilayer system. The triple QW sample (# 480) consist of a 22-nm-thick GaAs central well and two 10-nm-thick lateral wells each separated by $Al_{0.3}Ga_{0.7}As$ barrier. The central well width of the triple QW sample (# 299) is about 26 nm and both side wells have equal width of 12 nm each separated by $Al_{0.3}Ga_{0.7}As$ barrier.

The mechanism for generation of spin coherence in 2DEG was studied experimentally by means of pump-probe techniques: time resolved kerr rotation (TRKR) and resonant spin amplification (RSA). Spin polarization is generated by using a focused, circularly polarized light spot by photoelastic modulator. The probe beam polarization was not modulated and its change induced by the spin dynamics was detected with a bridge using coupled photodiodes. The samples were placed in a magnetic field up to 6 T applied in the Voigt configuration, perpendicular to the optical axis. TRKR measurements were performed as a function of experimental parameters in multilayers system. The g-factor of 0.452 for DQW (RC-447), 0.458 and 0.397 for TQW samples #480 and #299 were observed respectively. RSA was measured as a function of pump power, delay time, and wavelength. Long-lived spin coherence with dephasing time $T_2^* > 6$ ns has been found in bilayer system with large spin-orbit interaction. And $T_2^* > 10$ ns was observed in the TQW sample (#480). In contrast the TQW sample (#299) displayed fast decoherence and a small spin dephasing time of 689 ps was observed.

[1] G. A. Prinz, Magnetoelectronics, Science 282, 1660-1663 (1998).
[2] G. Thorgilsson *et al.*, Phys. Rev. B 85, 045306 (2012).
[3] D. H. Feng *et al.*, Appl. Phy. Lett 100, 122406 (2012).
[4] V. Sih, D. D. Awschalom, Appl. Phy. Lett 101, 081710 (2007).
[5] D. H. Feng *et al.*, Appl. Phy. Lett 102, 062408 (2013).
[6] J. Berezovsky *et al.*, Nature Physics 2, 831 (2006).
[7] F. G. G. Hernandez et al., Phys. Rev. B 88, 161305(R) (2013).
[8] F. G. G. Hernandez et al., Phys. Rev. B 90, 041302(R) (2014).



Magnetic field dependence of TRKR signal for the DQW sample at temperature T = 5 K, magnetic field λ = 817 nm and the pump/probe power 1mW/300µW.

Spin polarization induced by diamagnetic current in Rashba system

Naoto Norizuki, Akito Kobayashi, and Hiroshi Kohno
Nagoya University

In systems with Rashba spin-orbit interaction, an electric current is accompanied by a spin polarization shown in figure 1. This phenomenon, known as the Edelstein effect [1], has been well studied for the case of dissipative (Ohmic) current. On the other hand, there are currents which do not suffer from dissipation. A diamagnetic current induced by a magnetic field is one instance of them. It flows at the edge of the sample for a uniform magnetic field, whereas it flows in the bulk if the magnetic field is nonuniform.

In this work, we examine whether a spin polarization accompanies a diamagnetic current, and how if it does. We study the current response and spin response to a nonuniform magnetic field of electrons subject to Rashba spin-orbit coupling. We consider a 2D Dirac electron system, which is known for a large diamagnetism [2]. Such a system is realized in graphene on Au substrate, in which a large Rashba constant of order 100 meV was reported [3].

We calculate the diamagnetic current and spin polarization induced by a nonuniform magnetic field based on the linear response theory. The schematic image is shown in figure 2. We found that current-induced spin exists and is perpendicular to permanent current. The inverse process will be calculated too. The results are expressed by a magnetic susceptibility, and its dependence on the momentum and the chemical potential is studied in detail.

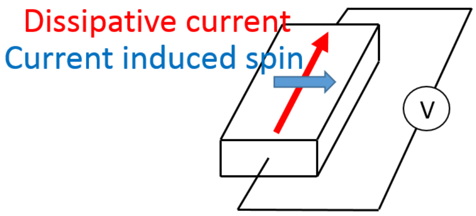


Figure 1

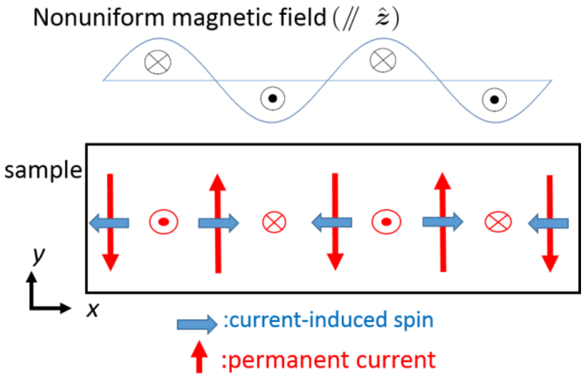


Figure 2

References

[1]V. M. Edelstein, Solid State Commun **73**, 3 233-235 (1990).
[2] H. Fukuyama, Prog. Theor. Phys. **45**, 704 (1971).
[3] D. Marchenko et al., Nat. Commun. **3**, 1232 (2012).

Physics below 1D magnetic textures in 2D superconductors.

Chris Carroll and Bernd Braunecker.

We study the limit of a line of dense spins within or atop a 2D s-wave superconductor in a continuum model. Spin order can be tuned from Ferromagnetic to spirals by self-organisation. Coupling of electronic and magnetic degrees of freedom are freely tuneable.

Recent work [1] indicates interaction between electrons, chains of magnetic moments and superconductivity gives rise to self-organised spiral chains and, for strong enough coupling, a topological superconducting phase without fine tuning. Equivalently, one can use a Ferromagnetic chain with Spin-Orbit interaction in the superconductor.

Most work has focused on the limit of "dilute" Shiba chains [2] with large inter-spin distances (excepting [3]) and are most accurate close to the centre of the superconducting gap. It is desirable to understand if there is an appreciable difference between the dilute and dense limits and to develop a theory valid far from the gap centre.

We perform analytic calculations of spectral properties, sub-gap density of states and response functions in terms of externally tuned parameters for dense magnetic chains in a 2D superconductor. Sub gap structure is resolved across the entire gap for all spiral wave-vectors and magnetic interaction strengths.

[1]: B. Braunecker, P. Simon. PRL **111**, 147202 (2013); J. Klinovaja, P. Stano, A. Yazdani, D. Loss. PRL **111**, 186805 (2013); M. M. Vazifeh, M. Franz. PRL **111**, 206802 (2013).

[2]: F. Pientka, L. I. Glazman, F. von Oppen. PRB **88**, 155420 (2013); P. M. R. Brydon, S. Das Sarma, Hoi-Yin Hui, J. D. Sau. PRB **91** 064505 (2015); A. Westström, K. Pöyhönen, T. Ojanen. PRB **91**, 064502 (2015); S. Hoffman, J. Klinovaja, T. Meng, D. Loss. arXiv:1503.08762.

[3]: H. Hui, P.M.R. Brydon, J. D. Sau, S. Terari, S. Das Sarma. Scientific Reports **5**, 8880 (2015)

Thermomagnetic Magnon Transport and Supercurrent

Kouki Nakata,[1] Pascal Simon,[2] and Daniel Loss[1]
[1]*University of Basel, Switzerland*
[2]*Universite Paris Sud, France*

Motivated by the recent rapid progresses [1-3] of experiments for ferromagnetic insulators, we [4] present the theory on thermal-magnon transport and magnon-supercurrents. We show the universal thermomagnetic relation for magnon transport analogous to the Wiedemann-Franz law for charge transport [R. Franz and G. Wiedemann, Annalen der Physik **165**, 497 (1853)], and discuss multi-magnon effects on the Onsager reciprocity relation [2] between the magnon Seebeck and Peltier coefficients. Taking into account the thermally induced magnon-phonon interactions [3], we clarify the resulting nonequilibrium magnon-supercurrent [3,4] in Bose-Einstein condensates of magnons as well as the Josephson and persistent magnon-supercurrents [4].

[1] S. O. Demokritov *et al.*, Nature **443**, 430 (2006). A. A. Serga *et al.*, Nat. Commun. **5**, 3452 (2014).
[2] K. Uchida *et al.*, Nat.Mater **10**, 737 (2011). J. Flipse *et al*., Phys. Rev. Lett. **113**, 027601 (2014). F. K. Dejene *et al*., Phys. Rev. B **90**, 180402(R) (2014). Y. Kajiwara *et al*., Nature **464**, 262 (2010).
[3] P. Clausen *et al.*, arXiv:1503.00482. M. Agrawal *et al*., Phys. Rev. Lett. **111**, 107204 (2013).
[4] K. Nakata, K. A. van Hoogdalem, P. Simon, and D. Loss, Phys. Rev. B **90**, 144419 (2014).
K. Nakata, P. Simon, and D. Loss, arXiv:1502.03865.
K. Nakata, P. Simon, and D. Loss, to be (will have been) submitted.
K. Nakata, P. Simon, and D. Loss, in preparation

Effect of nonadiabaticity on spin transitions in helical magnetic field

P. Wójcik, J. Adamowski, M. Wołoszyn and B.J Spisak
AGH University of Science and Technology, Faculty of Physics and Computer Science, Krakow, Poland

The experimental realization of an effective spin-transistor remains a challenge of spintronics since the pioneering concept proposed by Datta and Das [1]. A new spin-transistor design with the spin signal observed over the distance 50 µm has been recently demonstrated by Betthausen et al. in Ref. [2]. In this approach, the spin control is realized by combining the effect of homogeneous and helical magnetic fields. The latter is generated by ferromagnetic stripes located above the conduction channel. The spin state of electrons flowing through the channel is protected against a possible decay by keeping the transport in the adiabatic regime. The transistor action is driven by the diabatic Landau-Zener transitions induced by equating the homogeneous and helical magnetic fields. For the suitably chosen conditions the backscattering of spin polarized electrons appears, which gives raise to the large increase of the resistance.

In the present paper, we study the influence of the nonadiabaticity on the spin transistor action in the new spin transistor design. We have shown that in the non-adiabatic regime, apart from the well-known conductance dip located at the magnetic field equal to the helical-field amplitude, the additional conductance dips (with zero conductance) appear at magnetic field different from helical one. This effect is explained as resulting from the resonant Landau-Zener transitions between the spin-split subbands [3]. The physical phenomena predicted in our paper can be confirmed experimentally by using the device with the decreased distance between the ferromagnetic stripes, which allows to change the transport regime from adiabatic to nonabiabatic.

[1] S. Datta and B. Das, *Appl. Phys. Lett.* **56**, 665 (1990)
[2] C. Betthausen, T. Dollinger, H. Saarikoski, V. Kolkovsky, G. Karczewski, T. Wojtowicz, K. Richter, and D. Weiss, *Science*, **337,** 1221350 (2012)
[3] P. Wójcik, J. Adamowski, M. Wołoszyn, B.J. Spisak, *Semicond. Sci. Technol.,* in print (2015)

Correlation and random donors effects on electron transport in wide semicondiuctor quantum point contacts

I.I. Yakimenko and K.-F. Berggren
Department of Physics, Chemistry and Biology,
Linköping University, S-58183 Linköping, Sweden

We study effects of randomly distributed impurities on spin polarization and electron localization in realistic semiconductor quantum point contacts (QPCs). To this end we use density functional theory in local spin-density approximation (LSDA). Previous studies (as, for example, in [1]) have been restricted to the Thomas-Fermi approximation, and thus the effects of electron correlation and realistic confinement potentials were beyond the subject. Our studies have been performed for the two geometries of the gates, the first one with only split gates, and the other one with an additional top gate situated over the split gates. In the latter case there is a possibility to vary electron density within a fixed confinement which gives an opportunity to separate the effects on conductance caused by impurities and electron-electron interactions in a more distinct way. In both cases we recover the conventional fluctuation free parabolic electrostatic potential when the distance between the donor layer and the two-dimensional electron gas (2DEG) exceeds ~50 nm. In the opposite case, i.e., when the randomly distributed donors are placed more close to the 2DEG layer, there are drastic changes like the localization of electrons in the vicinity of the confinement potential minima which gives rise to fluctuation in conductance and resonances. At the same time the usual conductance steps vanish. By charging asymmetrically the split gates voltage we calculate the conductance as a function of the voltage applied to the top gate. In this way we find that resonances in conductance caused by randomly distributed donors are shifted and descreased in amplitude while the anomalies caused by interaction effects remain unmodified. Resonance peaks in the conductance derive from localized states within the QPC due to random fluctuations. The nature of electron localization has been discussed in our previous study [2] where we stress the crucial role of the shape of confinement potential on the formation of electron localization. In the present study we have shown that electron localization may be caused by randomly distributed donors and play an important role in electron transport, especially near the pinch-off regime. The results of our numerical simulations agree qualitatively with experimental studies [3-4]. We have also shown that for a wide QPC spin polarization appears in the form of stripes. This finding may be interesting in view of experimental study in [5] where it has been shown that the structure of such kind can be responsible for the anomalous behavior of the quantized conductance of a quantum wire in the shallow confinement limit. We also discuss the diminished effect of partially ionized random donors on the electronic potentials and the appearance of short-range order among the donors. The results of the present study is important for applications. For example, homogeneity and order of an assembly of nanostructures are crucial for their use in large-scale electronic and optical systems.

[1] J.A. Nixon, J.H. Davies, and H.U. Baranger, Phys. Rev. B **43**, 12638 (1991)
[2] I. I. Yakimenko, V. S. Tsykunov and K.-F. Berggren, J. Phys. Condens. Matter **25**, 072201 (2013)
[3] L.W. Smith, K. J. Thomas, M. Pepper, D. A. Ritchie, I. Farrer, J.P. Griffiths, G.A.C. Jones, J. of Phys.: Conf. Series **376**, 012018, (2012)
[4] L. W. Smith, H. Al-Taie, F. Sfigakis, P. See, A. A. J. Lesage, B. Xu, J. P. Griffiths, H. E. Beere, G. A. C. Jones, D. A. Ritchie, M. J. Kelly, and C. G. Smith, Phys. Rev. B **90**, 045426 (2014).

Skyrmion density correlations in critical chiral paramagnets

Laura Köhler, Achim Rosch, and Markus Garst

The interactions between critical paramagnons in chiral magnets like MnSi or Cu3OSeO3 suppress the critical temperature and, in addition, drive the transition weakly first-order. Within the resulting fluctuation-disordered regime strong correlations prevail that substantially renormalize the correlation length in quantitative agreement with Brazovski theory [1,2,3]. Within this regime, we theoretically address the correlations of the skyrmion density that can be identified with the local vector chirality of the magnetization. These correlations are expected to be particularly pronounced for finite magnetic fields close to the skyrmion crystal phase. We compute the corresponding correlation function within the Brazovski approximation with the aim to identify additional microwave resonances.

[1] M. Janoschek et al. Phys. Rev. B 87, 134407 (2013).
[2] A. Bauer, M. Garst and C. Pfleiderer, Phys. Rev. Lett. 110, 177207 (2013).
[3] J. Kindervater et al. Phys. Rev. B 89, 180408(R) (2014).

Spin-polarized transport through parallel-coupled quantum dots in the Kondo regime

D. Krychowski, S. Lipiński
Institute of Molecular Physics, Polish Academy of Sciences, M. Smoluchowskiego17, 60-179 Poznań, Poland

Recent experimental studies of Kondo effect in multiple quantum dots have revealed a complex competition between geometry and correlations making evident, that these structures are particularly attractive for quantum information processing and spintronics. We study two tunnel-coupled quantum dots parallel-attached (PDQD) to magnetic electrodes. We focus on the Kondo range, discussing both atomic and molecular Kondo regimes. The many-body problem is considered within the mean field slave boson approach of Kotliar and Ruckenstein. Apart from interference effects we also analyze the role of singularities of density of states (DOS) of the leads on Kondo-Fano physics and compare the results with featureless band. As the illustrative examples of singular DOS we choose carbon nanotube and graphene nanoribbon. In the region of Van Hove singularities Kondo temperature is strongly enhanced. The figure below illustrates how PDQD can be used in transferring polarization of conductance. In the presented case the magnetic electrodes are coupled only to the upper dot (see the inset). Depending on the gate voltage, the same or opposite sign of transferred polarization of conductance is observed.

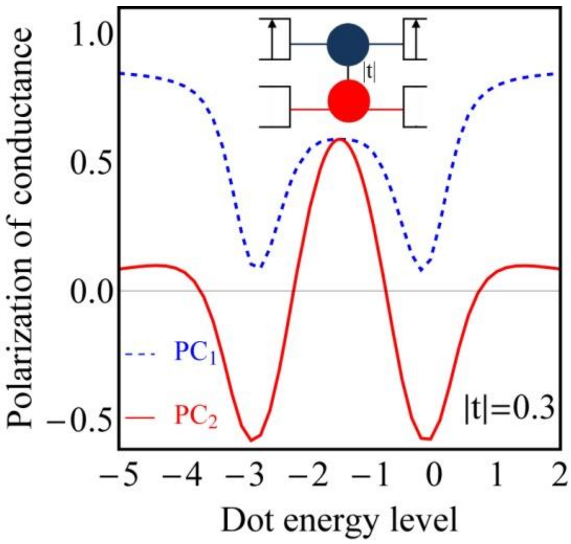


Fig. 1. Polarizations of conductance of the upper ($PC_1 = (G_1^{\uparrow} - G_1^{\downarrow})/(G_1^{\uparrow} + G_1^{\downarrow})$) and lower dot ($PC_2$), G_i^{σ}- conductance of the dot. Polarization of magnetic electrodes attached to the upper dot is 0.6 and the lower electrodes are nonmagnetic.

Support of the Polish National Science Centre from funds awarded through the decision No. DEC-2013/10/M/ST3/00488 is gratefully acknowledged.

Local field effects on spin polarized electrons injected into encapsulated graphene device

Yongho Seo*
Faculty of Nanotechnology and Advanced Material Engineering, and Graphene Research Institute, Sejong University, Seoul, 143-747, Korea
E-mail: yseo@sejong.ac.kr

Many attempts to implement graphene based spin-transistor have been performed. Spin valve effect is expected in graphene channel, as the electron in graphene has a long mean-free path. N. Tombros *et al*. succeeded in spin injection into graphene and reported that the spin relaxation length in graphene was about 1.5 to 2 μm with insulating barrier such as aluminum oxide underneath ferromagnetic metal electrodes [1]. T. Maassen *et al*. also recently reported the similar result of spin relaxation length in graphene at low temperature [2]. We have investigated local electric and magnetic fields effect on spin-polarized electrons injected into graphene by using scanning gate microscopy. Similarly to Rashba effect or Hanle effect, the additional local fields perpendicular to graphene surface can lead to an observation of spin precession [1-3]. To fabricate the device, photo and e-beam lithography techniques were carried out to make metal contacts (Co/Au) on graphene. The local electrical and magnetic fields was induced from a tip at the cantilever. In order to pattern the graphene channel, atomic force microscope (AFM) lithography was employed. The spin alignment of two electrodes was controlled by changing the magnitude and direction of the external magnetic fields. In this study we developed dry transferring techniques to transfer graphene to hBN substrate and to make sandwich structures. Also, we used shadow mask lithography technique to prevent the residue problem caused by e-beam lithography. The graphene layer was encapsulated between two hBN layers and then was kept intact during fabricating devices. Electrical properties of the sandwich devices also are investigated.

[1] N. Tombros, C. Jozsa, M. Popinciuc, H. T. Jonkman and B. J. van Wees *Nature* 448,571-574 (2007)
[2] T. Maassen, J. J. van den Berg,N. IJbema, F. Fromm, T. Seyller, R. Yakimova and B. J. van Wees *Nano Lett.* 12, 1498–1502 (2012)
[3] Yu. S. Dedkov, M. Fonin,U. Rüdiger and C. Laubschat *Phy. Rev. Lett.* 100, 107602 (2008)

Proximity-induced Josephson Pi-Junctions in Topological Insulators

Constantin Schrade, A. A. Zyuzin, Jelena Klinovaja, and Daniel Loss
Department of Physics, University of Basel

We study two microscopic models of topological insulators in contact with an s-wave superconductor. In the first model the superconductor and the topological insulator are tunnel coupled via a layer of scalar and randomly oriented spin impurities. Here we require that spin-flip tunneling dominates over normal tunneling. In the second model the tunnel coupling is realized by an array of single-level quantum dots with randomly oriented spins. It is shown that the tunnel region forms a Pi-junction where the effective order parameter changes sign. Interestingly, due to the random spin orientation the effective descriptions of both models do not violate time-reversal symmetry. As an application we hence discuss how the proposed junctions can be used to generate and manipulate Kramers pairs of Majorana fermions without the need of any magnetic fields.

Spin injection devices with a two-dimensional electron gas channel in (Al,Ga)As/GaAs heterostructure

T. Kuczmik, D. Popp, M. Oltscher, J. Loher, D. Schuh, D. Bougeard, M. Ciorga, and D. Weiss

Institute for Experimental and Applied Physics, University of Regensburg, 93040 Regensburg, Germany

Many new functionalities in spintronic device concepts, like Datta-Das spin field effect transistor [1], require efficient electrical spin injection into a two-dimensional electron gas (2DEG). Whereas spin injection phenomena in bulk semiconductors have been extensively studied in recent years, the number of experimental reports on spin injection into high mobility 2D systems is rather scarce.

We have recently demonstrated efficient spin injection into a high mobility 2DEG confined in an inverted (Al,Ga)As/GaAs heterostructure, using (Ga,Mn)As/GaAs Esaki diodes as spin selective contacts [2]. In this contribution we discuss some issues related to the design of the employed heterostructure (see Fig.1) and to sample fabrication steps that are critical to realize working spin injection devices with a 2D channel. Particular attention has to be devoted to avoiding a parasitic conducting channel that can be parallel to the 2DEG channel and therefore can compromise spin transport in the latter. Such parallel channels can be formed either above the 2DEG channel, in the *n*-doped part of the Esaki diode, or below the active channel, on the (Al,Ga)As side of the heterojunction, in the region of the δ-doping. We compare the results of nonlocal spin valve measurements on samples with and without any parasitic channel and discuss in details how the presence of such a channel affects the measured spin signal.

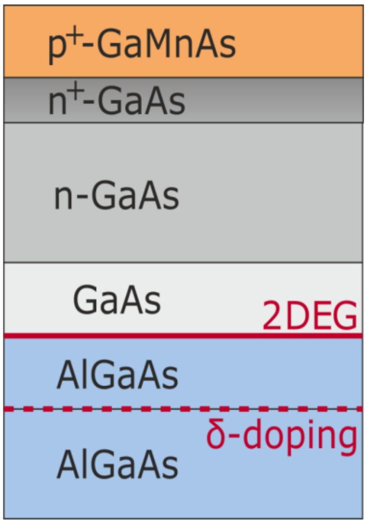


Fig.1 Typical profile of the heterostructure used for fabrication of spin injection devices with a 2D transport channel.

The work has been supported by the German Science Foundation (DFG) through the project SFB689.

[1] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
[2] M. Oltscher *et al.*, Phys. Rev. Lett. **113**, 236602 (2014).

Chiral magnets: boundary instability, skyrmion creation and interaction with defects

Jan Müller, Markus Garst, and Achim Rosch
University of Cologne, Institute for Theoretical Physics, 50937 Cologne, Germany

Magnetic whirls in chiral magnets, so-called skyrmions, have gained a lot of attention during the last years. Skyrmions have been measured in bulk B20 materials [1], where the lack of inversion symmetry gives arises to Dzyloshinskii-Moriya interaction (DMI). They also have been measured in thin films [2], stabilized by interfacial DMI. Their stability and highly efficient coupling to electric current [3] makes them a promising candidate for future information technology devices.

Within the field-polarized phase, the magnetization at the edge of the sample twists away from the field direction due to the DMI interaction. As a result of this non-trivial spin configuration, magnon modes exists that are bound to the sample edge. Lowering the magnetic field, such a magnon mode becomes soft triggering a local instability. We demonstrate the the effect can be used for the creation of single skyrmions in a nanowire by purely using magnetic field pulses.

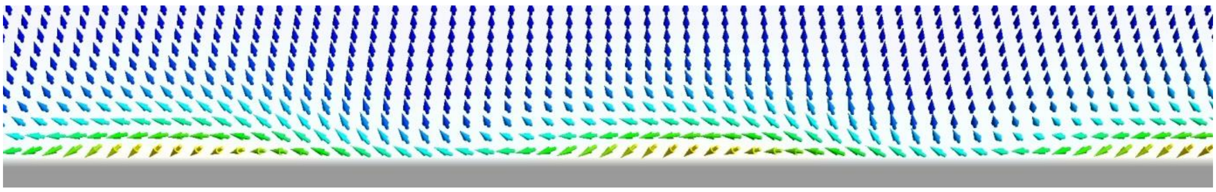


Figure: Bound magnon at the surface of a two-dimensional chiral magnet. Result from a variational expansion around the ground state configuration.

Further, we have studied the interplay of skyrmions with defects [4], i.e. with non-magnetic holes in the sample, based on an analytic Thiele approach that is supported by a numerical evaluation of the interaction potential and also numerical simulations of the Landau-Lifshitz-Gilbert equation. Apart from a complete phase diagram with a range of interaction regimes, we found an effective acceleration for skyrmions at ultra low current densities and give analytic estimations for a skyrmion Hall effect induced by defects.

[1] S. Mühlbauer, et al. Science 323, 915-919 (2009).
[2] X. Z. Yu, et al. Nature 465, 901-904 (2010).
[3] F. Jonietz, et al. Science 330, 1648-1651 (2010).
[4] J. Müller, A. Rosch, Phys. Rev. B 91, 054410 (2015).

Magnon band structure of magnetic helices and skyrmion crystals

Johannes Waizner, Markus Garst
University of Cologne, Cologne, 50937, Germany

In chiral magnets long-range ordered magnetic crystals form with a lattice spacing proportional to the inverse of spin-orbit coupling. The magnetic helix corresponds to a one-dimensional crystal while the skyrmion lattice effectively realizes a two-dimensional magnetic crystal. We study the magnon excitations of these crystals that experience a characteristic Bragg scattering off their periodicity resulting in a magnon band structure. For the helix, in particular, this leads to gaps in the spectrum that inhibit magnon propagation along the pitch direction resulting in flat magnon bands at large momenta, which is confirmed by inelastic neutron scattering [1]. Our theory also explains quantitatively the magnetic resonances of the three chiral magnets $MnSi$, $Fe_{1-x}Co_xSi$ and Cu_2OSeO_3 [2].

[1] M. Kugler, G. Brandl, J. Waizner, M. Janoschek, R. Georgii, A. Bauer, K. Seemann, A. Rosch, C. Pfleiderer, P. Böni, and M. Garst, *arXiv*: 1502.06977
[2] T. Schwarze, J. Waizner, M. Garst, A. Bauer, I. Stasinopoulos, H. Berger, C. Pfleiderer, and D. Grundler, *Nature Materials* 14, 478 (2015).

Tunable spin dependent transport in Dot–Ring Nanostructure

E. Zipper, I. Janus-Zygmunt, B. Kędzierska, A.Gorczyca-Goraj, M. M. Maśka
Institute of Physics, University of Silesia, Katowice, Poland

We consider quantum nanostructures composed of a semiconductor quantum dot (QD) surrounded by a quantum ring (QR) in the Coulomb blockade regime. Such structure has been recently fabricated by pulse droplet epitaxy [1]. The properties of such nanostructures (called hereafter DRN) can be strongly modified by changing the shape and the height of the barrier separating the QD and QR parts and/or the relative position of the minima of the potential wells [2]. The manipulation of these parameters by, e.g., electrical gating leads to the change of the radial distribution of wave functions which strongly influence many properties. A spin blockade in a single electron transistor in QD resulting from spin polarized leads has been discussed in [3]. In this paper we propose another mechanism for spin dependent current which utilizes the peculiar properties of DRN in the presence of spin unpolarised leads.

Transport through the nanostructure depends crucially on the tunneling rates of its states to the leads. In the case of DRN, this coupling depends on the distribution of the electron's wave function: states localized in QD (QR) are weakly (strongly) coupled to the electrodes [4]. To obtain spin polarized current we design DRN in which there exist spin dependent couplings. We assume that in our system the outer QR has definite (e.g. spin-down) polarization. Such structures can be fabricated in various ways, e.g., one can place a ferromagnetic nanoring above the DRN thus polarising the outer QR. Another possibility would be fabrication of a core-double shell nanowire of, e.g., n-type (In,Fe)As or (In,Fe)Sb [5]. The first shell would be the tunneling barrier, the second one the spin polarised QR.

Thus spin-down (spin-up) electrons experience thin (thick) tunnel barriers and we have to consider the DRN energy states with spin-down and spin-up separately. The spin-up wave function is situated mainly in QD, whereas the spin-down wave function is situated mainly in QR giving rise to spin dependent tunnel rates: $\Gamma_{\uparrow} < \Gamma_{\downarrow}$. We show that depending on the detailed arrangement of the spin energy levels, which can be manipulated by electrical gating, one can obtain spin related positive differential resistance (PDR) or negative differential resistance (NDR). What is more, by changing the gate voltage one can switch DRN between PDR and NDR regimes.

[1] C. Somaschini, S. Bietti, N. Koguchi and S. Sanguinetti, Nanotech. **22**, 185602 (2011).
[2] E. Zipper, M. Kurpas, and M. M. Maśka, New J. of Phys.**14**, 093029 (2012); M. Kurpas, E. Zipper, and M. M. Maśka, in "Physics of Quantum Rings", Vladimir M. Fomin (editor), Springer 2014, p. 455
[3] M. Ciorga *et al.*, Appl. Phys. Lett. **80**, 2177 (2002).
[4] M. Kurpas, B. Kędzierska, I. Janus-Zygmunt, A. Gorczyca-Goraj, E. Wach, E. Zipper, M. M. Maśka, arXiv:1503.03510 (2015)
[5] P. N. Hai, L. D. Anh, M. Tanaka, Appl. Phys. Lett.**101**, 252410 (2012); L. D. Anh, P. N. Hai, M. Tanaka, Appl. Phys. Lett. **104**, 0422404 (2014).

Anomalous Behavior In Magneto Transport Measurements In Liquid-gated Pt Thin Films

Kil-joon Min,[1] Teayueb Kim,[2] , Dong-Hun Chae[1*] and Sungjung Joo[1*]
[1]*Korea Research Institute of Standards and Science, Daejeon, Korea*
[2]*Department of Applied Physics, Korea University, Sejong, Korea*

The carrier density in solid state materials plays a key role for electronic and other physical properties. The conventional way for the carrier density modulation is the chemical doping. However, it introduces an inevitable structural distortion and has limited density tunability owing to the fundamental chemical solubility. On the other hand, the carry density modulation is also realizable throughout the field effect, which is a key technique for the modern electronics. With the superior density modulation using ionic gating, they have experimentally demonstrated field-induced correlated states of matters such as ferromagnetism [1].

We observed a super linear behavior in the Hall resistance in liquid-gated Pt thin films. This effect is consistent with a previous experimental result reported by Iwasa group in Japan. They interpreted this phenomenon with the anomalous Hall Effect usually emerging in ferromagnetic materials even though Pt is considered to be a paramagnetic material according to the Stoner criterion. Here, we present our experimental progress and preliminary results.

[1] Phys. Rev. Lett. 111, 216803 (2013)

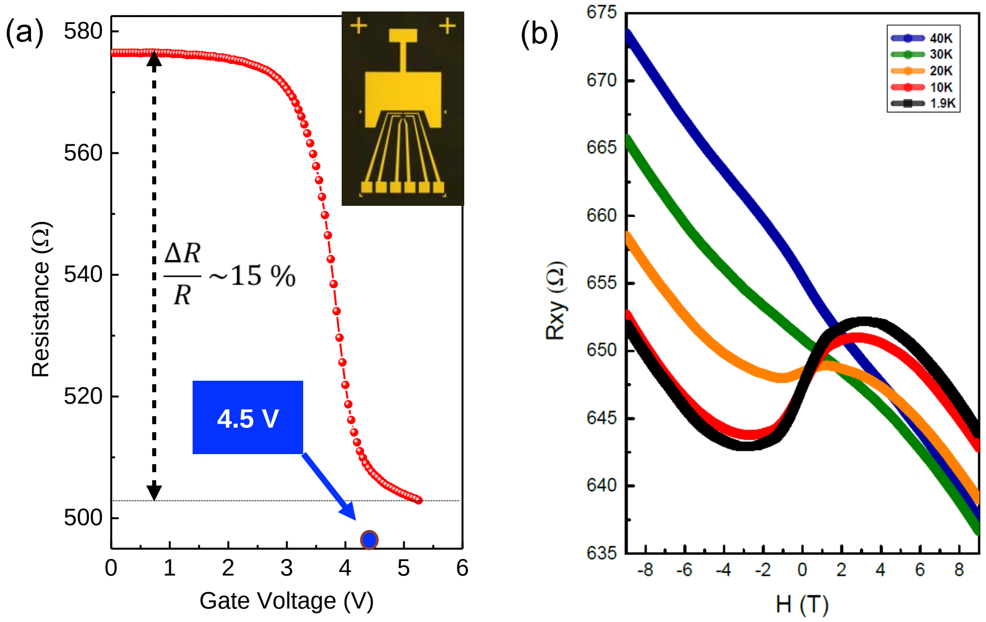


Figure 1. (a) Resistance for between Vg=0 and 6 V. Reduction of R was about15% with the application of gate voltage at T=220 K. (b) Anomalous behavior in the Hall resistance is highly non-linear. Hall coefficient of paramagnetic materials is not considered to have temperature dependence. In this experiment, the downward banding was observed firstly at 30 K with positive gate voltage.

Circuit QED with hole-spin qubits in Ge/Si nanowire quantum dots

Christoph Kloeffel,[1] Mircea Trif,[2] Peter Stano,[1,3,4] and Daniel Loss[1,4]
[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*
[3]*Institute of Physics, Slovak Academy of Sciences, 845 11 Bratislava, Slovakia*
[4]*CEMS, RIKEN, Wako, Saitama 351-0198, Japan*

We propose [1] a setup for universal and electrically controlled quantum information processing with hole spins in Ge/Si core/shell nanowire quantum dots. Single-qubit gates can be driven through electric-dipole-induced spin resonance, with spin-flip times shorter than 100 ps. Long-distance qubit-qubit coupling can be mediated by the cavity electric field of a superconducting transmission line resonator, where we show that operation times below 20 ns seem feasible for the entangling square-root-of-iSWAP gate. The absence of Dresselhaus spin-orbit interaction (SOI) and the presence of an unusually strong Rashba-type SOI [2,3] enable precise control over the transverse qubit coupling via an externally applied, perpendicular electric field. The latter serves as an on-off switch for quantum gates and also provides control over the g factor [4], so single- and two-qubit gates can be operated independently. Remarkably, we find that idle qubits are insensitive to phonons [4,5] and charge noise, and we discuss strategies for enhancing noise-limited gate fidelities.

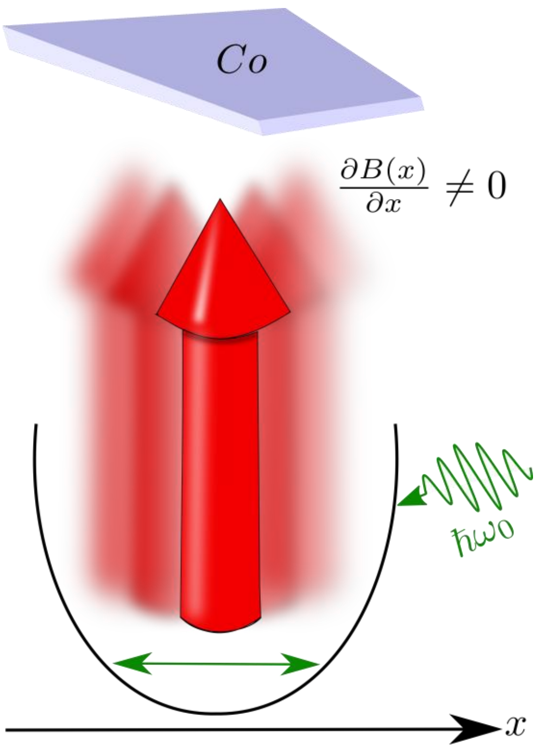
[1] C. Kloeffel, M. Trif, P. Stano, and D. Loss, Phys. Rev. B **88**, 241405(R) (2013).
[2] C. Kloeffel, M. Trif, and D. Loss, Phys. Rev. B **84**, 195314 (2011).
[3] C. Kloeffel and D. Loss, Annu. Rev. Condens. Matter Phys. **4**, 51 (2013).
[4] F. Maier, C. Kloeffel, and D. Loss, Phys. Rev. B **87**, 161305(R) (2013).
[5] C. Kloeffel, M. Trif, and D. Loss, Phys. Rev. B **90**, 115419 (2014).

Electric Dipole Spin Resonance In The Presence Of Valley Degeneracy

Marko J. Rancic and Guido Burkard
University of Konstanz

We theoretically investigate the electric dipole spin resonance (EDSR) in a single Si/SiGe quantum dot in the presence of a magnetic field gradient, e.g., produced by a micomagnet. The control of electron spin states can be achieved by applying an oscillatory electric field, which induces periodic back and forth motion of the electron spin inside the quantum dot. This motion inside a magnetic field gradient, produces an effective periodic in-plane magnetic field, and allows for driven spin rotations near resonance [1]. By solving a Lindblad master equation, we discuss possible electron spin relaxation and decoherence mechanisms relevant to EDSR.

In Si there is 5% of naturally occurring nuclear spin 1/2 isotope, which causes the electron spin to decohere. Nuclear spins are included in our model through the additional random Overhauser magnetic field. Furthermore, a valley dependent *g*-factor, combined with intervalley scattering gives rise to another electron spin decoherence mechanism. The goal of our study is to describe the efficiency of a spin echo sequence in the presence of all mentioned relaxation and decoherence mechanisms.



The visualization of EDSR with a cobalt (Co) micromagnet embedded on top of the quantum dot. The micromagnet induces an in-plane magnetic field gradient.

[1] E. Kawakami, P. Scarlino, D. R. Ward, F. R. Braakman, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, M. A. Eriksson, and L. M. K. Vandersypen, Nature Nanotech. **9**, 666-670 (2014).

Long-Distance Coupling Settings for Qubits in Quantum Dots

Marcel Serina, Luka Trifunovic, and Daniel Loss
Department of Physics, University of Basel, Klingelbergstrasse 82,CH-4056 Basel, Switzerland

We analyze the long-distance coupling between different types of charge and spin qubits in quantum dots. We assume two different settings, electrostatic coupling through the floating metallic gate induced by image charges and coupling through the Majorana modes formed on the edge of the semiconductor nanowire with proximity-induced superconductivity and spin-orbit coupling. We optimize the experimental setup of the double dots and floating gates as well as different structures broadly used to fabricate the quantum dots. In the second proposal, externally adjustable overlap of the Majorana modes could be used to couple the charge and spin qubits in the proximity of the nanowire ends by means of the non-local nature of Majorana modes.

Moving away from simple SiGe self-assembled nanodevices

Lada Vukušić, Hannes Watzinger, Elisabeth Lausecker, Alisha Truhlar, Raimund Kirchschlager, Josip Kukučka, Violetta Sessi, Martin Glaser, Armando Rastelli, Friedrich Schäffler, and Georgios Katsaros

Institute of Semiconductor and Solid State Physics, Johannes Kepler University, Altenbergestr. 69, 4040 Linz, Austria

e-mail: lada.vukusic@jku.at

P-type SiGe nanostructures have emerged as a promising material system for the realization of spin qubits, due to the combination of two significant properties: long spin coherence time as expected for group IV semiconductors (low hyperfine interaction) and a strong valence-band spin-orbit coupling [1].
In our group we study molecular beam epitaxy grown SiGe self-assembled nanostructures which are realized by direct growth of Ge on Si substrates via the Stranski-Krastanow (SK) growth mode. In 2010 the first realization of single-hole transistors based on such nanocrystals was reported and various low temperature transport measurements revealed highly anisotropic and tunable g-factors, together with strong and tunable spin-orbit coupling [2].

Simple devices based on random single islands are, however, not a sufficient and attractive "solution" for spin manipulation experiments. Therefore, our goal is to move towards: a) self-organized nanocrystals and b) double dot devices and charge detectors in this material system.

In order to control positions of self-assembled Ge islands, Ge islands can be grown on Si substrates on which periodic pits have been defined by nanoimprint lithography. For creating double dots, we aim to electrostatically "break" a single nanocrystal into two quantum dots, while for charge sensing we try to capacitively couple two neighbouring nanocrystals.

Here we will present our recent progress in these two directions and report first quantum transport measurements.

[1] Y. Hu et al., Nature Nanotechnology **2**, 622 (2007) ; Y. Hu et al., Nature Nanotechnology **7**, 47-50 (2012) ; A. P. Higginbotham et al., Nano Letters **14**, 3582 (2014)
[2] G. Katsaros et al., Nature Nanotechnology **5**, 458-464 (2010); G. Katsaros et al. , Phys. Rev. Lett. **107**, 246601 (2011); N. Ares et. al., Phys. Rev. Lett. **110**, 046602 (2013) ; N. Ares et. al., Applied Phys. Lett. **103** (26), 263113 (2013)

Nuclear spin relaxation in Rashba nanowires

Alexander A. Zyuzin, Tobias Meng, Viktoriia Kornich, and Daniel Loss
Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

We study the nuclear spin relaxation in a ballistic nanowire with hyperfine and Rashba spin-orbit interactions (SOI) and in the presence of magnetic field and electron interactions. The relaxation rate shows pronounced peaks as a function of magnetic field and chemical potential due to van Hove singularities in the Rashba bands. As a result, the regimes of weak and strong SOIs can be distinguished by the number of peaks in the rate. The relaxation rate increases with increasing magnetic field if both Rashba subbands are occupied, whereas it decreases if only the lowest one is occupied.

A. A. Zyuzin, T. Meng, V. Kornich, and D. Loss, PRB 90, 195125 (2014).

Decoupling trion decay and nuclear dynamics in semiconductor quantum dots

Wouter Beugeling,[1] Natalie Jäschke,[2] Götz S. Uhrig,[1] and Frithjof B. Anders[2]
[1]Lehrstuhl für Theoretische Physik I, Technische Universität Dortmund,
Otto-Hahn Straße 4, 44227 Dortmund, Germany
[2]Lehrstuhl für Theoretische Physik II, Technische Universität Dortmund,
Otto-Hahn Straße 4, 44227 Dortmund, Germany

Electron spins in semiconductor quantum dot systems can be manipulated using magnetic fields and laser pulses. Recent experiments aim at coherent control of the spin. The theoretical description of the dynamics, based on the central spin model, is challenging due to the large range of the typical time scales of the relevant processes. In particular, the decay time of the excited states (trions) on one hand and the effect of the coupling to the nuclear spins in the substrate on the other hand differ by several orders of magnitude.

The decay of the trions is modelled with a Lindblad equation that governs the time evolution of the density matrix of the system. A numerical analysis of the time evolution of the density matrices is elusive because the number of degrees of freedom grows very fast with the number of nuclear spins.

In this work, we propose an approximation scheme that captures the relevant dynamics. The aim is to describe systems with so many nuclear spins that the distribution of couplings can be considered as almost continuous, in order to emulate experimental settings. The basic idea of our method is a decoupling of the time scales of the trion decay and of the much slower nuclear dynamics. We also present a hybrid approach combining the quantum dynamics for the electronic spin subject to laser pulse sequences and a classical simulation of the spin bath. Using the latter approximation, we can describe the buildup of non-equilibrium nuclear magnetic spin polarization. We discuss both the advantages and limitations of these approximation methods, and compare them to each other and to exact results for small systems.

All-electrical measurement of the spin-triplet relaxation times in self-assembled quantum dots

K. Eltrudis[1], A. Al-Ashouri[1], A. Beckel[1], A. Ludwig[2], A. D. Wieck[2], A. Lorke[1] and M. Geller[1]

[1]*Faculty of Physics and CENIDE, University of Duisburg-Essen, Lotharstr. 1, 47057 Duisburg, Germany*

[2]*Chair for Applied Solid State Physics, Ruhr-Universität Bochum, Universitätsstr. 150, 44780 Bochum, Germany*

Self-assembled quantum dots (QDs) are one of the promising building blocks for quantum information processing, as they can be used to store and manipulate spin quantum bits (qubits) having a long spin relaxation time [1]. **We demonstrate here an all-electrical initialization of a two-electron spin-triplet state and measure for the first time by electrical means its spin relaxation time.** The lifetime of this two-electron spin state is of the order of tens of microseconds at zero magnetic field, which is two orders of magnitude longer than the single spin relaxation time of a hole in a InGaAs QD [2].

The self-assembled QDs are embedded in a GaAs/AlGaAs field-effect transistor structure. A two dimensional electron gas (2DEG) coupled to the QDs serves as charge reservoir as well as sensitive detector for the electron states in the QDs. The measurement technique we use here is based on the time-resolved transconductance spectroscopy [3,4]. This set-up allows us, as a first step, to prepare the two-electron triplet state by using a charge pulse at the voltage V^1_{triplet}= -0.22 V, see Fig. 1(a). After different charging times we are able to measure the triplet occupation in the emission current during read-out (when the electrons leave the QDs back to the 2DEG) and determine the spin-relaxation time to τ_{triplet} = 17 µs, see Fig. 1(b).

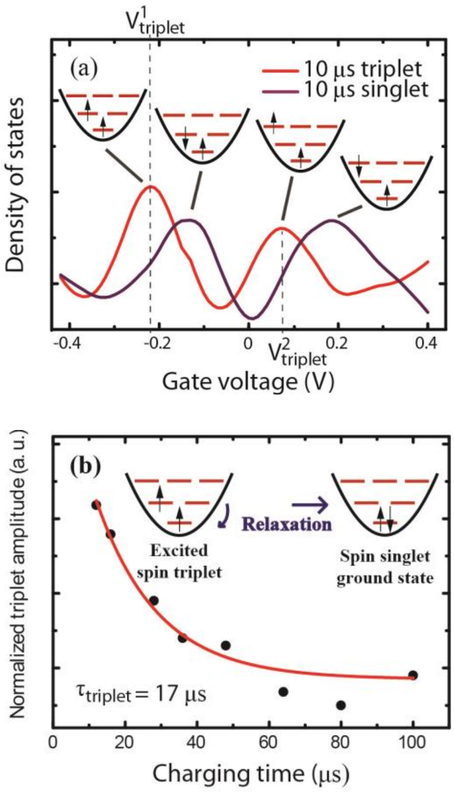


Fig 1: (a) The two-electron QD helium spectrum with two excited triplet states and two excited singlet states
(b) The normalized triplet amplitude vs. time, which yields the spin relaxation time

Furthermore, Fig. 1(a) shows a second triplet peak at a gate voltage V^2_{triplet}= 0.07 V which can be attributed to a state where the second electron is transferred into the d-shell. Subsequently, these electrons occupy the p-shell after a fast relaxation without spin-flip. It demonstrates an alternative way to prepare the two- electron spin triplet and therefore the same spin-relaxation time is expected. The long timescale for the decay promises future coherent optical manipulation of such a spin-qubit and transfer of the spin-qubit state to a single photon in an electrically addressed spin-photon interface [5].

[1] M. Kroutvar, et al., Nature **432,** 81 (2004)
[2] R. Dahbashi, et al., Phys. Rev. Lett. **112**, 156601 (2014)
[3] B. Marquardt. et al., Nature Commun. **2**, 209 (2011)
[4] A. Beckel, et al., Phys. Rev. B **89**, 155430 (2014)
[5] S.T. Yilmaz, P. Fallahi, and A. Imamoğlu, Phys. Rev. Lett. **105**, 033601 (2010)

Dynamics of the electron spin in a quantum dot with a narrowed Overhauser-field

Lars B. Gravert,[1] Peter Lorenz[1], Joachim Stolze[1], and Götz S. Uhrig[1]
[1] *Lehrstuhl für Theoretische Physik I, Technische Universität Dortmund*

Many experimental studies suggest that narrowing the Overhauser-field distribution yields an increased coherence time of the central spin within a semiconductor quantum dot [1,2,3]. We introduce a method to calculate time-dependent observables in presence of a narrowed Overhauser-field with the use of *density matrix renormalization group* (DMRG) which allows us to treat much larger spin baths than other numerical approaches [4]. The model to describe the electronic spin in a quantum dot is the central spin model.

We can calculate the time evolution of observables for arbitrary couplings between the central spin and any bath spin as well as arbitrary magnetic fields applied to the electron spin. In these calculations we can reach up to 1000 bath spins within a reasonable time treating the model fully quantum mechanical.

We use analytic results for the central spin model with homogeneous couplings to gauge our numerical approach and illustrate the accuracy of the calculations. Then, we investigate the effect of the width of the Overhauser-field distribution to the dynamics of the central spin for non-uniform couplings of the bath spins and various magnetic field strengths applied to the central spin. From our data we show that the coherence time of the central spin increases significantly for sharp distributed Overhauser-field depending on the strength of the magnetic field.

[1] A. Greilich et al., Science **317**, 1896 (2007).
[2] C. Latta et al., Nature Phys. **5**, 758 (2009).
[3] I. T. Vink et al., Nature Phys. **5**, 764 (2009).
[4] D. Stanek, C. Raas, and G. S. Uhrig, Physical Review B **88**, 155305 (2013).

Effective Triple Quantum Dot Hamiltonian: influence of spin-orbit interaction

Marko Milivojević,[1] Dimitrije Stepanenko[2]
[1]NanoLab, Center for Quantum Theoretical Physics, Department of Physics, University of Belgrade, Studentski trg 12, 11158 Belgrade, Serbia
[2]Center for Solid State Physics and New Materials, Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia

We study the effective spin Hamiltonian of a three-electron triple quantum dot in GaAs in the presence of an external magnetic field and the spin-orbit interaction. We find the resulting spin interaction both in the usual linear geometry and in the more general case of triangular arrangement of the dots. In the linear arrangement, the dominant interaction is an isotropic exchange with anisotropic corrections similar to the known case of a double quantum dot. The presence of third dot modifies the intensity of the interaction, and there is a residual three-spin interaction. The anisotropy, in the lowest order, is given as a rotated exchange, with the direction of rotation set by both the intensity of intrinsic spin-orbit coupling and the orientation of the dots. The anisotropy, up to the second order, can be accounted for by a suitable choice of the local spin basis. In the triangular arrangement, the spin-orbit interaction cannot be represented by a choice of the spin basis, except in the special case of equilateral triangle. This irreducible anisotropy is traced to the existence of multiple paths that start and finish at a given dot.

Electron spin rotations induced by oscillating Rashba interaction in quantum wires

Jarosław Pawłowski, Stanisław Bednarek
Faculty of Physics and Applied Computer Science,
AGH University of Science and Technology, Kraków, Poland

An electron spin is conventionally manipulated by applying a magnetic field, but electric-field control/manipulation of the spin is a key issue for spintronics devices [1,2,3]. Confining local oscillating magnetic fields in a semiconductor naondevice has proven to be challenging. However, spin control and manipulation by means of an electric field can be achieved through spin-orbit coupling [3]. In standard EDSR technique, instead of using a microwave which is the source of resonantly oscillating magnetic field, by applying oscillating voltages to the local electrodes we force an oscillating motion of an electron. The spin-orbit interaction couples an electron momentum with its spin. If we enforce the motion of the electron, the spin-orbit interaction will enable a spin rotation in a static external magnetic field. This type of rotations were performed for electrons trapped in planar electrostatic quantum dots [4]. However, much shorter operation times obtained for electrons trapped in quantum dots in InAs or InSb nanowires defined by local gating [5,6].

Here we consider rotations of a single electron spin confined in a gated electrostatic quantum dot defined within InSb quantum wire. We propose an alternative method of performing the spin rotations, which does not require a use of any (oscillating or static) external magnetic fields. For this purpose, electron confinement potential is modulated giving the oscillating Rashba type spin-orbit coupling. The whole device containing the wire and surrounding metal electrodes is modelled by the Poisson equation with spatially-varying material-dependent permittivity. We solve this equation numerically for alternating values of voltages applied to the local electrodes, obtaining the time-dependend confining potential within the wire. In resulting quantum-wire-based single-electron nanodevice we can perform spin rotations around two different axes separately without using any external magnetic field.

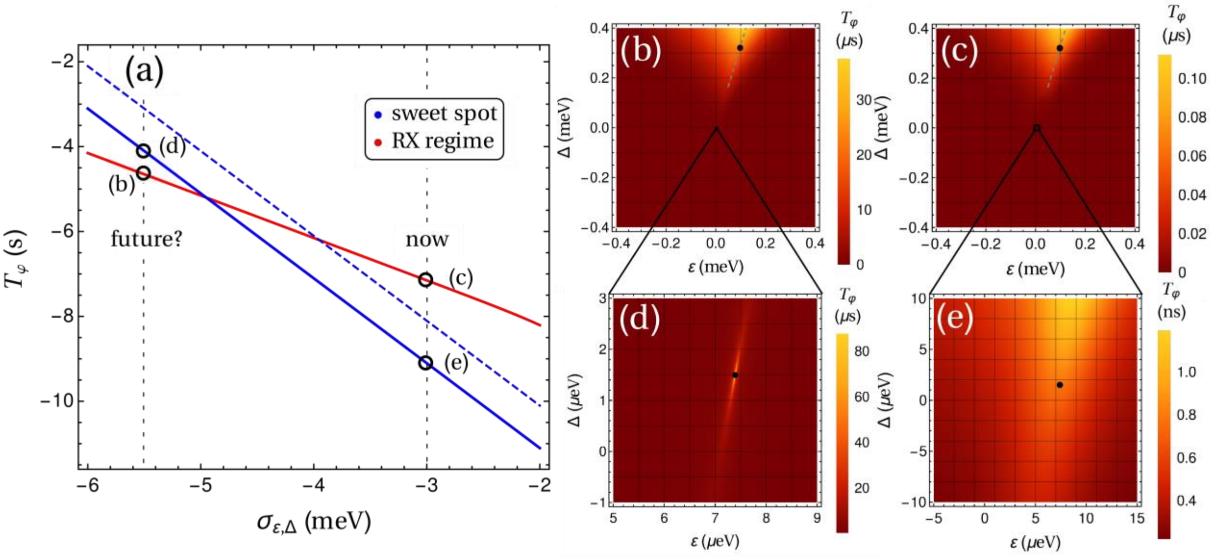
[1] S. D. Sarma, *American Scientist* **89**, 516 (2001).
[2] I. M. Miron et al., *Nature materials* **9**, 230 (2010).
[3] O. Krupin et al., *New Journal of Physics* **11** 013035 (2009).
[4] K. C. Nowack et al., *Science* **318**, 1430 (2007).
[5] J. W. G. van den Berg et al., *Physical Review Letters* **110**, 066806 (2013).
[6] S. M. Frolov et al., *MRS Bulletin* ***38***, 809 (2013).

The asymmetric resonant exchange qubit under the influence of electrical noise [1]

Maximilian Russ and Guido Burkard

Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

We investigate the influence of charge noise on a resonant exchange (RX) qubit in a triple quantum dot. This RX qubit is a variation of the exchange-only [2] spin qubit which responds to a narrow-band resonant frequency [3,4]. Our noise model includes uncorrelated charge noise in each quantum dot giving rise to two independent (noisy) bias parameters ε and Δ. We calculate the energy splitting of the two qubit states as a function of these two detuning parameters in order to find "sweet spots", in which the qubit is least susceptible to noise. Our investigation shows that such sweet spots exist within the low bias regime, in which the bias detuning parameters have the same magnitude as the hopping parameters. The location of the sweet spots in the (ε, Δ) plane depends on the hopping strength and the asymmetry between the quantum dots. In the regime of weak charge noise, we identify a new favorable operating regime for the RX qubit based on these sweet spots. We further calculated the pure dephasing time where we included second order couplings for our new sweet spot and the usual RX regime (Figure below).



(a) Comparision of the dephasing times T_φ at the sweet spot and in the usual RX regime for different noise levels. For decreasing noise level the sweet spot becomes favorable, since T_φ increases much steeper at the sweet spot than in the usual RX regime. The dashed line corresponds to improved parameter settings. (b)-(e) Density plots of the dephasing time in the (ε, Δ)-plane for the marked noise levels.

[1] arXiv:1502.06109 [cond-mat.mes-hall]

[2] D. P. DiVincenzo, D. Bacon, J. Kempe, G. Burkard, and K. B. Whaley, Nature 408, 339 (2000).

[3] J. Medford et al., Phys. Rev. Lett. 111, 050501 (2013).

[4] J. M. Taylor, V. Srinivasa, and J. Medford, Phys. Rev. Lett. 111, 050502 (2013).

Anisotropy of hole g-factors in Ge hut wires

H. Watzinger[1], L. Vukušić[1], V. Sessi[2], E. Lausecker[1], A. Truhlar[1], R. Kirchschlager[1], J. Kukučka[1], M. Glaser[1], A. Rastelli[1], F. Schäffler[1] and G. Katsaros[1]

[1] *Semiconductor Physics Division, Johannes Kepler University Linz, Altenberger Str. 69, 4040 Linz, Austria*

[2] *NaMLab GmbH, Nöthnitzer Str. 64, 01187 Dresden, Germany*

Research on nanowires is of both fundamental and technological interest [1, 2]. The electronic properties of these quantum-mechanically one-dimensional structures make them particularly interesting for quantum transport applications.

In our group we are investigating SiGe nanowires, so-called hut wires (HWs), via magneto-transport measurements. For the growth of the wires a molecular beam epitaxy system is used. Due to the Stranski-Krastanow growth mechanism, self-assembled hut clusters emerge after the deposition of a few monolayers of Ge. Such hut clusters elongate and form HWs with lengths up to 1 micrometer and above, after annealing them for a few hours. A particularly interesting feature of the HWs is that they are solely oriented along [100] and [010] [3], whereas the wire height and width remain constant below 2 and 20 nm, leading thus to very strong confinement. Finally, the wires are covered with a 5 nm thick Si cap and therefore get almost fully strained in lateral direction [4].

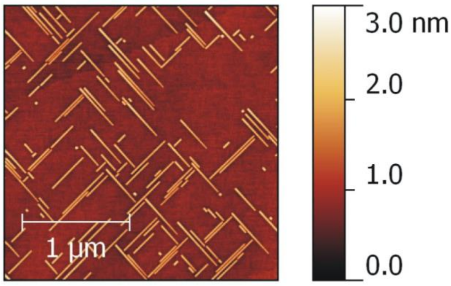


Figure: Atomic Force Micrograph of Ge HWs

Three terminal devices are created in order to be able to investigate the basic electronic properties of the quantum dots formed in such HWs. For the magneto-transport measurements, the devices are cooled down in a He3 refrigerator with a base temperature of about 250 mK. Single hole transport trough the quantum dot formed within the HWs can be observed. By performing magnetic field spectroscopy measurements, a considerably high anisotropy between the in-plane and out-of-plane g-factors is observed. Such has been predicted recently my Maier et al. [5]. A more systematic investigation of the g-factors additionally points out that there is a strong dependence of these g-factor values and anisotropies on the number of holes in the dot. We attribute our observations to a change of the wave function character from predominantly heavy hole like to more light hole like when the number of holes increases.

[1] Jie Xiang, Wei Lu, Yongjie Hu, Yue Wu, Hao Yan & Charles M. Lieber, Nature 04796 (2006)
[2] Wei Lu, Charles M. Lieber, J. Phys. D: Appl. Phys. 39 R387-R406 (2006)
[3] H. Watzinger, M. Glaser, J. J. Zhang, I. Daruka, and F. Schäffler, APL Materials 2, 076102 (2014)
[4] J. J. Zhang, G. Katsaros, F. Montalenti, D. Scopece, R. O. Rezaev, C. Mickel, B. Rellinghaus, L. Miglio, S. De Franceschi, A. Rastelli, and O. G. Schmidt, PRL 109, 085502 (2012)
[5] F. Maier, C. Kloeffel, and D. Loss, PRL B 87, 161305(R) (2013)

Thresholds and Majorana Modes for Surface Codes

James R. Wootton
University of Basel

The surface code is a quantum error correcting code that is well-known for its high noise threshold of $p_c = 1\%$ [1]. However, it is not clear what this means in terms of physically relevant quantities such as the T_1 and T_2 times, and the fidelities and operation times for entangling gates and measurements. Here we address this by considering the required resources for a proof-of-principle experiment, in which a logical qubit could be stored more reliably in the code than when stored in a single spin qubit. The minimum number of spin qubits required is found for different noise levels, finding the thresholds required for feasible system sizes.

We also generalize aspects of Kitaev's honeycomb lattice model [2] to generate a new class of codes, which we call `matching codes' [3]. These realize the same anyon model as the surface codes. However, they are particularly well suited to engineering twist defects that behave as Majorana modes. A proof of principle system that demonstrates the braiding properties of the Majoranas is discussed that requires only three qubits.

[1] A. G. Fowler et al., Phys. Rev. A 86, 032324 (2012).
[2] A. Kitaev, Ann. Phys. 321, 2 (2006).
[3] J. R. Wootton, J. Phys. A: Math. Theor. 48 215302 (2015).

Valley relaxation in graphene due to charged impurities

Péter Boross[1] and András Pályi[1,2]
[1]*Institute of Physics, Eötvös University, Budapest, Hungary*
[2]*MTA-BME Condensed Matter Research Group, Budapest University of Technology and Economics, Budapest, Hungary*

Monolayer graphene is an example of materials with multi-valley electronic structure. In such materials, the valley index is being considered as an information carrier. Consequently, relaxation mechanisms leading to loss of valley information are of interest.

Here [1], we calculate the rate of valley relaxation induced by charged impurities in graphene. A special model of graphene is applied, where the p_z orbitals are two-dimensional Gaussian functions, with a spatial extension characterised by an effective Bohr radius. We obtain the valley relaxation rate by solving the Boltzmann equation, for the case of noninteracting electrons, as well as for the case when the impurity potential is screened due to electron-electron interaction. For the latter case, we take into account local-field effects and evaluate the dielectric matrix in the random phase approximation.

Our main findings:
(i) The valley relaxation rate is proportional to the electronic density of states at the Fermi energy.
(ii) Charged impurities located in the close vicinity of the graphene plane, at distance less than 0.3 Å, are much more efficient in inducing valley relaxation than those farther away, the effect of the latter being suppressed exponentially with increasing graphene-impurity distance.
(iii) Both in the absence and in the presence of electron-electron interaction, the valley relaxation rate shows pronounced dependence on the effective Bohr radius. The trends are different in the two cases: in the absence (presence) of screening, the valley relaxation rate decreases (increases) for increasing effective Bohr radius.

This last result highlights that a quantitative calculation of the valley relaxation rate should incorporate electron-electron interactions as well as an accurate knowledge of the electronic wave functions on the atomic length scale.

[1] P. Boross and A. Pályi, arXiv:1502.05195

Cryogenic setup for hybrid spin-charge qubit characterization at 4 K

A. Crippa,[1,2] M. L. V. Tagliaferri,[1,2] S. Cocco,[2] M. De Michielis,[2] G. Ferrari,[3] E. Prati,[2,4] and M. Fanciulli[1,2]

[1]*Dipartimento di Scienza dei Materiali, Università di Milano-Bicocca, Via R. Cozzi 53, 20126 Milano, Italy*

[2]*Laboratorio MDM, IMM-CNR, Via C. Olivetti 2, 20864 Agrate Brianza (MB), Italy*

[3]*Dipartimento di elettronica e informazione, Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milano, Italy*

[4]*Istituto di Fotonica e Nanotecnologia, CNR, Piazza Leonardo da Vinci 32, 20133 Milano, Italy*

Exchange-only spin qubit represents the most compact solid-state architecture for quantum information purposes. Fast single electron manipulation requires the development of specific cryogenic electronics for high-fidelity transmission of nanosecond voltage pulses and for detection and amplification of the readout.

We report the development and characterization of a setup for electrical measurements at 4 K of multigate transistors for hybrid spin-charge qubit implementation. In such kind of qubit the information is encoded in the arrangement of 3 electrons in two dots combined with the 2+1 spin state [1]. The setup has been conceived to minimize the degradation of the carrier signals (DC, pulsed and RF) and maximize the signal-to-noise ratio of the device output.
Connectors, bias tees, printed circuit boards (PCBs) have been designed to guarantee optimal operability at 4 K. Input DC lines are low-pass filtered in proximity of the sample itself to preserve signal integrity as much as possible, whereas RF lines are sandwiched between two ground planes of the 6-layer PCB hosting the sample. Such lines are mutually shielded by fencing vias [2], which ensures a crosstalk lower than -50 dB below 3 GHz between adjacent lines. The golden-plated ground of the chip carrier is controllable by an independent DC line, thus acting as a back gate contact.
Up to four samples are wire-bonded to a custom CMOS circuit operating at 4 K. The circuit includes a multiplexer for a digital selection of the device under test and a low-noise transimpedence amplifier for current sensing (bandwidth of 30 kHz and equivalent input noise ~9 fA/Hz^1/2, limited by the PXI-Daq). The insertion of such detection electronics into the dewar reduces the input parasitic capacitance and the thermal noise contribution, boosting the performance respect to a standard amplifier kept at room temperature.
The RF dispersive readout technique senses the change in capacitance due to tunneling events in the quantum dot: it allows for detection of interdot transitions not accessible via transport measurements.

Our platform is designed to achieve GHz operability in order to control electron dynamics for exchange-only spin systems. Practically the electronic setup allows accurate all-electrical pre-characterizations at 4 K with the aim of identifying those samples suitable for further investigations at mK temperatures.

[1] E. Ferraro, M. De Michielis, G. Mazzeo, M. Fanciulli, and E. Prati, *Quantum Information Processing* **13**, 1-19 (2014).
[2] J. I. Colless and D. J. Reilly, *Rev. Sci. Instrum*. **83**, 023902 (2012).

Spin polarization in δ<Mn> InGaAs/GaAs light-emitting diodes

M.V. Dorokhin[1], Yu.A. Danilov[1], P.B. Demina[1], E.I. Malysheva[1], A.V. Zdoroveischev[1], A.V. Kudrin[1]

[1]*APhysico-Technical Research Institute, Lobachevsky State University of Nizhni Novgorod, 603950, Nizhni Novgorod, Russia*

Diodes emitting circularly-polarized light controlled by an applied magnetic field are one of the basic elements for spintronics [1]. Usually, spin-polarized carriers are electrically injected into the LED active region from a ferromagnetic (FM) layer [1,2]. The drawback of spin injection is the carriers spin scattering during the transfer from the FM layer to the active region [1]. This is specially critical for spin-LEDs based on hole injection [2]. An alternative is the device where the spin polarization of the carriers is generated directly in the active region due to the interaction with an adjacent ferromagnetic layer [3]. The proximity effect of a ferromagnetic layer on the carriers' spin polarization has been investigated for a number of structures [ex.3-5].

In this paper we present a detailed investigation of spin-LEDs consisting of an InGaAs/GaAs QW with a δ<Mn> layer inserted at the GaAs barrier close to the QW. Circularly-polarized photoluminescence (PL) and electroluminescence (EL) emissions from the LEDs were studied as a function of temperature and magnetic field.

The structures were fabricated by a two-stage epitaxial growth method. First, a thick n-GaAs buffer layer, 10 nm $In_xGa_{1-x}As$ QW (x = 0.16) and a thin undoped GaAs spacer layer (d_s = 2 - 10 nm) were grown subsequently at 650^{o}C on n^+- GaAs (001) substrates by metal-organic vapor phase epitaxy. At the next stage, the δ-doped <Mn> layer and the 10-30 nm GaAs cap layer were grown at 380-400^{o}C in the same reactor by laser sputtering of Mn and GaAs targets, respectively. The nominal Mn content in the δ-doped layer (Q_{Mn}) was varied from 0.1 to 0.3 monolayers. The Au contact was deposited on the top of the sample and back Ohmic contact was fabricated from the substrate side to form LED.

PL spectra were measured away from the top Au contacts using a 8 mW He-Ne laser. EL was collected from the back of the samples through the GaAs substrate which is transparent for the QW emission. For EL measurements, the LEDs were forward-biased with an operating current of 10 mA. The external magnetic field was applied along the normal to the QW plane (Faraday geometry). The measurement temperature was 10-100 K.

When a magnetic field is applied, both PL and EL emission become partly circularly polarized. The magnetic field-dependent circular polarization obtained from both photo- and electroluminescence follow the magnetic field dependence of a magnetization of δ<Mn> [5]. Depending on the growth parameters the EL/PL circular polarization shows an unusual sign inversion that can be explained by an interplay of the Zeeman splitting and Mn-hole interaction effects. Our results can help to understand the origin and control of the spin polarization on Mn doped GaAs structures, a fundamental step for the development of Mn-based spintronic devices.

[1] M. Holub and P. Bhattacharya, J. Phys. D: Appl. Phys. **40**, R179 (2007).
[2] D.K. Young, J.A. Gupta, E. Johnston-Halperin, et.al., Semicond. Sci. Tech. **17**, 275 (2002).
[3] R.C. Myers, A.C. Gossard and D.D. Awschalom, Phys.Rev. B. **69**, 161305(R) (2004).
[4] B.P. Zakharchenya and V.L. Korenev, Phys. Uspekhi. **48**, 603 (2005).
[5] O.V. Vikhrova, Yu.A. Danilov, M.V. Dorokhin, et.al., Tech. Phys. Lett. **35**, 643 (2009).

Growth and Characterization of τ-MnAl with Perpendicular Magnetic Anisotropy

J. Kally,[1] D. Rench,[1] J. S. Jeong,[2] K.-H Tu,[3] R. Wu,[2] K. A. Mkhoyan,[2] C. A. Ross,[3] and N. Samarth[1]

[1] *Dept. of Physics and Materials Research Institute, The Pennsylvania State University, University Park PA 16802*

[2] *Dept. of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis MN*

[3] *Dept. of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge MA*

The epitaxial stabilization of MnAl thin films in the τ-phase (tetragonal crystal structure) results in a metallic ferromagnet with a strong uniaxial out-of-plane magnetic anisotropy. The ensuing perpendicular magnetic anisotropy makes these films potentially attractive for energy efficient, high density magnetic memory applications. These thin films are also of contemporary interest for semiconductor spintronics since they can be integrated with III-V semiconductor devices. We describe the epitaxial growth of τ-MnAl films on (001) GaAs, as well as the characterization of their structural, magnetic and transport properties. Further, we demonstrate a route for nanopatterning τ-MnAl films into pillars of sub-100 nm scale diameter.

Thin films of τ-MnAl (~10-20 nm thickness) are prepared by molecular beam epitaxy on (001) GaAs at 250 ^{0}C. X-ray diffraction measurements show that these τ-phase films are under tensile strain caused by the 2% lattice mismatch with the GaAs substrate. High-resolution transmission electron microscopy images show a well-ordered crystal while energy dispersive spectroscopy confirms stoichiometric control of the composition. Magnetometry measurements reveal a very high coercively of 10 kOe, a saturation magnetization of 400 emu/cc and a uniaxial magnetic anisotropy constant K_u =10 Merg/cm^3 One of the important parameters that will determine the technological potential of these thin films is the spin polarization. To estimate this, we are carrying out measurements of the tunneling magnetoresistance in magnetic tunnel junctions that incorporate MnAl as one of the ferromagnetic layers. Finally, we show that a novel block-copolymer technique provides an effective pathway for fabricating hexagonal arrays of MnAl pillars with diameter 70 nm and period 90 nm. Magnetic force microscopy clearly shows single-domain states and SQUID magnetometry gives a coercivity of ~15kOe for the patterned array.

This work was supported by C-SPIN, one of six centers of STARnet, a Semiconductor Research Corporation program, sponsored by MARCO and DARPA.

Magneto-logic device using non-magnetic semiconductors at room temperature

Taeyueb Kim[1, 2], Sangsu Kim[1], Sungjin Kim[1], Jinki Hong[1*], Sungjung Joo[3], Jin Dong Song[4] and Joonyeon Chang[5]

[1]Department of Display and Semiconductor Physics, Korea University, Sejong, Korea
[2]Center for Spintronics, Korea Institute of Science and Technology, Seoul, Korea
[3]Center for Electricity & Magnetism, Korea Research Institute of Standards and Science, Daejeon, Korea
[4]Center for Opto-Electronic Materials and Devices, Korea Institute of Science and Technology, Seoul, Korea
[5]Post-Silicon Semiconductor Institute, Korea Institute of Science and Technology, Seoul, Korea
E-mail address: jkhongjkhong@korea.ac.kr

Recently, new type of transistor has been proposed in which electric switching function is manipulated by magnetism instead of electricity. Non-volatile reconfigurable processor is a logic device based on this magnetic switch, promising zero quiescent power and novel functions such as programmable logic operation and non-volatile built-in memory [1].

We investigate transport mechanism of these devices by the use of experimental and theoretical method. The characteristic feature of our devices comes from field dependent carrier generation and recombination in InSb or GaAs. The recombination process is highly dependent on the angle between the field direction and sample plane, and it also dependent on field polarity. The carrier recombination process is a core mechanism of the diode characteristics of our devices, which is maximized when the magnetic field is parallel to the sample plane. Thus, the present device can be considered as an electrical switch whose ON/OFF performance is controlled by both the polarity and the magnitude of magnetic field. In circuits composed of these switches, logical operations are programmed dynamically by magnetic signals, showing magnetic-field-controlled semiconductor reconfigurable logic at room temperature.

[1] Sungjung Joo, Taeyueb Kim, Sang Hoon Shin, Ju Young Lim, Jinki Hong, Jin Dong Song, Joonyeon Chang, Hyun-Woo Lee, Kungwon Rhie, Suk Hee Han, Kyung-Ho Shin & Mark Johnson, *Nature* 494, 72-76 (2013).

Pauli spin blockade in CMOS silicon double dots

Dharmraj Kotekar Patil[1], Romain Maurand[1], Andrea Corna[1], Xavier Jehl[1], Silvano de franceschi[1], Sylvain Barraud[2], Marc Sanquer[1]

[1]*CEA, INAC, SPSMS, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France*

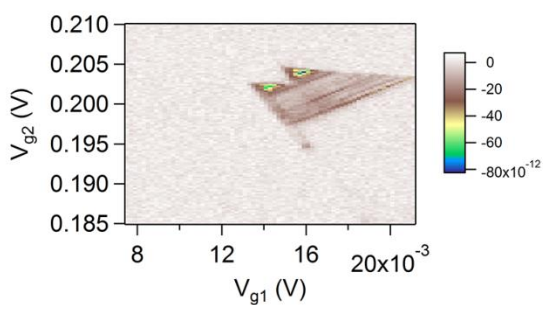
[2]*CEA, LETI, MINATEC Campus, 17 rue des Martyrs, 38054 Grenoble, France*

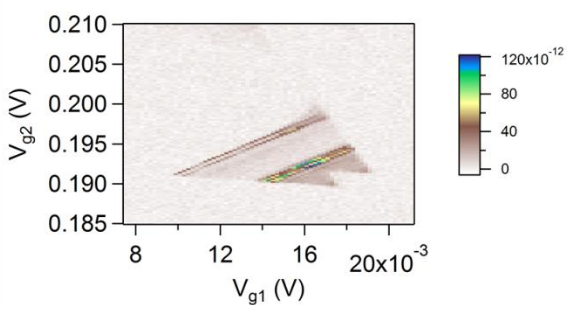
Double quantum dots in silicon are attractive candidate to encode quantum information. Long coherence times are expected in silicon due to absence of nuclear spin which is the main source of decoherence in III-V semiconductors. Here we report on tunable double quantum dot in silicon fabricated of CMOS platform using an Silicon-on-Insulator silicon nanowire (diameter ~ 10-15nm) with two front gates (length ~30nm) and a back gate. In the few electron regime, we observe Pauli spin blockade with relatively large singlet triplet spacing of approx. 1.6meV. In the spin blocked state we observe a leakage current at the bottom of bias triangle at the triple points of the stability diagram which can be suppressed by application of magnetic field. We attribute this leakage current to spin flip co-tunneling [2]. In the non-spin blockade state, we see bias triangles with very small inelastic tunneling which allows us to observe a clear excited state = few meV above the ground state. We attribute this excited state to the valley orbit splitting. This suggests that our quantum dots are larger than P donors [3] but smaller than previously reported double quantum dots in silicon [2][4]. Similar experiments are performed with double quantum dots with holes in silicon with preliminary results showing signatures of Pauli spin blockade.

[1] N. S. Lai, W. H. Lim, C. H. Yang, F. A. Zwanenburg, W. A. Coish, F. Qassemi, A. Morello, A. S. Dzurak, Scientific Reports 1, Article number: 110 (2011)

[2] B. Roche, E. Dupont-Ferrier, B. Voisin, M. Cobian, X. Jehl, R. Wacquez, M. Vinet, Y.-M. Niquet, and M. Sanquer, Phys. Rev. Lett. 108, 206812

[3] H. W. Liu, T. Fujisawa, Y. Ono, H. Inokawa, A. Fujiwara, K. Takashina, and Y. Hirayama Phys. Rev. B 77, 073310





Simulation of micro-magnet stray-field dynamics for spin qubit manipulation

R. Neumann, L. R. Schreiber
Quantum Technology Group, JARA-Institute for Quantum Information, RWTH Aachen University, Germany

An electron spin localized in a nuclear-spin free host material e.g ^{28}Si exhibits very long dephasing times beyond 10 ms and is thus suitable for representing a quantum bit [1]. Manipulation of such a qubit can be done all-electrically by electric dipole spin resonance. If silicon is used as the host material, a gradient magnetic field across the quantum dot is required, in order to strongly couple an AC electric field to the spin qubit [2]. This gradient magnetic field can be generated by a micro-magnet fabricated on top of the silicon sample. Thermal fluctuations of its magnetization, however, might limit the coherence time of the spin qubit.

Therefore, we simulated the thermal fluctuations of a cobalt micromagnet at 100 mK and in an external magnetic field of 500 mT by the stochastic Landau-Lifshitz-Gilbert equation [3]. For the simulations we used a typical device geometry (Fig. 1a) of a metallic gate defined double quantum dot in a Si/SiGe heterostructure with a cobalt micro-magnet on top. The geometry of the micro-magnet is equal to the one used in Ref. 4, in which a Rabi frequency beyond 100 MHz was demonstrated for an electron spin localized in GaAs/(Al,Ga)As. From the quantum noise spectral density of the magnetic stray-field at the position of the double quantum dot (Fig. 1b) the spin relaxation time T_1 and dephasing time T_2 of the spin qubit solely due to the stray-field fluctuations are calculated. While the micro-magnet fluctuations have only a small effect on the dephasing ($T_2 > 50$ s), it limits the qubit relaxation time. The shortest T_1 we calculated is 3 s. Furthermore, we investigated the balance between a high Rabi-frequency and the addressability error in a double dot hosting two qubits, i.e. the error due to off-resonant driving of the neighboring qubit [3]. The examined device enables a Rabi frequency of 15 MHz with an addressability error (probability of an unintentional spin flip of the neighboring qubit) below 10^{-3}. The addressability error can be further reduced by sophisticated pulse shaping.

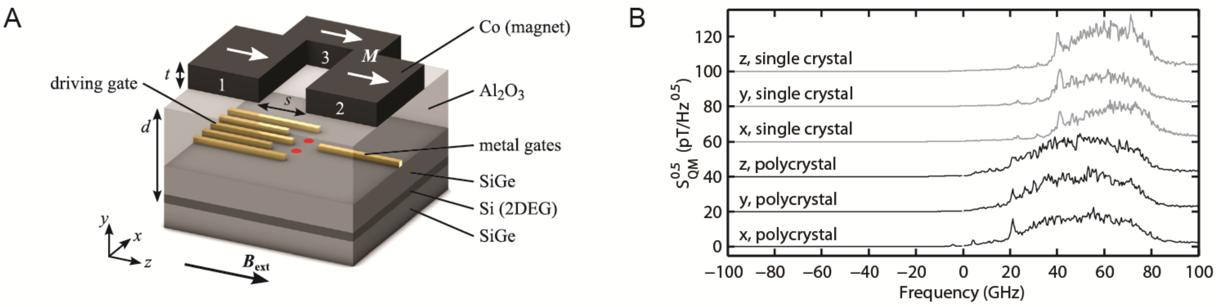


Fig. 1: (A) Electrostatically defined double quantum dot (red dots) in the Si/SiGe quantum well and Co micro-magnet geometry investigated. (B) Quantum noise spectral density components of the magnetic stray-field at the double dot position for a polycrystalline and single crystal Co magnet.

[1] M. Veldhorst *et al.*, Nat. Nanotechnol **9**, 981 (2014).
[2] E. Kawakami *et al.*, Nat. Nanotechnol. **9**, 666 (2014).
[3] R. Neumann *et al.*, accepted for publication in Journal of Applied Physics (2015).
[4] Yoneda *et al.*, Phys. Rev. Lett. **113**, 267601 (2014).

Spin-valley mediated Kondo effect in donor-silicon quantum dot

M.L.V. Tagliaferri,[1,2] A. Crippa,[1,2] M. De Michielis,[1] M. Fanciulli,[1,2] R. Wacquez,[3] M. Vinet,[3] and E. Prati[1,4]

[1] *Laboratorio MDM, CNR-IMM, via c. Olivetti 2, 20864 Agrate Brianza (MB) Italy*
[2] *Dipartimento di Scienza dei Materiali, Università di Milano Bicocca, via Cozzi 53, 20125 Milano, Italy*
[3] *CEA-LETI-MINATEC CEA-Grenoble, 17 rue des Martyrs 38054 Grenoble, France*
[4] *Istituto di Fotonica e Nanotecnologia, CNR, piazza Leonardo da Vinci 32, 20133 Milano, Italy*

Kondo states with SU(4) symmetry in quantum dots are of current interest [1]. Such symmetry emerges from the entanglement of the electronic spin and a pseudo-spin, which has been provided by charge [1] or orbital [2] degeneracies. Due to its intrinsic properties, i.e. the 6-fold valley degeneracy of the conduction band minima, silicon naturally allows for studies of Kondo effect beyond the standard Anderson model. At the nanoscale the degeneracy breaks down and the valley parity index behaves like a pseudo-spin.

Here we study a trigate field effect transitor (FET) fabricated on a phosphorous implanted (10^{18} cm^{-3}) silicon-on-insulator (SOI) wafer. The device channel is 20 nm long, 50 nm large and 8 nm thick. At 4.2 K we detect quantum transport mediated by a single P donor hybridized with a quantum dot strongly coupled with the reservoirs. The few electron regime is investigated through measurements of first and second order transport. Kondo effect emerges in the whole first spin-valley shell of silicon [3], giving an insight on the valley physics in silicon.
The asymmetry in the first peak and Coulomb diamond stems from the conservation of valley parity index during tunneling: only phenomena preserving this degree of freedom are allowed. The Kondo resonance is observable in non-equilibrium conditions: consistent with a small exchange interaction between states with opposite valley parity [4], the Kondo resonance appears only for electron with the same valley index.
The valley conservation rule losses its effectiveness when two electron reside in the donor, since the wave function is a composition of different valley parity indices. The small exchange interaction leads to a zero bias Kondo resonance. We observe thus a competitive mechanism between valley and spins degrees of freedom: tunneling allows for valley mixing, but exchange interaction between different valley indices weakens the spin-spin coupling. A two level Kondo effect is so expected.
These results provide an experimental confirmation of a weak exchange coupling between states with different valley parity and reinforce silicon as a suitable material for study on exotic Kondo manifestations.

[1] A. J. Keller et al., *Nature Phys.*, **10**, 145-150 (2014).
[2] A. Makarowski et al., *Phys. Rev. B*, **75**, 241407(R) (2007).
[3] A. Crippa et al., arXiv:1501.02665v2, (2015).
[4] M. Eto and Y. Hada, *AIP Conf. Proc.*, **850**, 1382-1383 (2006).

Lateral Quadruple Quantum Dot for Spin Qubit Applications

A. Bogan,[1,3] L. Bergeron,[2] L. Gaudreau[1,2], S. A. Studenikin[1], A. Kam[1],
P. Zawadzki[1], Z. Wasilewski[1], and A. Sachrajda[1]
[1]*National Research Council of Canada, Ottawa, Canada*
[2]*University of Sherbrook, Sherbrook, Quebec, Canada*
[3]*University of Waterloo, Waterloo, Ontario, Canada*

We present a lateral AlGaAs/GaAs based quantum dot nanostructure which is designed to be operated in the single, double, triple, and quadruple quantum dot regimes. Large arrays of such devices have been proposed as components of quantum information processors [1].

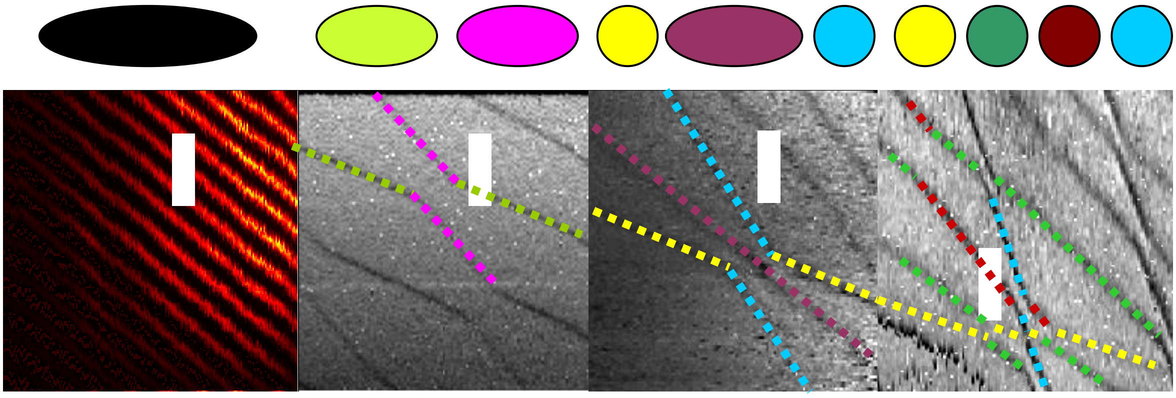


Figure 9: Transport (left) and charge stability diagrams of the device in four different configurations. Dashed lines highlight charge addition lines corresponding to each dot.

Lateral quantum dot nanostructures have evolved slowly from supporting single and double quantum dots, in which single and two-spin qubits have been studied in depth, to the triple quantum dot and the all-exchange qubit [2, 3]. Two different designs have emerged for the triple quantum dot. Each is optimized for the competing interests of scalability in the number of coupled dots [2, 4, 5] and tunability over a wide range of desirable conditions [3], allowing one to explore interactions between different encoding schemes in the same device.

We will demonstrate the device's flexibility by showing that it can be operated as one large dot, three different kinds of Double Quantum Dot (DQD), three kinds of Triple Quantum Dot (TQD), or a Quadruple Quantum Dot (QQD). Parameters of the device in several regimes will be discussed.

We also present two different approaches to finding the few electron regime while maintaining coupling to the leads. The first approach involves forming four large dots and depleting them of electrons. The second method involved creating two large dots, each of which is coupled to its own lead, and splitting them in the few-electron regime. We will discuss the problem of charge latching [6] and indirectly filling the central dots in both approaches.

[1] D. Loss, D. DiVincenzo, Phys.Rev. A 47, 120–126 (1998).
[2] Medford et. al. Phys. Rev. Lett. 111, 050501 (2013).
[3] L. Gaudreau et al., App. Phys. Lett. 95, 193101 (2009).
[4] F. R. Braakman et. al. Nature Nanotechnology 8, 432–437 (2013).
[5] T. Takakura et al., App.Phys.Lett. 104, 113109 (2014).
[6] Yang et. al., Appl. Phys. Lett. 105, 183505 (2014).

Dynamics of entanglement between two singlet-triplet qubits: role of nuclear spin baths and charge noise

Igor Bragar and Łukasz Cywiński
Laboratory for Cryogenic and Spintronic Research, Insitute of Physics, Polish Academy of Sciences, Warszawa, Poland

A singlet-triplet (*S*-*T*) qubits is a promising realization of a spin qubit [1], in which a quantum state of the qubit is stored in the joint spin state of two electrons located in two quantum dots. Specifically, the two states of the logical qubit are the singlet *S* and neutral triplet T_0 two-electron states. Recently it has been shown that it is possible in the experiment to perform a procedure of entangling of two *S*-*T* qubits [2]. However, the two-qubit states obtained in that experiment were not maximally entangled – due to the presence of environmental noise they were partially mixed.

We present a theoretical analysis of factors that do not allow for obtaining a maximally entangled state of two *S*-*T* qubits. In particular we consider the influence of fluctuations of gradient of effective magnetic field (the Overhauser due to the nuclei) between the two dots electrons in a qubit, ΔB_z, as well as fluctuations of the exchange splitting between *S* and T_0 states, *J*, on the efficiency of entangling procedure.

First we consider the influence of these two factors on free evolution decay (FID) signal as well as on echo signal of a single *S*-*T* qubit. It turns out that even quasistatic fluctuations of either ΔB_z or *J* lead to complete decay of the signal in the case of FID while in the case of spin echo experiment the signal is only lowered proportionally to the rms of quasistatic fluctuations.

The analysis of an entangling procedure of two qubits [2], in which a Hahn echo-like sequence of single-qubit rotations is employed in order to suppress the influence of environmental noise, shows that main obstacle to obtaining highly entangled states are fluctuations of two-qubit coupling, $J_{12} \sim J_1 J_2$, which are not removed by two-qubit echo. We will present analytical and numerical calculations of decoherence caused by fluctuations of J_1 and J_2 caused by random telegraph and 1/f-like charge noise.

This research is supported by funds of Polish National Science Center (NCN), grant no. DEC-2012/07/B/ST3/03616.

[1] J. R. Petta et al., Science **309,** 2180 (2005).
[2] M. D. Shulman et al., Science **336**, 202 (2012).

Control of the hybridization of an arsenic excited state in a silicon nanowire transistor

A. Corna[1], D. Kotekar-Patil[1], R. Maurand[1], R. Lavieville[2], S.Barraud[2], X. Jehl[1], S. De Franceschi[1], and M. Sanquer[1]

[1]*Université Grenoble Alpes, INAC-SPSMS, F-38000 Grenoble, France and CEA, INAC-SPSMS, F-38054 Grenoble, France*
[2] *Université Grenoble Alpes, F-38000 Grenoble, France and CEA, LETI MINATEC campus, F-38054 Grenoble, France*

The ability to couple a surface state with a donor wavefunction is a keypoint for donor electronics [1] and donor-based spin qubits [2]. Here we investigate such a coupling in a silicon transistor conduction channel embedding an arsenic donor.
The samples, fabricated on 300-mm silicon-on-insulator (SOI) wafers, are similar to those described in [3]. A 12-nm-thick and 45-nm-wide silicon nanowire was etched from the SOI layer and covered at its center by a 55 nm long TiN-polysilicon gate with a SiO_2-HfSiON insulating layer. This front gate covers three sides of the silicon channel. A 145-nm-thick buried oxide separates the channel from the silicon substrate, which can be biased to apply a controlled electric field perpendicular to the channel.
We studied the source-drain conductance as a function of the front- and back-gate voltages (Vfg and Vbg, respectively) at T=4.2K. In figure 1, we can see an isolated line, which we attribute to tunneling through an isolated donor diffused into the channel. This line anti-crosses the conduction band in two points. We performed a tunnel spectroscopy by measuring differential conductance as a function of source-drain bias and gate voltage (not shown). We identify an excited state 10 – 20 meV above the ground state. The gate-dependent excitation energy, ΔE, is shown in figure 2. The lowest ΔE values are located at the anticrossing points, where donor states and interface states are more strongly hybridized [4][5].
We thank support from the EU under projects TOLOP, SiAM and SISPIN.

[1] F. A. Zwanenburg *et al*, Rev. Mod. Phys. 85, 961 (2013).
[2] B.E. Kane, Nature **393**, 133-137 (1998).
[3] B. Voisin *et al*, Nano Lett., **2014**, 14 (4), pp 2094–2098.
[4] R. Rahman *et al*, Phys. Rev. B **80**, 165314 (2009).
[5] G. P. Lansbergen *et al*, Nature Physics **4**, 656 - 661 (2008).

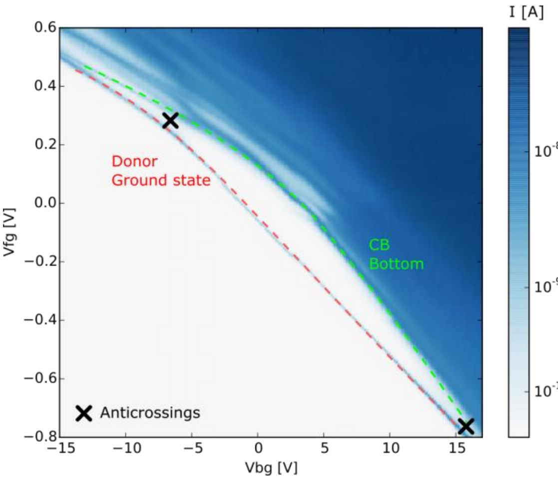


Figure 1: Current as function of the two gates at 4.2 K

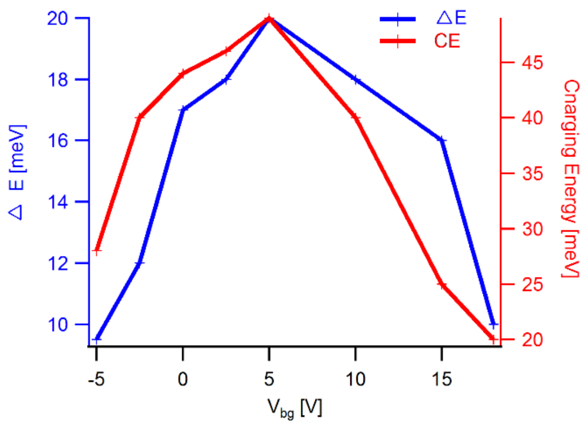


Figure 10: Energy of donor excited state and charging energy

The impact of nuclear spin dynamics on electron transport through donors

S. K. Gorman,[1] M. A. Broome,[1] W. J. Baker,[1] and M. Y. Simmons[1]
[1]*Centre of Excellence for quantum computation and communication technology, School of Physics, University of New South Wales, New South Wales, Australia*

Electron transport through single donors in silicon has been proposed as a coherent spin transport protocol for on-chip shuttling of quantum information [1]. The spin dynamics of such a chain of donors is an extremely complicated system with many competing interactions: Zeeman, hyperfine, and exchange. In order to understand the complex dynamics of such a system it is easier to examine the smallest unit - a two donor system in transport, see Fig. (a). Here, we present an analysis of electron transport through two weakly coupled precision placed phosphorus donors in silicon. In particular, we examine the (1, 1) ←→ (0, 2) charge transition where we predict a new type of current blockade driven entirely by the nuclear spin dynamics.

The impact of the nuclear spins can be seen after an ESR excitation in Fig (b). At low magnetic fields the current drops rapidly. This is nuclear spin blockade (NSB). Using this nuclear spin blockade mechanism we devise a protocol to readout the state of single nuclear spins using electron transport measurements only, see Fig. (c). We extend our model to include realistic effects such as Stark shifted hyperfine interactions and multi-donor clusters. In the case of multi-donor clusters we show how nuclear spin blockade can be alleviated allowing electron spin transport.

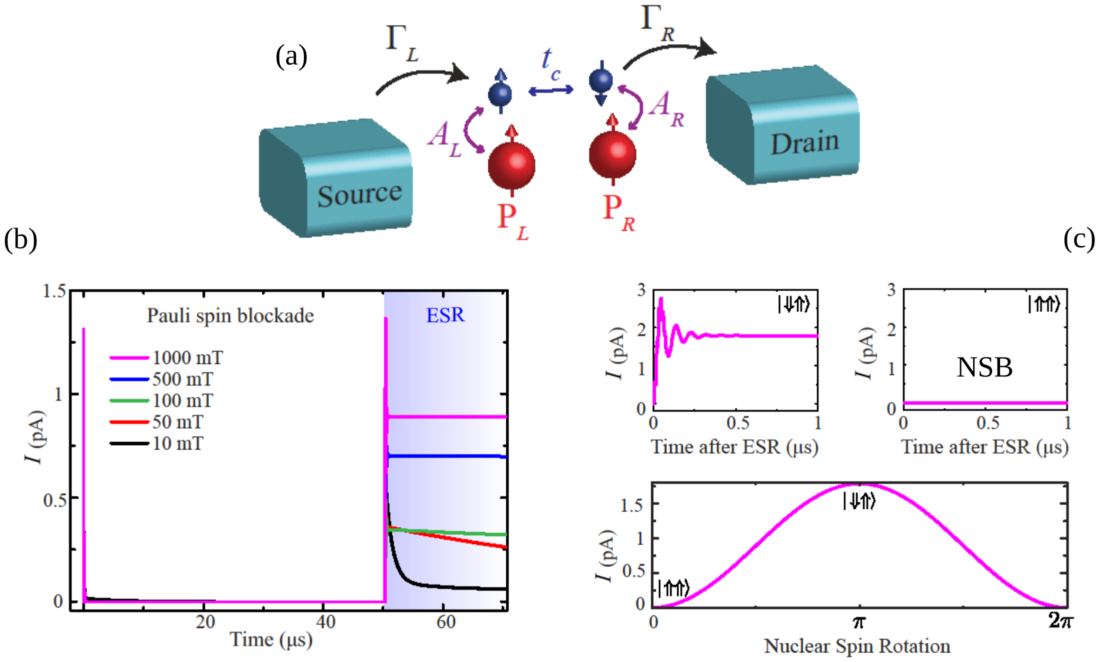


FIG (a) A schematic representation of transport through a double donor system during Pauli spin blockade. Electrons can tunnel from the source to the phosphorus donor nuclei (red), P_L and from P_R to the drain at rates Γ_L and Γ_R, respectively. The two donor electrons (blue) are coherently tunnel coupled at the rate, t_c and have a contact hyperfine interaction with the nuclear spins, A_L and A_R with their respective nuclei. (b) The current through a double donor showing Pauli spin blockade and nuclear spin blockade after an ESR excitation for low magnetic fields. (c) The dependence of the current on the orientation of the nuclear spins at high magnetic fields used for nuclear spin readout.

[1] A. J. Skinner, M. E. Davenport, B. E. Kane, Phys. Rev. Lett., 90:087901, 2003

In-plane magnetoconductance fluctuation due to spin-orbit interaction

Y. Iwasaki,[1] Y. Hashimoto,[1] T. Nakamura,[1] Y. Iye,[1] and S. Katsumoto[1]
[1]*The Institute for Solid State Physics, The University of Tokyo,*
5-1-5 Kahiwa-no-ha, Kashiwa, Chiba, Japan 277-8581

Spin-orbit interaction (SOI) in two-dimensional (2D) systems works as an effective magnetic field on electron spins and in some cases causes spin precessions. Since in-plane magnetic field modulates such precessions and phase of spin-part wavefunction, conductance fluctuation (CF) versus in-plane magnetic field reflects local spin motion and corresponding local spin-orbit field [1]. We report here angular dependence of CF, which reflects local spin-orbit field.

Quantum point contacts (QPC) as injectors/detectors were fabricated on an InAs quantum well (Fig.1(a)) with the electron concentration 1.21×10^{12} cm^{-2} and the mobility 66000 cm^2/Vs. From the modulation in the Shubnikov-de Haas oscillation, the Rashba strength was estimated as 3.6×10^{-11} eVm [2]. The experiment was conducted at T=135 mK in a dilution refrigerator. Figure 1(b) shows the two-terminal conductance between the electrodes 2 and 5 indicated in Fig.1(a) as a function of in-plane magnetic field B. A clear dip at B = 0 and fluctuating pattern at high B were observed. The fluctuation was symmetric to B = 0 and reproducible for several different sweeps while it diminished at 4.2 K, manifesting its origin as a quantum interference phenomenon. Additionally we rotated in-plane B and observed the angular dependence of CF amplitude (Fig.1(b) upper panel) where the conductance variance took minimum at $\theta = 0$ (x-oriented) and maximum at $\theta=\pi/2$ (y-oriented) (Fig.1(c)). This result is consistent with the fact that the SOI effective magnetic field B_{SOI} is oriented to y-axis in this sample. Also the CF amplitude depended on the path of electrons (Fig.1(b) lower panel); the straight path (between contacts 5 and 2) provided the highest CF variance while the wound path (between contacts 5 and 4) did the lowest CF variance. This is attributed to the semi-ballistic nature of the electron propagation and distribution of injection/detection momentum.

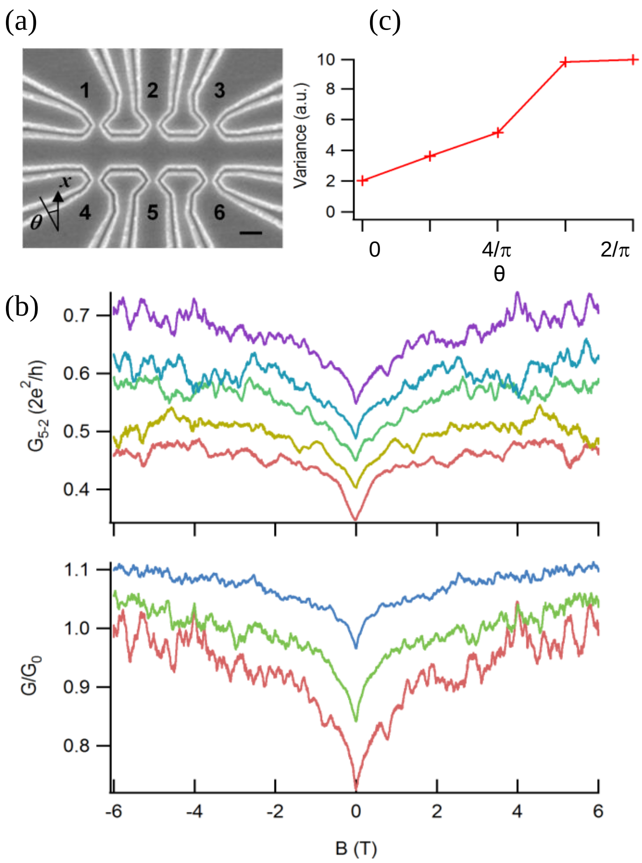


Figure 1: (a) The SEM image of sample. Scale bar is 1μm. (b) upper panel: in-plane B dependence of conductance G between contacts 5 and 2 in the unit of $2e^2/h$. The offset corresponds θ (rotation angle of B) changing from 0 (bottom) to π/2 (top). lower panel: G between contacts 5 and 2 (bottom), 5 and 1 (middle), 5 and 4 (top) with $\theta = \pi/2$, normalized by values at B=-6.0 T (G_0). (c) Conductance variance versus θ calculated from (b). Data from B=-6.0 T to -1.5T were used after subtracting the background.

[1] M. Scheid, I. Adagideli, J. Nitta and K. Richter, Semicond. Sci. Tech. 24, 064005 (2009).
[2] J. Nitta, T. Akazaki, H. Takayanagi and T. Enoki, Phys. Rev. Lett. 78, 1335 (1997).

Clean Graphene Nanoribbons with Crystallographic Edges

Y. B. Kalyoncu, M. Rehmann, D. Hug, S. Zihlmann, L. Marot and D. M. Zumbuhl
Swiss Nanoscience Institute (SNI) and Department of Physics, University of Basel

Graphene has attracted a lot of interest as an extraordinary material for fundamental research and applications. Graphene nanoribbons (GNRs) are of particular interest as a playground for novel quantum states: in ribbons with crystallographic zigzag (zz) edge termination, ferromagnetic order of electron spins localized on the edge has been predicted [1], with spins at opposite ribbon edges pointing potentially in opposite directions due to inter-edge exchange. In armchair GNRs, on the other hand, theory has predicted that a giant spin-orbit coupling can be artificially induced with an adjacent array of nanomagnets [2], opening the door for helical states and topological phases sustaining Majorana fermions.

Fabricating clean GNRs with high quality crystallographic edges is very challenging. We use a technique employing a cold remote hydrogen plasma [3] which exhibits highly anisotropic etching yielding hexagonal shaped etch pits with zz edges. When a nitrogen plasma is used instead of a hydrogen plasma, armchair edges should result [4]. Here, we present an experimental characterization of the remote plasma process on graphite flakes, and we show how the process can be made to work also on single layer graphene. Further, in combination with ebeam lithography, we define clean zigzag graphene nanoribbons on a hexagonal boron nitride crystal (see Fig. 1), which are characterized with atomic force microscopy, micro-Raman spectroscopy and by performing electronic transport spectroscopy at temperatures down to 1.5 K. The transport data suggests ballistic 1D subbands exhibiting quantized conductance plateaus when sweeping back gate voltage, serving as a starting point for studying edge (anti)ferromagnetism and helical states in GNRs.

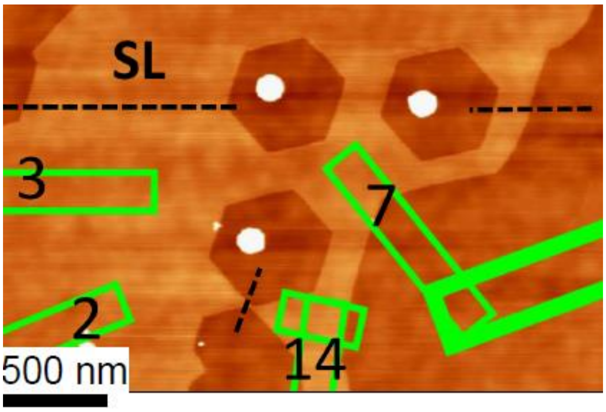


Figure 11 : AFM image of single-layer graphene device on a hexagonal boron nitride crystal. Nanoribbons are formed from adjacent hexagonal etch pits created with a remote hydrogen plasma. Contacts are outlined in green. Along the black dashed lines, graphene was removed with an oxygen ion plasma to prevent short circuiting.

[1] Y.-W. Son, M. L. Cohen, and S. G. Louie, Nature 444, 347 (2006).
[2] J. Klinovaja and D. Loss, Phys. Rev. X 3, 011008 (2013).
[3] R. Yang, L. Zhang, Y. Wang, Z. Shi, D. Shi, H. Gao, E. Wang, G. Zhang, Adv. Mat. 22, 4014 (2010).
[4] B. McCarroll and D. W. McKee, Carbon 9, 301 (1971).

Impurity states induced by transition metals in ZnTe(110) surface

Ken Kanazawa, Taku Nishimura, Shoji Yoshida, Hidemi Shigekawa and Shinji Kuroda
Grad. School of Pure & Appl. Sci., Univ. of Tsukuba, Tsukuba, Japan

Study on diluted magnetic semiconductors (DMSs), which consist of host semiconductors and dopants of transition-metal (TM) atoms, has been energetically performed because of their possibility of application to future spintronic devices. From the viewpoint of technological applications in the new research field of nanotechnology combined with magnetism, it is important to investigate magnetic behaviors of materials down-sized to the atomic scale on the semiconductor surface. Scanning tunneling microscopy / spectroscopy (STM / STS) is one of the most powerful methods of studying such TM impurity states at a single-atom scale. Here, we performed STM/STS study on TM atoms adsorbed on a ZnTe(110) surface.

We prepared a ZnTe(110) clean surface as a substrate by cleaving a single crystal p-type ZnTe(100) wafer (P-doped, ~1×10^{18} cm^{-3}) in a high vacuum (~10^{-5} Pa). We deposited Cr atoms on the surface at room temperature by the electron beam deposition method. All STM and STS measurements were performed in an ultrahigh vacuum (~1×10^{-9} Pa) at a liquid nitrogen temperature (~80 K) using an electrochemically sharpened W tip (ϕ= 0.3 mm).

After the adsorption of Cr atoms, a large number of small protrusions with bright contrast corresponding to Cr atoms were observed. A typical STM image of adsorbed Cr atoms at a negative sample bias viltage is shown in Fig. 1(b). Comparing with the results of our previous cross-sectional STM study for MBE-grown (Zn,Cr)Te [1], we concluded that the bright points correspond to Cr atoms substituting for Zn atoms in the first layer of the surface. Next, in order to investigate the impurity states, we carried out STS measurements above a substitutional Cr atom. Figure 2 shows the differential conductance (d*I*/d*V*) -*V* spectra, which correspond to the energy dependence of the local density of states (LDOS), obtained at the positions over areas with and without Cr atoms. The spectrum obtained over the area without Cr was almost zero in the bias voltage range -0.7 V < V_s < 2.2 V, reflecting the electronic states of a p-type semiconductor substrate. On the other hand, the d*I*/d*V* spectrum measured around the Cr atoms exhibited a larger d*I*/d*V* than that obtained over the area of ZnTe without Cr in the small bias region. This result shows the existence of several Cr impurity states within the bandgap of the host ZnTe.

[1] K. Kanazawa et al., Nanoscale 6, 14667 (2014).

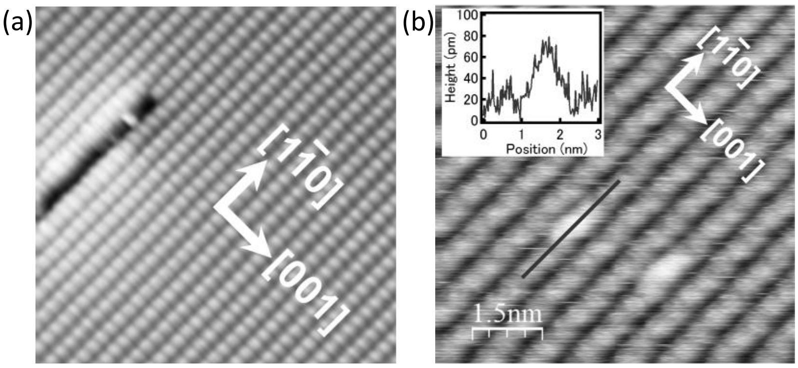


Fig. 1 High-resolution STM images of (a) the cleaved ZnTe(110) surface and (b) Cr atoms adsorbed on the surface. The inset of (b) shows the line profile measured along the line in the STM image.

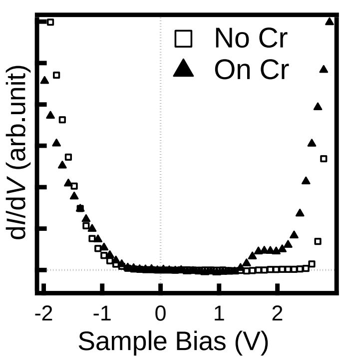


Fig. 2 Differential conductance (d*I*/d*V*) –*V* curves obtained over areas with and without Cr atoms.

Voltage induced conversion of helical to uniform nuclear spin polarization in a quantum wire

Viktoriia Kornich,[1] Peter Stano,[2] Alexander A. Zyuzin[1], and Daniel Loss[1,2]
[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2]*RIKEN Center for Emergent Matter Science, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

We study the effect of bias voltage on the nuclear spin polarization of a ballistic wire, which contains electrons and nuclei interacting via hyperfine interaction. In equilibrium, the localized nuclear spins are helically polarized due to the electron-mediated Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction. Focusing here on nonequilibrium, we find that an applied bias voltage induces a uniform polarization, from both helically polarized and unpolarized spins available for spin flips. Once a macroscopic uniform polarization in the nuclei is established, the nuclear spin helix rotates with frequency proportional to the uniform polarization. The uniform nuclear spin polarization monotonically increases as a function of both voltage and temperature, reflecting a thermal activation behavior. Our predictions offer specific ways to test experimentally the presence of a nuclear spin helix polarization in semiconducting quantum wires.

Extending coherence of S-T_0 qubits using symmetric exchange gates synchronized to nuclear spin evolution

Filip K. Malinowski[1], Frederico Martins[1], Peter D. Nissen[1], Michael J. Manfra[2]
Charles M. Marcus[1], Ferdinand Kuemmeth[1]
[1]*Center for Quantum Devices, Niels Bohr Institute, Univ. of Copenhagen, 2100 Copenhagen, Denmark*
[2]*Dept. of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA.*

Spin qubits based on few electron quantum dots in GaAs/AlGaAs heterostructures are one of the most promising systems suitable for quantum computation. In singlet-triplet qubits exchange oscillations are traditionally implemented by tilting the (1,1) charge state away from the symmetry charge configuration ("detuning"), thereby temporarily hybridizing with the (0,2) charge state. However, the resulting qubit evolution suffers from an approximately exponential sensitivity to detuning noise, motivating operation at sweet spots [1] or in the multi-electron regime [2].

Here we demonstrate rapid, high-quality exchange oscillations that are to first order insensitive to detuning noise. This is accomplished by applying nanosecond pulses to the middle gate ("barrier"), thereby inducing symmetric tunneling to both (2,0) and (0,2). Unlike detuning-induced qubit rotations, the coherence of barrier-induced rotations is not limited by electrical noise, but by nuclear spin fluctuations parallel to the applied magnetic field.

Implementing dynamic decoupling sequences based on symmetric exchange gates we efficiently decouple the S-T_0 qubit from longitudinal nuclear spin fluctuations. At high magnetic fields we find that qubit dephasing (exceeding tens of microseconds) is limited by transverse nuclear spin fluctuations, similar to what has been observed at intermediate magnetic field [3]. We further increase the qubit coherence by exploiting a modified CPMG sequence in which the spacing between π pulses is locked to particular differences of nuclear spin precession times (^{69}Ga, ^{71}Ga, ^{75}As). By applying up to 3000 π pulses we observe coherence times in excess of 700 μs, five orders of magnitudes longer than a the duration of a single π rotation.

Research is supported by IARPA through the MQCO Program, and the Danish National Research Foundation.

[1] O. E. Dial et al. Phys. Rev. Lett. **110**, 146804 (2013).
[2] A. P. Higginbotham et al. Phys. Rev. Lett. **112**, 026801 (2014).
[3] H. Bluhm et al. Nature Physics **7**, 109 (2011).

Time-resolved measurement of Overhauser fields using a singlet-triplet qubit

Frederico Martins[1], Filip K. Malinowski[1], Peter D. Nissen[1], Michael J. Manfra[2]
Charles M. Marcus[1], Ferdinand Kuemmeth[1]

[1]*Center for Quantum Devices, Niels Bohr Institute, Univ. of Copenhagen, 2100 Copenhagen, Denmark*
[2]*Dept. of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA.*

In materials with nonzero nuclear spins, such as GaAs, the random orientation of nuclear spins produces a fluctuating effective Zeeman field (Overhauser field) that directly couples to electron spins. In gate-defined double quantum dots, the resulting Zeeman gradients is on the scale of millitesla, enough to induce qubit evolution, motivating work on understanding the dynamics of Overhauser field gradients [1] and using them for coherent qubit control [2].

Here we use the time evolution of a GaAs singlet-triplet qubit as a sensitive probe of Overhauser field gradients. Repeated high fidelity single shoot measurements of the qubit allows us to monitor Overhauser fluctuations in real time. By combining different types of qubit dephasing protocols we obtain spectral density of the fluctuating Overhauser field over a wide frequency range, from 10^{-3} Hz up to 10^{2} Hz.

This power spectrum is extended by studying the scaling of the coherence time T_2 obtained via Carr-Purcell-Meiboom-Gill (CPMG) pulse sequences, similar to [3], but with up to 256 π rotations at various magnetic fields.

With both techniques, covering a frequency range over 6 orders of magnitude, we find that the spectrum of the Overhauser field cannot be described by a simple power law. We show that the exponent of power-law model depends on frequency and magnetic field. Furthermore, at high-magnetic field, we observe spectral weight at discrete frequencies related to nuclear Larmor frequencies of 69Ga, 71Ga and 75As, with important implications for achieving long electron spin coherence in this material.

Research is supported by IARPA through the MQCO Program, and the Danish National Research Foundation.

[1] D. J. Reilly, J. M. Taylor, E. A. Laird, J. R. Petta, C. M. Marcus, M. P. Hanson, and A. C. Gossard Phys. Rev. Lett., 101, 236803 (2008).

[2] S. Foletti, H. Bluhm, D. Mahalu, V. Umansky, Amir Yacoby, Nature Physics **5**, 903 - 908 (2009)

[3] J. Medford, L. Cywinski, C. Barthel, C. M. Marcus, M. P. Hanson, A. C. Gossard, Phys. Rev. Lett. 108, 086802 (2012).

Anomalous Hall effect and persistent current due to spin chirality in a diffusive regime

Kazuki Nakazawa, Hiroshi Kohno
Department of Physics, Nagoya University, Nagoya, Japan

Anomalous Hall effect (AHE) in ferromagnetic metals has been known to arise as a combined effect of magnetization (exchange splitting) and spin-orbit coupling (SOC) after the works by Karplus, Luttinger and Smit in 1950s [1,2]. Later in 1990s, another mechanism was found by Ye *et al*. for systems with a non-coplanar spin configuration having spin chirality; in such systems, the spin chirality gives a Berry phase to electrons through the exchange interaction and leads to AHE [3].

Subsequently, Tatara and Kawamura showed that AHE can result without the concept of Berry phase by treating the exchange coupling perturbatively [4]. They considered a model with discretely-distributed quenched spins, and calculated the anomalous Hall (AH) conductivity for the case that the distance r between the localized spins is shorter than the electron's mean free path l (ballistic regime). As a physical picture of this chirality-induced AHE, Tatara suggested a (equilibrium) persistent current around the spin chirality in the ballistic regime [5].

In this work, we extend the previous works [4,5] to the diffusive regime ($r > l$) by considering vertex corrections due to normal impurities [6]. This amounts to electron's diffusive motion as well as spin conservation at each scattering from the normal impurity, and leads to an expression of the AH conductivity which respects spin conservation. We also investigate the persistent current in the diffusive regime, and show that the "typical" value of the persistent current reproduces the AH conductivity in the diffusive regime [6].

[1] R. Karplus and J. M. Luttinger, Phys. Rev. **95** (1954) 1154.
[2] J. Smit, Physica **21** (1955) 877.
[3] J. Ye *et al.*, Phys. Rev. Lett. **83** (1999) 3737.
[4] G. Tatara and H. Kawamura, J. Phys. Soc. Jpn. **71** (2002) 2613.
[5] G. Tatara and H. Kohno, Phys. Rev. B **67** (2003) 113316.
[6] K. Nakazawa and H. Kohno, J. Phys. Soc. Jpn. **83** (2014) 073707.

Evidence for Helical Nuclear Spin Order in GaAs Quantum Wires

T. Patlatiuk, C.P. Scheller[1], T.-M. Liu[1], G. Barak[2], A. Yacoby[2],
L.N. Pfeiffer[3], K.W. West[3], D.M. Zumbühl[1]

[1] *Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2] *Department of Physics, Harvard University, Cambridge, Massachusetts 02183, USA*
[3] *Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA*

The conductance of the first mode reaches 2e2/h at high temperatures T>10K, as expected. As T is lowered, the conductance is gradually reduced to 1e2/h [1], becoming T independent at T≤0.1K, while the device cools far below 0.1K. This behavior is seen in several wires, is independent of density, and not altered by moderate magnetic fields B. The conductance reduction by a factor of two suggests lifting of the electron spin degeneracy in the absence of B. Our results are consistent with theoretical predictions [2] for helical nuclear order in the Luttinger liquid regime.

Currently different methods are investigated to get more direct access to the helical nuclear order. In particular, resistively detected NMR, tunneling spectroscopy and non-local spin detection potentially allow measuring the nuclear polarization, the partially gapped electronic dispersion and the polarized electrons ejected from the nuclear helimagnet, respectively.

[1] C.P. Scheller, T.-M. Liu, G. Barak, A. Yacoby, L.N. Pfeiffer, K.W. West, and D.M. Zumbühl, Possible Evidence for Helical Nuclear Spin Order in GaAs Quantum Wires, Phys. Rev. Lett 112, 066801 (2014)

[2] B. Braunecker, P. Simon, and D. Loss, Nuclear magnetism and electron order in interacting one-dimensional conductors, Phys. Rev. B 80, 165119 (2009)

A Tight-Binding Approach to Strain in Monolayer Transition-Metal Dichalcogenides

Alexander J Pearce and Guido Burkard
Department of Physics, University of Konstanz, D-78464 Konstanz, Germany

We present a model of the electronic properties of strained monolayer transition-metal dichalcogenides (e.g. MoS_2, $MoSe_2$, WSe_2 etc) based on a tight binding approach. Mechanical deformations of the lattice offer a powerful route for tuning the electronic structure of transition-metal dichalcogenides, as modifications of atomic bond lengths lead directly to corrections in the electronic Hamiltonian.[1]

Firstly, we present effective low energy Hamiltonians for both the K and Γ high symmetry points of the Brillouin zone. Then we introduce the corrections to these Hamiltonians due to any arbitrary in-plane mechanical deformation. We find that the application of uniaxial strain allows for tuning of the band gap at both high symmetry points considered and most dramatically also allows cross-over to an indirect band gap which has been observed in experiments.[2,3,4] We also see modifications of the band effective masses with consequences for many optical and electronic properties of the system.

[1] H. Suzuura and T. Ando, Phys. Rev. B 65 235412 (2002).
[2] K. He, C. Poole, K.F. Mak and J. Shan, Nano Lett. 13, 2931 (2013).
[3] H.J. Conley, B. Wang, J.I. Ziegler, R.F. Haglund Jr., S.T. Pantelides and K.I. Bolotin, Nano. Lett. 13, 3626 (2013).
[4] C.R. Zhu, G. Wang, B.L. Liu, X. Marie, X.F. Qiao, X. Zhang, X.X. Wu, H. Fan, P.H. Tan, T. Amand and B. Urbaszek, Phys. Rev. B 88, 121301(R) (2013).

Progress towards THz-Frequency Antiferromagnetic Spin Pumping

Gregory M. Stiehl,[1] Jared Strait,[1] Amit KC,[2] John T. Heron,[1] Darrell G. Schlom,[1] David Lederman,[2] Farhan Rana,[1] and Daniel C. Ralph[1]
[1]*Cornell University, Ithaca, NY 14853*
[2]*Department of Physics and Astronomy, West Virginia University, Morgantown, VA 26506*

Can spin-transfer torque from an applied spin current be used to manipulate or excite spin dynamics within an antiferromagnet? Because antiferromagnets have a weak susceptibility to magnetic fields and THz resonant frequencies, this is simultaneously both a difficult and potentially fruitful question to pursue. Recent theoretical predictions [1] have suggested studying the Onsager reciprocal to spin-transfer torque, known as spin-pumping, as a potential route forward.

Here, we present progress on THz-frequency antiferromagnetic spin pumping measurements. Antiferromagnetic moments in crystalline antiferromagnet insulator / polycrystalline platinum bilayers are driven into resonance by a coherent THz source, and we attempt to detect spin pumping from the antiferromagnet to the Pt by measuring a DC voltage generated by the inverse spin Hall effect in the Pt. We are exploring a variety of materials (both rock salt and fluoride antiferromagnets) and crystal orientations.

[1] R. Cheng, J. Xiao, Q. Niu and A. Brataas, *Phys. Rev. Lett.* **113**, 057601 (2014)

Spin-dependent Andreev transport through a triple quantum dot system

Kacper Wrześniewski and Ireneusz Weymann
Faculty of Physics, Adam Mickiewicz University in Poznań,
ul. Umultowska 85, 61-614 Poznań, Poland

We analyze the spin-resolved Andreev transport through a triple quantum dot coupled to superconducting and ferromagnetic electrodes. The results are obtained by means of the real-time diagrammatic technique in the sequential tunneling regime with respect to the coupling to ferromagnetic leads, while the coupling to superconductor is treated exactly. We analyze the behavior of the Andreev current, the corresponding differential conductance and the tunnel magnetoresistance in both the linear and nonlinear response regimes. It is shown that the Andreev current can be suppressed in certain transport regimes, leading to negative differential conductance. Moreover, negative tunnel magnetoresistance and breaking of the symmetry with respect to bias reversal are also observed. The mechanisms leading to those non-trivial transport characteristics, and their dependence on the parameters of the model, are discussed in detail.

Three-dimensional magnetic architectures studied with X-PEEM

M. Wyss,[1,*] A. Kleibert,[2] A. Farhan,[3,4] A. Buchter,[1] B. Gross,[1] A. Mehlin,[1] D. Rüffer,[5] F. Matteini,[5] G. Tütüncüoglu,[5] F. Heimbach,[6] A. Fontcuberta i Morral,[5] D. Grundler,[6,7] and M. Poggio[1]

[1]*Departement of Physics, University of Basel, 4056 Basel, Switzerland*

[2]*Swiss Light Source, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland*

[3]*Laboratory for Micro- and Nanotechnology, Paul Scherrer Institute, Switzerland*

[4]*Laboratory for Mesoscopic Systems, Department of Materials, ETH Zürich, 8093 Zürich, Switzerland*

[5]*Laboratoire des Matériaux Semiconducteurs, EPFL, 1015 Lausanne, Switzerland*

[6]*Lehrstuhl für Physik funktionaler Schichtsysteme, Physik Department E10, Technische Universität München, James- Franck-Str. 1, 85748 Garching, Germany*

[7]*Faculté des Sciences et Techniques de l'Ingénieur STI, EPFL, 1015 Lausanne, Switzerland*

In three-dimensional magnetic architectures, vortex states are of strong contemporary interest since they produce much lower stray fields than uniform states; as a result, they minimize magneto-static interactions between nanomagnets and therefore may find application in densely packed magnetic memories or as magnetic sensors. Theoretical calculations predict the existence of complex low-field magnetic configurations including vortex-like domain walls in ferromagnetic nanotubes (NTs) [1]. However, their experimental realization in three-dimensional systems is not trivial. Depending on the orientation of the applied magnetic field relative to the NTs, magnetic states in three-dimensional structures can be rather complex compared to states in planar samples. Recent cantilever magnetometry experiments measuring both the magnetization and the stray field produced by single CoFeB and NiFe NTs with hexagonal structures have shown experimental evidence for complex configurations at low magnetic fields during reversal including vortex states. Since this kind of magnetometry lacks the spatial resolution necessary to image such nanomagnetic states, so far, an unambiguous identification of the intermediate magnetic states was not possible [2].

We use the unique sensitivity and spatial resolution of X-ray Photoemission Electron Microscopy (X-PEEM) in combination with X -ray magnetic circular dichroism (XMCD) at the Swiss Light Source, Paul Scherrer Institut [3] to investigate the magnetic reversal mechanism of single CoFeB and NiFe NTs at room temperature. The NTs are aligned on a Si substrate parallel as well as perpendicular to the in situ applied magnetic field direction. So far we were able to record magnetic images of uniform magnetized states in CoFeB NTs after applying a magnetic field of ±50mT. Furthermore the first real-space magnetic image of a stable multi-domain state in a perpendicular aligned NiFe nanotube was recorded.

The possibility of real-space imaging of intermediate states has the potential to give us unprecedented insights into the formation and nature of low-field or ground state configurations in three-dimensional magnetic nano-objects, in particular in magnetic NTs. Such information is crucial if these nanomagnets are to become part of any future memory devices.

*Corresponding author: Marcus.Wyss@unibas.ch

[1] P. Landeros, A. Allende, J. Escrig, E. Salcedo, and D. Altbir, Appl. Phys. Lett. 90, 102501 (2007).
[2] A. Buchter, J. Nagel, D. Rueffer, F. Xue, D.P. Weber, O.F. Kieler, T. Weimann, J.Kohlmann, A.B. Zorin, E. Russo-Averchi, R. Huber, P. Berberich, A. Fontcuberta i Moral, M. Kemmler, R. Kleiner, D. Koelle, D. Grundler, and M. Poggio, Phys. Rev. Lett. 111, 067202 (2013).
[3] L. Le Guyader, A. Kleibert, A.F. Rodríguez, S. El Moussaoui, A. Balan, M. Buzzi, J. Raabe, F. Nolting, J. Electron. Spectrosc. Relat. Phenom. 185, 371 (2012).

Linear response theory of spin-wave spin torques induced by temperature gradient

Terufumi Yamaguchi and Hiroshi Kohno
Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Japan

Manipulation of magnetic structures by unconventional means is one of the important topics in spintronics. Among various means, driving a magnetic structure by a temperature gradient has received a particular attention. Such phenomena were observed experimentally in a ferromagnetic metal [1] and a ferromagnetic insulator [2], but the relevant mechanism is under discussion. One of the expected mechanisms is the spin torque due to thermally-induced spin waves, in particular in insulators.

There are some studies on the effects of propagating spin waves on magnetic structures [3,4,5]. A temperature gradient can also induce a flow of spin waves, whose spin current will exert spin torques. Ordinary spin torques (in the absence of Dzyaloshinsky-Moriya interaction) have two components, one comes from the conservation of angular momentum (spin-transfer torque), and the other is its dissipative correction (called β-term) which is the damping of magnetization. A calculation of spin torques due to thermally-induced spin waves was presented based on a phenomenological equation (stochastic Landau-Lifshitz-Gilbert equation) [6].

In this work, we formulate a theory of spin torques due to spin waves induced by a temperature gradient based on the linear response theory, and calculate the spin-transfer torque and the β-term. To treat the temperature gradient, we follow Luttinger and introduce a 'gravitational potential' [7]. We discuss, in particular, the relation of the β parameter to α. Also, we apply the results to some specific magnetization structures, such as a domain wall, and discuss their dynamics.

References

[1] S. U. Jen and L. Berger, J. Appl. Phys. **59**, 1285 (1986).
[2] W. Jiang *et al*., Phys. Rev. Lett. **110**, 177202 (2013)
[3] D.-S. Han *et al*., Appl. Phys. Lett. **94**, 112502 (2009).
[4] S.-M. Seo *et al*., Appl. Phys. Lett. **98**, 012514 (2011).
[5] J. Iwasaki *et al*., Phys. Rev. B **89**, 064412 (2014).
[6] A. A. Kovalev, Phys. Rev. B **89**, 241101(R) (2014).
[7] J. M. Luttinger, Phys. Rev. **135**, A1505 (1964).

Magnetoresistance of InAs nanowires with magnetic side gates

G. Fábián,[1] A. Baumgartner,[1] M.H. Madsen,[2] J. Nygård[2] and C. Schönenberger[1]
[1]*Institute of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*
[2]*Center for Quantum Devices and Nano-Science Center, Niels Bohr Institute, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen, Denmark*

Epitaxially grown InAs nanowires (NWs) are a versatile, highly tunable material platform at the heart of many new developments in nanoscale and quantum electronics. The strong spin-orbit coupling and the large and variable g-factors [1] make NWs promising for spin physics and applications in spintronics.

Here, we introduce a novel approach to control electron spins on single and multiple quantum dots (QDs). We fabricate NW QDs equipped with ferromagnetic side gate pairs (FSPs) made of Permalloy ($Ni_{80}Fe_{20}$) with selectable characteristic external magnetic fields (switching fields), at which the magnetization is reversed [2,3]. If the two magnetic poles of the FSPs near the NW can be fabricated close enough, the stray field leads to a controlled and spatially confined magnetic field on the QDs, while the formation of magnetic end-domains should be suppressed. The stray field can be used either at zero, or superposed to a finite external field. In addition, the FSPs can be used as local electrical gates, for example to tune the QD wave functions (Stark effect).
We present proof-of-principle magneto-resistance (MR) experiments in which we find QD-state dependent MR, i.e., the amplitude, energy and broadening of a QD resonance depend on the magnetic field applied to the QD. For most resonances, the maximum resistance shows a sharp change at the FSP switching fields (here ~35 mT), consistent with a FSP stray field of about ±50 mT. Depending on the QD state, the MR switching can be positive or negative, with resistance changes of up to 50%.
However, we also find QD states that exhibit a considerably more complex MR, e.g. similar to tunneling magnetoresistance between two ferromagnets. As a tentative explanation for the latter we discuss a simple double-QD model, while we can understand the more basic features in a single-QD model.
FSPs are not only relevant for spin-transport experiments, but can also be used for conceptually new experiments. For example, spatially periodic magnetic fields from FSPs might result in novel quasi-particles called fractional Fermions [4], or one might use FSPs to create non-collinear spin projection axes on the two QDs of a NW-based Cooper pair splitter [5,6] (conceptually related to Ref. [7]), which should allow for a test of Bell’s inequality with electrons.

[1] d’Hollosy *et al.*, AIP Conf. Proc. **1566**, 359 (2013)
[2] Aurich *et al.*, Appl. Phys. Lett. **97**, 153116 (2010)
[3] Samm *et al.*, J. Appl. Phys. **115**, 174309 (2014)
[4] Klinovaja *et al.*, Phys. Rev. Lett. **109**, 236801 (2012)
[5] Hofstetter *et al.*, Nature **461**, 960 (2009)
[6] Fülöp *et al.*, Phys. Rev. B **90**, 235412 (2014)
[7] Braunecker *et al.*, Phys. Rev. Lett. **111**, 136806 (2013)

Shot noise of carbon nanotube and graphene measured with GHz impedance matching circuit

Minkyung Jung,[1] Thomas Hasler,[1] Vishal Ranjan,[1] Peter Rickhaus,[1] Simon Zihlmann,[1] Peter Makk,[1] Gabriel Puebla-Hellmann,[2] Andreas Wallraff,[2]and Christian Schönenberger[1]
[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2]*Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland*

Shot noise, the fluctuation of electric current out of equilibrium, originates from the transmission of quantized charge [1]. Shot noise is a powerful tool to probe information about transmission in mesoscopic solid state devices that is not available from the dc current [2,3]. Here, we present shot noise measurements on a carbon nanotube quantum dot and suspended graphene *pn* junctions at a few GHz regime. First, we demonstrate shot-noise measurements of a carbon nanotube in the single quantum dot regime by using a superconducting impedance matching circuit. We successfully couple a carbon nanotube (CNT) quantum dot to a GHz superconducting matching circuit using a stamping transfer technique. The stub impedance matching circuit has a bandpass effect for noise emitted by the sample around its resonance frequency of 3 GHz. Super-Poissonian noise in the inelastic cotunneling regime and in the multilevel sequential tunneling regime are observed as well as sub-Poissonian noise in coincidence with steps in the Coulomb staircase. In the second part, we present preliminary shot noise results measured in ballistic graphene *pn* junctions. Devices are fabricated by first defining an array of Ti/Au gates on a high-resistivity oxidized Si substrate. After covering lift-off resist (LOR) on the top of the bottom gate array, an exfoliated graphene is transferred on the bottom gate array by using a mechanical transfer technique. Pd source-drain contacts are deposited to define ohmic contacts. Finally, LOR layer underneath the graphene flake is e-ebeam exposed and developed to suspend the graphene [4]. The device is directly coupled to the lumped element LC matching circuit with the resonance frequency of 1.3 GHz. After current annealing, the device shows a Fabry-perot interference pattern in *pn* junction, showing that our device is fully ballistic. We present shot noise data measured in full ballistic devices with different channel width over length ratios.

[1] C. Beenakker and C. Schönenberger, Physics Today **56,** 37 (2003).
[2] R. De-Picciotto *et al.*, Nature **389**, 162 (1997).
[3] M. Henny *et al*., Science **284**, 296 (2000).
[4] P. Rickhaus *et al.*, Nature comm. **4**, 2342 (2013)

Clean CNT quantum dots coupled to GHz superconducting impedance matching circuits

V. Ranjan[1], T. Hasler[1], M. Jung[1], G. Puebla-Hellmann[1,2], A. Nunnenkamp[1], M. Muoth[3], C. Hierold[3], A. Wallraff[2] and C. Schonenberger[1]

[1]*Department of Physics, University of Basel*
[2]*Department of Physics, ETH Zurich*
[3]*Department of Mechanical and Process Engineering, ETH Zurich*

We couple a locally tunable suspended CNT quantum device to an impedance-matching circuit based on superconducting transmission lines. Our circuit is aimed at providing an efficient channel to transfer (collect) microwave radiation into (from) a quantum device. In addition, the circuit offers bandwidths (BW) in the MHz range even for device impedances on the order of 1MOhm. These features, on one hand, allow us to demonstrate high-BW measurements for deducing both conductance and susceptance changes in the quantum device at GHz frequencies, and on another hand, take advantage of near unity collection of emitted radiation power for fast shot noise measurements. Besides, we employ a selective assembly technique of CNT transfer to address the fabrication and device yield issues while obtaining clean transport spectra in combination with low microwave loss circuits.

Geometric echo of a purely geometric spin qubit in diamond

Yuhei Sekiguchi, Yusuke Komura, Shota Mishima, Touta Tanaka, Naeko Niikura and Hideo Kosaka
Yokohama National University, 79-5 Tokiwadai, Hodogaya, Yokohama 240-8501, Japan

An electron spin can be a purely geometric qubit that has exclusively a geometric phase when the system is degenerate. In contrast that the conventional dynamic qubit requires an energy gap to be controlled, geometric qubit does not in principle. We here show the geometric phase control of a purely geometric qubit in a degenerate subspace of a V-type spin 1 electronic system of a nitrogen vacancy center in diamond under zero magnetic field [1]. The zero-field split state serves as an ancillary state to interact with a controlling microwave (Fig. (a)). The degenerate qubit operation is achieved by changing the geometric phase of the microwave–defined bright state while leaving the dark state unchanged [2]. We demonstrate geometric spin echo to recover the geometric spin coherence after 100 times of the free induction decay (Fig. (b)). Dependence of the echo signal on the axial magnetic field indicates that correlation between spin bath is the major decoherence source and minimized under zero magnetic field. The demonstration reveals the importance of the spin degeneracy for long-lived memory. The degenerate geometric qubit is not only resilient to environmental noise but also robust against control error and free from dynamic phase locking.

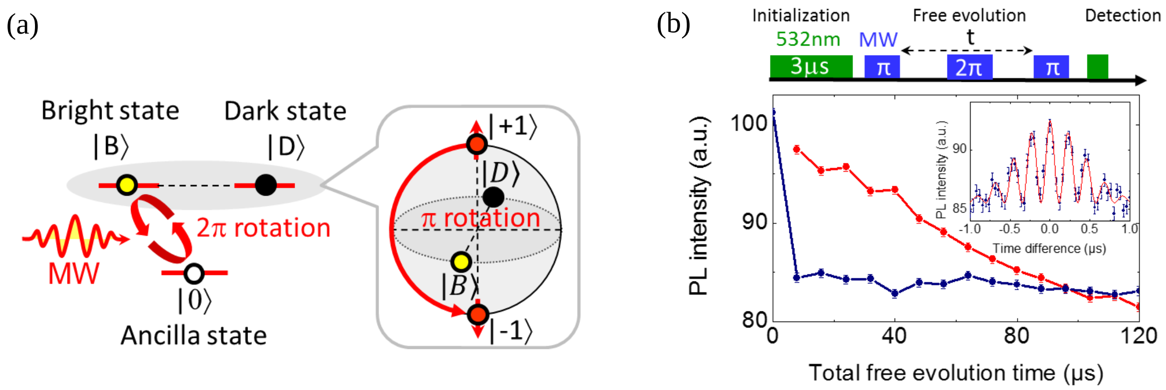


Fig. (a) The energy level diagram of a ground state electron spin system in an NV center in diamond. Inset illustrates the geometric spin bit-flip operation in degenerate space as a result of 2π rotation from the bright state |B⟩ through the ancilla state |0⟩. (b) Geometric spin free induction decay (Ramsey interference) and geometric spin echo. Inset shows refocused echo signal after 70μs of free evolution.

[1] H. Kosaka and N. Niikura, Entangled absorption of a single photon with a single spin in diamond. *Phys. Rev. Lett.* **114**, 053603 (2015).
[2] H. Kosaka *et al*. Spin state tomography of optically injected electrons in a semiconductor. *Nature* **457**, 702–705 (2009).

Tunnel junction thermometry down to 7 mK

M. Palma[1], A. Feshchenko[2], L. Casparis[1], I. M. Khaymovich[2], D. Maradan[1], O.-P. Saira[2], M. Meschke[2], J. P. Pekola[2], D. M. Zumbühl[1]

[1] *Department of Physics, University of Basel, Switzerland*
[2] *Low Temperature Laboratory, Department of Applied Physics, Aalto University, Finland*

Low temperatures in nanoelectronic devices open the door for new states of matter such as helical nuclear spin phases [1,2] and exotic fractional quantum Hall states. Further, low temperatures enhance quantum coherence – beneficial for quantum interference, spintronics and quantum computation. We have developed an advanced nuclear demagnetization refrigerator [3] for nanoelectronics with multiple stages of shielding and filtering, with the goal of achieving device temperatures below 1 mK. Measuring temperature in a nanoelectronic device is one of several challenges below 10 mK. Here, we present a tunnel junction thermometer comprising a normal metal/insulator/superconductor (NIS) stack realized with $Cu/Al_2O_3/Al$ [4]. A thermal analysis shows that overheating in both superconductor and normal metal remain negligible, opening the door for operation down to 1 mK.

We have developed a simple method to extract the electronic temperature T_e in the exponential regime of the I-V curve, where T_e is given by the semi-logarithmic slope $T_e = dV/d(\ln I)\, e/k_B$, with electron charge e and Boltzmann constant k_B. This method has the advantage that the extracted temperature is independent of device parameters (e.g. superconducting gap, normal state resistance) and does not require calibration, i.e. it is a primary thermometer. Deviations from the exponential regime due to subgap leakage (at low currents) and higher order effects (at high currents) result in elevated temperatures, thus presenting a limitation of this method. However, for the present leakage (Dynes parameter γ=2.2e-5), this deviation is smaller than ~7% for temperatures down to 1 mK when using the semi-logarithmic slope of the differential conductance g(V) instead of the I-V curve [4].

The NIS thermometer agrees very well with the refrigerator temperature down to 10 mK. Upon demagnetizing the nuclear refrigerators, the NIS thermometer saturates at ~7 mK when the demagnetization stages are below 3 mK [4]. However, the NIS temperature decreases slowly over time, arriving at ~7 mK only several weeks after cool down, suggesting internal heat release originating e.g. from the silver epoxy sample holder. Future improvements will employ low heat-release materials such as sapphire or pure metals e.g. for the socket and chip carrier. We emphasize that the NIS thermometer is extremely sensitive to perpendicular magnetic fields. If the field is not compensated to better than one Gauss (far below the critical field ~15 mT of the Al thin film), then the NIS temperature is off by a large factor.

Finally, we have observed steps in the I-V curve within the superconducting gap at voltages below the exponential regime. These steps appear symmetrically around zero bias and are independent of magnetic field below the critical field. Interestingly, the Fermi-Dirac function describes the broadening of these steps very well, giving temperatures that agree with the NIS temperature obtained from the exponential regime as described earlier. Though reminiscent of Andreev states in a confined geometry, these features are not currently understood.

[1] P. Simon and D. Loss, *Phys. Rev. Lett*. **98**, 156401 (2007).

[2] C. P. Scheller, T.-M. Liu, G. Barak, A. Yacoby, L. N. Pfeiffer, K. W. West, and D. M. Zumbühl, *Phys. Rev. Lett.* **112**, 066801 (2014).

[3] L. Casparis, M. Meschke, D. Maradan, A. C. Clark, C. P. Scheller, K. K. Schwälder, J. P. Pekola, D. M. Zumbühl, Rev. Sci. Instrum. **83**, 083903 (2012).

[4] A. V. Feshchenko, L. Casparis, I. M. Khaymovich, D. Maradan, O.-P. Saira, M. Palma, M. Meschke, J. P. Pekola, and D. M. Zumbühl, arxiv:1504.03841 (2015)

Spin-orbit mediated spin relaxation in a single-electron quantum dot

L. C. Camenzind,[1] L. Yu,[1] D. E. F. Biesinger,[1] J. Zimmerman,[2] A. C. Gossard,[2] and D. M. Zumbühl[1]

[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2]*Materials Department, University of California, Santa Barbara, CA93106, USA*

Spins in quantum dots are promising candidates for the realization of qubits – the elementary units of a quantum computer – and hold the potential for scaling to a large number of qubits. Stable qubits with long coherence times are of crucial importance to execute numerous coherent quantum gates. Great progress was recently made to decouple the electron spins from the nuclear spins of the host material. A fundamental limit to the spin coherence is set by the spin relaxation time T_1. In a magnetic field, spins relax predominantly by phonon-emission mediated by the spin-orbit (SO) coupling [1,2]. Since the SO coupling in GaAs is weak, very long T_1 times have been measured, reaching 1 s at 1T [3].

Here, we present measurements of the spin relaxation rate in a gate-defined single-electron quantum dot formed in a GaAs 2D electron gas. An adjacent quantum dot in the tunnel-broadened regime is used as a sensitive charge detector with a bandwidth of ~30 kHz, similar to the setup described in [4]. This allows real-time single-shot read-out of the spin state via spin-to-charge conversion using energy selection. The device is mounted on a piezo-electric rotator placed inside a 14 T magnet, making it possible to accurately control the angle ϕ of the applied magnetic field $B_{||}$ in the plane of the 2D electron gas, while the out-of-plane component is kept small (<5º). To measure T_1, three-step pulse sequences with microsecond resolution are applied to one of the dot gates. Identical pulses of reverse polarity and reduced amplitude are applied to a sensor gate to compensate the cross capacitance. The experiment is performed in a dilution refrigerator with an electron temperature of 100 mK.

The spin relaxation rate W, measured at 4 T, exhibits a sinusoidal dependence on the B-field angle ϕ with a period of 180°, as similarly reported recently [5]. The extrema are seen when the field is pointing nearly along the [110] and [1-10] crystal axes, changing by a factor of about 20 from minimum to maximum. When the field is oriented along the [1-10] direction – where maximal spin relaxation times are observed – T_1 reaches ~5 s at B = 1 T, extending the previous record [3] by a factor of five. Upon increasing the field to 12 T, the T_1 time is reduced by approximately five orders of magnitude, close to the expected B^5 dependence [1]. For a comparison to theory, the quantum dot orbitals are playing a major role. Therefore, we perform pulsed-gate spectroscopy to extract orbital excited-state energies, and obtain very good agreement with theory also for the angle dependence $W(\phi)$, indicating that Rashba and Dresselhaus SO strengths have the same relative sign and are within ~20% of each other.

In the future, we intend to manipulate the dot orbitals with gate voltages, implement electrical control of the Rashba SO interaction using top- and back gates [6], and also investigate the B-field angle dependence of the spin tunnelling asymmetry. Finally, we plan to study alternate spin relaxation mechanisms, e.g. 2-phonon processes in double dots.

[1] V.N.Golovach, A. Khaetskii, and D. Loss, Phys. Rev. Lett. **93**, 016601 (2004).
[2] P. Stano and J. Fabian, Phys. Rev. B **74**, 045320 (2006).
[3] S. Amasha, K. MacLean, I. Radu, D. M. Zumbuhl, M. A. Kastner, M. P. Hanson, and A. C. Gossard, Phys. Rev. Lett. **100**, 046803 (2008).
[4] D. E. F. Biesinger, C. P. Scheller, B. Braunecker, J. Zimmerman, A. C. Gossard, and D. M. Zumbuhl, arXiv:1505.03195 (2015).
[5] P. Scarlino, E. Kawakami, P. Stano, M. Shafiei, C. Reichl, W. Wegscheider, and L. M. K. Vandersypen, Phys. Rev. Lett. **113**, 256802 (2014).
[6] F. Dettwiler, J. Fu, S. Mack, P. J. Weigele, J. C. Egues, D. D. Awschalom, and D. M. Zumbuhl, arXiv:1403.3518 (2014).

Spontaneous Edge Accumulation of Spin Currents in Finite-Size Two-Dimensional Diffusive Spin-Orbit Coupled SFS Heterostructures

Mohammad Alidoust,[1] and Klaus Halterman[2]
[1]Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
[2]Michelson Lab, Physics Division, Naval Air Warfare Center, China Lake, California 93555, USA

The accumulation of spin currents at the edges of spin-orbit coupled heterostructures in the presence of an external magnetic or electric field has been an interesting topic to the condensed matter physics [1-5]. This effect was theoretically predicted [1] and shortly thereafter observed experimentally [2]. Here, we theoretically study spin and charge currents through finite-size two-dimensional s-wave superconductor/uniform ferromagnet/s-wave superconductor (S/F/S) junctions with intrinsic spin-orbit interactions (ISOIs) using a quasiclassical approach. Considering experimentally realistic parameters, we demonstrate that the combination of spontaneously broken time-reversal symmetry and lack of inversion symmetry can result in spontaneously accumulated spin currents at the edges of finite-size two-dimensional magnetic S/F hybrids. Due to the spontaneous edge spin accumulation, the corners of the F wire host the maximum spin current density. We further reveal that this type of edge phenomena are robust and independent of either the actual type of ISOIs or exchange field orientation. Moreover, we study spin current-phase relations in these diffusive spin-orbit coupled S/F/S junctions. Our results unveil net spin currents, not accompanied by charge supercurrents, which spontaneously accumulate at the sample edges through a modulating superconducting phase difference [6]. We also demonstrate that a S/N/S hybrid with a single spin-active interface generates essentially similar features [7]. Finally, we discuss possible experimental implementations to observe these edge phenomena [6-7].

[1] M.I. Dyakonov and V.I. Perel, Phys. Lett. 35A, 459 (1971); J.E. Hirsh, Phys. Rev. Lett.83, 1834 (1999).
[2] Y.K. Kato, R.C. Myers, A.C. Gossard, and D.D. Awschalom, Science 306, 1910 (2004); J. Wunderlich, B. Kastner, J. Sinova, and T. Jungwirth, Phys. Rev. Lett.94, 047204 (2005).
[3] E.G. Mishchenko, A.V. Shytov, and B.I. Halperin, Phys. Rev. Lett.93, 226602 (2004).
[4] B.K. Nikolic, S. Souma, L.P. Zarbo, and J. Sinova, Phys. Rev. Lett.95, 046601 (2005).
[5] M. Duckheim, D. Loss, M. Scheid, K. Richter, I. Adagideli, P. Jacquod, Phys. Rev. B 81, 085303 (2010)
[6] M. Alidoust and K. Halterman, New J. Phys. 17, 033001 (2015).
[7] M. Alidoust and K. Halterman, Journal of Physics: Condensed Matter 27 (23), 235301 (2015).

Spins in quantum dots for stimulated phonon emission

V. N. Golovach,[1] A. Khaetskii,[2] X. Hu,[2] and I. Zutic[2]
[1]*Centro de Fisica de Materiales (CFM-MPC), Centro Mixto CSIC-UPV/EHU, Manuel de Lardizabal 5, E-20018 San Sebastian, Spain*
[2]*IKERBASQUE, Basque Foundation for Science, E-48013 Bilbao, Spain*
[3]*Department of Physics, University at Buffalo, SUNY, Buffalo, New York 14260-1500, USA*

The spins of electrons confined to quantum dots couple efficiently to the acoustic phonon field of the underlying semiconductor material. The coupling involves the spin-orbit interaction and a Zeeman splitting of the spin-doublet energy level on the quantum dot [1]. We consider a general setting, in which a quantum dot is subject to the action of a phonon field which is taken to consist of a coherent component, arising from stimulated phonon emission, and an incoherent component, arising from spontaneous phonon emission. We discuss the favorable conditions for stimulated phonon emission in a number of geometries and as a function of the phonon resonator length. In particular, we consider a geometry [2] in which the quantum dots are formed in a semiconductor nanowire and the population inversion is achieved by the means of spin-selective tunneling [3]. In the limit of a short nanowire, we determine the optimal distribution of the quantum dots across the nanowire and discuss also the crossover to the case of a long nanowire studied in Ref. [2]. The corresponding Pauli master equations are derived and solved for different situations and the threshold conditions for the onset of stimulated phonon emission are discussed.

[1] Vitaly N. Golovach, Alexander Khaetskii, and Daniel Loss, *Phonon-induced decay of the electron spin in quantum dots*, Phys. Rev. Lett. 93, 016601 (2004).
[2]A. Khaetskii, V.N. Golovach, X. Hu, I. Zutic, *Proposal for a phonon laser utilizing quantum-dot spin states*, Phys. Rev. Lett. **111**, 186601 (2013).
[3] G. Katsaros, V. N. Golovach, P. Spathis, N. Ares, M. Stoffel, F. Fournel, O. G. Schmidt, L. I. Glazman, and S. De Franceschi, *Observation of spin-selective tunneling in SiGe nanocrystals*, Phys. Rev. Lett. **107**, 246601(2011).

Interactions between a pinned ferromagnetic vortex and individual nitrogen-vacancy spins

Jesse Berezovsky,[1] Robert Badea,[1] and Michael Wolf[1]
[1] *Case Western Reserve University, Cleveland OH, 44106 USA*

Nitrogen-vacancy (NV) spins coupled to a driven ferromagnetic vortex may provide an integrated platform for implementing one- and two-qubit operations. A ferromagnetic vortex creates a strong localized magnetic field gradient for addressing individual spins or tuning dipole-coupled spins into or out of resonance, with switching times ~10s of ns. A small magnetic field is used to control the vortex position, and hence the coupling to NV spins. We map the response of the vortex position to applied field using differential Kerr microscopy [1]. The vortex behavior can be understood via an effective potential that is the sum of a broad paraboloid and sharp “pinning” features caused by defects. Fig. 1(a) shows examples of vortex displacement vs. applied field at two different positions. An overall linear increase is due to the shifting minimum of the paraboloid, with plateaus and jumps occurring because of pinning. From a series of these scans, we can map the effective pinning potential across a sample (Fig. 1(b)).

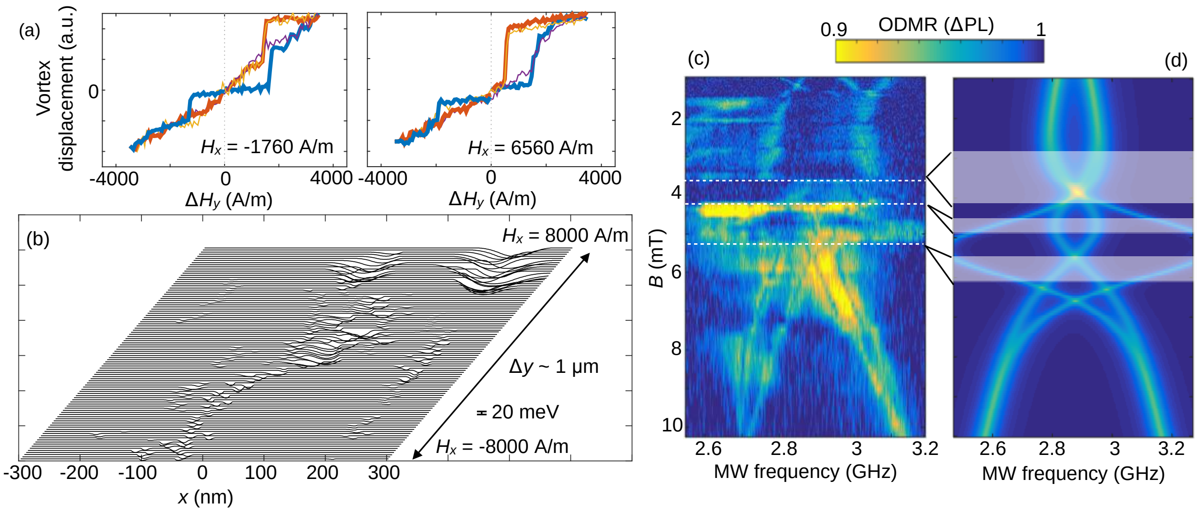


Figure 1. (a) Ferromagnetic vortex displacement vs. magnetic field. (b) Map of vortex pinning potential. (c) ODMR spectra of NV spins vs. applied field as vortex is driven past. White lines indicate depinning events. (d) Simulated ODMR spectra showing simplified vortex-NV interaction.

With a 25-nm-diameter diamond nanocrystal containing several NVs deposited on top of a vortex, the resonances between ground state spin levels of the NVs are shifted drastically as the vortex is scanned nearby. Fig. 1(c) shows optically-detected magnetic resonance (ODMR) spectra as a static magnetic field drives the vortex past the NVs, with simulated data shown in (d). Without the vortex, these spectra would show a linearly increasing Zeeman splitting. When the vortex is close to the NVs ($B \approx 5$ mT), adjacent NVs within the same nanoparticle show large splittings. The effect of vortex pinning appears as sudden jumps in the ODMR spectra with magnetic field. Several such jumps are indicated by white dotted lines, with the jumped-over region shaded in the simulation.

The ability to map the pinning landscape and drive the vortex within that landscape provides a rich array of possibilities for highly local coherent spin control and coupling.

[1] Badea, R., J. A. Frey, and J. Berezovsky. "Magneto-optical imaging of vortex domain deformation in pinning sites." *JMMM* (2015).

Probing spin states in a triple quantum dot by Fourier transform spectroscopy

Takashi Nakajima,[1,2] Matthieu R. Delbecq,[1,2] Tomohiro Otsuka,[1,2]
Shinichi Amaha,[1] Jun Yoneda,[1,2] Akito Noiri,[2] Kenta Takeda,[1,2] Arne Ludwig,[3]
Andreas D. Wieck,[3] and Seigo Tarucha[1,2]
[1] *Center for Emergent Matter Science, RIKEN, Saitama, Japan*
[2] *Department of Applied Physics, Univ. of Tokyo, Tokyo, Japan*
[3] *Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, Bochum, Germany*

Single electron spin in semiconductor quantum dots is a good candidate of qubit for its long coherence time and potential scalability[1]. The required basic quantum gate operations for universal quantum gate operations: fast single-spin rotations by electron spin resonance[2] and entanglement operation of two spins by exchange interaction between neighboring spins[3], have been demonstrated. To facilitate similar qubit controls by electrical pulse applications in systems with three or more quantum dots, one needs to understand how the energy eigenstates change as a function of control parameters in those systems.

In this presentation, we introduce a new Fourier transform spectroscopy of spin states in a triple quantum dot (TQD) with a micromagnet (Fig. (a)). In the (1,1,1) charge state of the TQD, in which each quantum dot contains one electron, complex energy diagram of the coupled spin states are expected to arise because of the inhomogeneous Zeeman splitting energy due to the micromagnet (Fig. (b)). To probe this energy diagram, we prepare excited spin states within the (1,1,1) charge configuration by applying voltage pulses on the TQD and measure the coherent evolution of the states by fast single-shot spin readout. We observed coherent oscillations of the singlet return probability reflecting the energy gap between the different spin states, from which we can evaluate TQD energy spectrum without ambiguity by taking Fourier transform. The obtained experimental data (Fig. (c)) shows good agreement with the theoretical calculation.

By utilizing the obtained energy diagram of the coupled spin states in the TQD, we demonstrate individual control of the spin qubits through the addressable single-electron spin resonance and the exchange interaction between the neighboring spins. This realizes the first full control of three spin qubits in semiconductor quantum dots.

[1] D. Loss et al., Phys. Rev. A 57, 120 (1998).
[2] J. Yoneda et al., Phys. Rev. Lett. 113, 267601 (2014).
[3] J. R. Petta et al., Science 309, 2180 (2005), R. Brunner et al., Phys. Rev. Lett. 107, 146801 (2011).

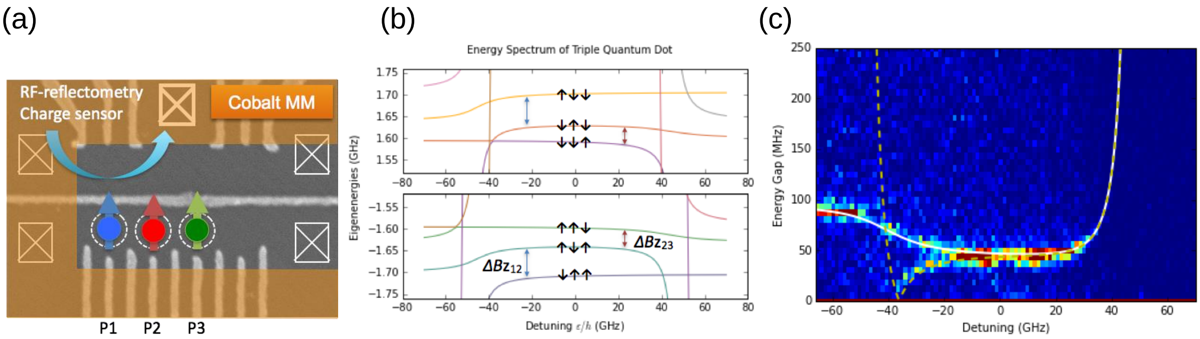


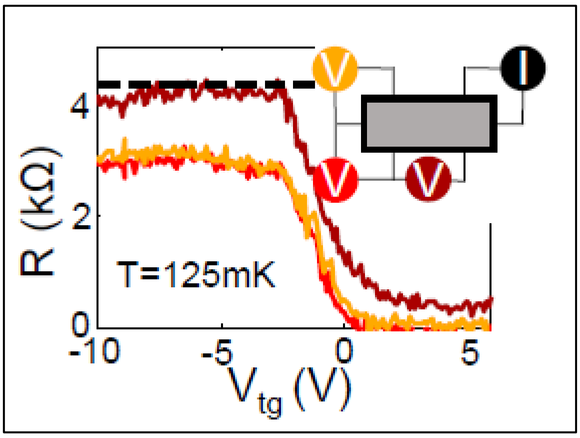
Figure (a) Schematic of the TQD device, (b) Expected energy diagram of the three spin system, (c) Fourier transform spectrum obtained in the experiment.

Non-local Transport in InAs/GaSb Quantum Wells

S. Müller[1], A. Nath Pal[1], M. Karalic[1], T. Tschirky[1],
C. Charpentier[1], W. Wegscheider[1], K. Ensslin[1], T. Ihn[1]
[1]*Solid State Physics Laboratory, ETH Zurich, 8093 Zurich, Switzerland*

The Quantum Spin Hall Effect (QSHE) is a phenomenon which has been predicted to arise in 2D topological insulators [1, 2]. It manifests itself in the form of symmetry protected helical edge states. The first experimental observation of the QSHE was made in 2007 on HgTe quantum wells [3]. In 2008, it was proposed that InAs/GaSb double quantum well systems can also host the QSHE, even allowing for the manipulation of the QSHE using electrostatic gating in a manner not possible in HgTe quantum wells [4]. In the following years, a handful of groups performed experiments on InAs/GaSb double quantum well systems, providing evidence for the existence of the QSHE therein [5, 6, 7].

Our recent transport measurements on InAs/GaSb double quantum well systems focus on probing the non-local charge transport expected to occur due to the helical edge states. We observe non-local signals in small area Hall bar geometries, however the non-local resistances lie below the expected quantization values for ideal helical edge states. We attribute the reduced resistance to residual bulk conductivity, even though measurements in large area Hall bar geometries indicate that the bulk is insulating.



Example transport measurement on an InAs/GaSb double quantum well system. The non-local resistance $R = V/I$ is shown as a function of the top-gate voltage V_{tg}. The inset depicts the measurement configuration.

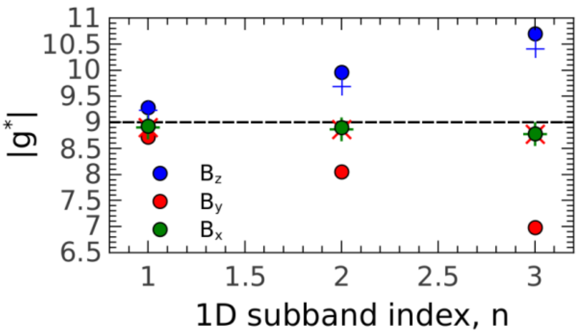
[1] Kane, C. L. & Mele, E. J. Quantum Spin Hall Effect in Graphene. *Phys. Rev. Lett.* **95,** 226801 (2005)
[2] Bernevig, B. A. & Zhang, S.-C. Quantum Spin Hall Effect. *Phys. Rev. Lett.* **96,** 106802 (2006).
[3] König, M. *et al.* Quantum Spin Hall Insulator State in HgTe Quantum Wells. *Science* **318,** 766–770 (2007).
[4] Liu, C., Hughes, T., Qi, X.-L., Wang, K. & Zhang, S.-C. Quantum Spin Hall Effect in Inverted Type-II Semiconductors. *Physical Review Letters* **100,** (2008).
[5] Suzuki, K., Harada, Y., Onomitsu, K. & Muraki, K. Edge channel transport in the InAs/GaSb topological insulating phase. *Phys. Rev. B* **87,** 235311 (2013).
[6] Knez, I. *et al.* Observation of Edge Transport in the Disordered Regime of Topologically Insulating InAs/GaSb Quantum Wells. *Phys. Rev. Lett.* **112,** 026602 (2014).
[7] Pribiag, V. S. *et al.* Edge-mode Superconductivity in a Two Dimensional Topological Insulator. *Nature Nanotechnology* (2015). doi:10.1038/nnano.2015.86

The effect of the spin-orbit interaction on the anisotropy of the effective g-factor in quantum point contacts

K. Kolasiński, A. Mreńca, and B. Szafran
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059 Kraków, Poland

Semiconductor heterostructures with two dimensional electron gas (2DEG) allow for studies of quantum transport phenomena including integer and fractional Hall effects [1], conductance quantization in quantum point contact (QPC) [2] or Aharanov-Bohm oscillations in quantum rings [3,4]. At low temperatures, in conditions of coherent electron flow, the transport is determined by the Fermi level wave function. For some materials, InGaAs in particular, the non-zero Rashba coupling constant translates the spin degree of freedom into the electric properties of devices.

In this paper we consider transport properties of the system with a quantum point contact built in InGaAs heterostructure. We study the influence of the SO interaction on the effective g-factor (g*) measurable in the experiment [5], where the large enhancement of the g* was observed when the magnetic field was oriented perpendicularly to the surface of the sample. The enhancement occurs already in GaAs in parallel to 0.7 conductance anomaly [0.7] and is explained by the exchange bias field due to electron-electron exchange interaction in a quasi 1D system. In InGaAs [5] besides the enhancement one finds an anisotropy of the g* as a function of the in plane (x,y) orientation of the magnetic field and a dependence on the number of subbands of the lateral quantization. According to our numerical studies the presence of the SO interaction is necessary to explain the of anisotropy in the effective g-factor. Similar conclusions was obtained previously in the hole gas systems [6]. We describe the electron-electron interaction effects using the the DFT approach.



The effective Lande factor as obtained for three perpendicular orientations of the magnetic field (z axis is perpendicular to the surface of the sample), calculated within the single particle model. Dots show the results for the Rashba SO coupling. Crosses the results without SO interaction.

[1] B. Hackens et al., Nature, Communications 1, 39 (2010).
[2] K. E. Aidala et al. , Nature Physics 3, 464 (2007).
[3] B. Hackens et al., Nature Physics 2, 826 (2006); F. Martins et al., Phys. Rev. Lett. 99, 136807 (2007).
[4] M. G. Pala et al., Phys. Rev. B 77, 125310 (2008); Nanotechnology 20, 264021 (2009).
[5] T. P. Martin, A. Szorkovszky, A. P. Micolich, A. R. Hamilton, C. A. Marlow, H. Linke, R. P. Taylor, and L. Samuelson, Appl. Phys. Lett. 93, 012105 (2008)
[6]R. Winkler, S. J. Papadakis, E. P. De Poortere, and M. Shayegan, Phys. Rev. Lett. 85, 4574 (2000).
[0.7] Anomaly – prosze wstawic odnnosnik do tej pracy pierwsza o 0.7, wysylalem go Panu.

A strongly driven single-spin qubit in a Si/SiGe double quantum dot with a micro-magnet

K. Takeda,[1] J. Kamioka,[2] T. Obata,[3] T. Otsuka,[1, 3] T. Nakajima,[1, 3]
M. R. Delbecq,[1, 3] S. Amaha,[1] J. Yoneda,[1] G. Allison,[1] A. Noiri,[3]
R. Sugawara,[3] T. Kodera,[2] S. Oda,[2] and S. Tarucha[1,3]
[1]*Center for Emergent Matter Science, RIKEN, Saitama, Japan*
[2] *Department of Physical Electronics and Quantum Nanoelectronics Research Center, Tokyo Institute of Technology, Tokyo, Japan*
[3]*Department of Applied Physics, The University of Tokyo, Tokyo, Japan*

Electron spins in Si quantum dots (QDs) are one of the promising candidates for implementation of solid state quantum computing because of their long coherence times. By recent extensive efforts in experiments using few-electron Si QDs, it becomes possible to manipulate single spins using a microwave antenna [1] or a micro-magnet [2], although the spin manipulation speeds (Rabi frequencies) in these measurements (~ MHz) are slower than those obtained for III-V semiconductor QDs (~100 MHz) [3,4]. The enhancement of the Rabi frequency is desirable because it increases the number of gate operations within the coherence time and thus potentially increases qubit gate fidelities.

In this work, we use a Si/SiGe double QD and a micro-magnet with optimized structure to enable fast and addressable single-spin qubit operations. The micro-magnet is designed to maximize the slanting fields for both dots and a local magnetic field difference between the two dots. The measurements are performed in a two-electron regime where each dot hosts one electron. First we perform individual readout of each spin in the double QD using the energy selective readout technique. Next we perform electron spin resonance measurement by applying microwave bursts to a gate electrode. We find that the separation of spin resonance conditions for each dot is ~ 29 mT (or ~ 800 MHz), which is consistent with our micro-magnet simulation results and large enough to enable high fidelity addressable fast single-qubit control. The time resolved measurements of the electron spin resonance show well defined Rabi oscillations and chevron patterns for each electron spin in the double QD. In this measurement, the maximum Rabi frequency obtained is ~ 40 MHz which is the highest value reported for single-electron spins in Si [1,2]. Finally we characterize the phase coherence time (T2*) using the Ramsey interference. The Ramsey measurement shows phase coherence times T2* ~ 2 \mu s for both two dots which are roughly two orders of magnitude longer than those in III-V semiconductor QDs [3, 4] and comparable to those obtained in other studies of natural Si QDs [2, 5].

[1] M. Veldhorst *et al*., Nat. Nanotechnol. (2014), arXiv preprint (2015).
[2] E. Kawakami *et al*., Nat. Nanotechnol. (2014).
[3] J. W. G. van den Berg *et al*., PRL (2013).
[4] J. Yoneda *et al*., PRL (2014).
[5] B.M. Maune *et al*., Nature (2012).

High Stability, Plasma Oxidized Tunnel Barriers with Cobalt Confining Layers for Spin Injection

Zachary Barcikowski[1,2] and Joshua Pomeroy[2]
[1]*James Clark School of Engineering, University of Maryland, College Park, MD*
[2]*National Institute of Standards and Technology, Gaithersburg, MD*

By implementing a set of benchmark solid state spin architectures, e.g. Meservey-Tedrow, Johnson-Silsbee, etc. we are developing a program to perform comparative studies between different material systems that have half metallic character. As we progress towards these capabilities, optimizing tunnel barrier fabrication represents a vital technological step. Tunnel barriers are prevalent in solid state spin devices for reasons such as alleviating large conductance mismatch between adjacent layers. Aluminum oxide is a popular choice for tunnel barriers in spin injection schemes as it is described well by an ideal barrier within the Wentzel-Kramers-Brillouin (WKB) formalism and the spin dependence of transmission can typically be ignored. As aluminum oxide tunnel barriers have approached fundamental limits of thinness, they have become especially sensitive to defect densities and oxygen concentration gradient. The present work examines two isolated degrees of freedom: 1) method of oxidation and 2) the use of confinement layers, for which we have made a comparative study in order to optimize the stability of the tunnel barrier. The method of oxidation, particularly between thermal and plasma oxidation used here, can significantly affect the uniformity and stoichiometry of the barrier. The use of Co confinement layers provides a chemical potential well for diffusing oxygen to maintain a stable and abrupt aluminum oxide barrier. Presented here are resistance-area (RA) product, resistance vs. time, and current-voltage (I-V) measurements taken over a period of weeks comparing the different process conditions with tunnel barrier stability.

Sustained temporal resistance oscillations in constrained geometries at the ν = 2/3 spin phasetransition

S. Hennel,[1] B. A. Bräm,[1] S. Baer,[1] L. Tiemann,[1] C. Rössler,[1] C.Reichl,[1] W. Wegscheider,[1] T. Ihn,[1] K. Ensslin, M. S. Rudner,[2] and B. Rosenow[3]

[1]*Solid State Physics Laboratory, ETH Zürich, 8093 Zürich, Switzerland*

[2]*Niels Bohr International Academy and Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark*

[3]*Institut für Theoretische Physik, Universität Leipzig, D-04009 Leipzig, Germany*

We observe highly visible temporal oscillations of the resistance measured across a tunable quantum point contact (QPC) in the ν = 2/3 fractional quantum Hall state, with a precise periodicity of the order of several minutes. Our observations are reminiscent of previously reported effects of electron-nuclear spin coupling in mesoscopic devices [1]. We perform a careful study of bias dependence and f i nd that the oscillations are driven by a constant DC current and strongly depend on the polarity of the current. The effect is only qualitatively symmetric under reversal of both bias and magnetic field direction, and does not depend on the filling factor inthe bulk of the sample but rather on the filling factor in the constriction. Using standard NMR techniques, we show that the oscillations are fully suppressed when the sample is irradiated with radio frequency in resonance with Ga or As nuclei. Short NMR sequences affect the oscillations only if coinciding in time with a sharp resistance maximum. Furthermore, the frequency of oscillations increases with increasing temperature. We develop a phenomenological model combining spin filtering and dynamic nuclear polarization at the ν = 2/3 spin phase transition [2] with nuclear spin diffusion.

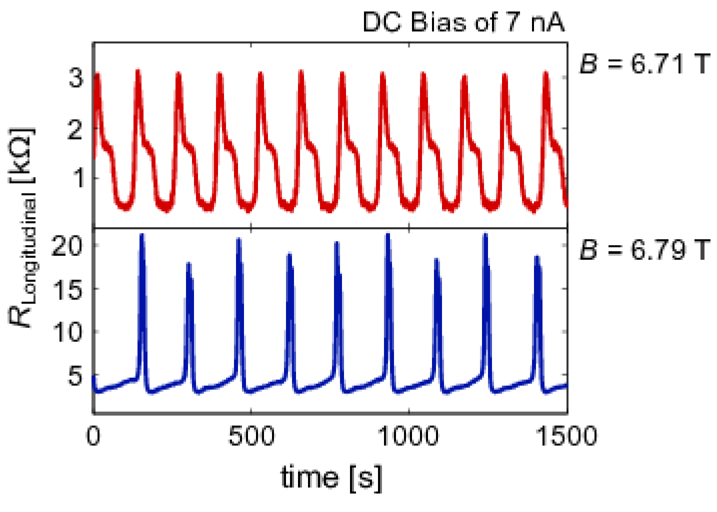


Fig. 1. Resistance oscillations measured for two values of magnetic field corresponding to the ν = 2/3 plateau in the effective QPC filling factor when a constant current of 7nA is driven through the QPC. The resistance has been measured with standard low frequency lock-in techniques using an AC excitation of 100pA.

[1] G. Yusa et al., Phys. Rev. B 69, 16302(R) (2004)
[2] S. Kronmüller et al., Phys. Rev. Lett. 82, 4070 (1999)

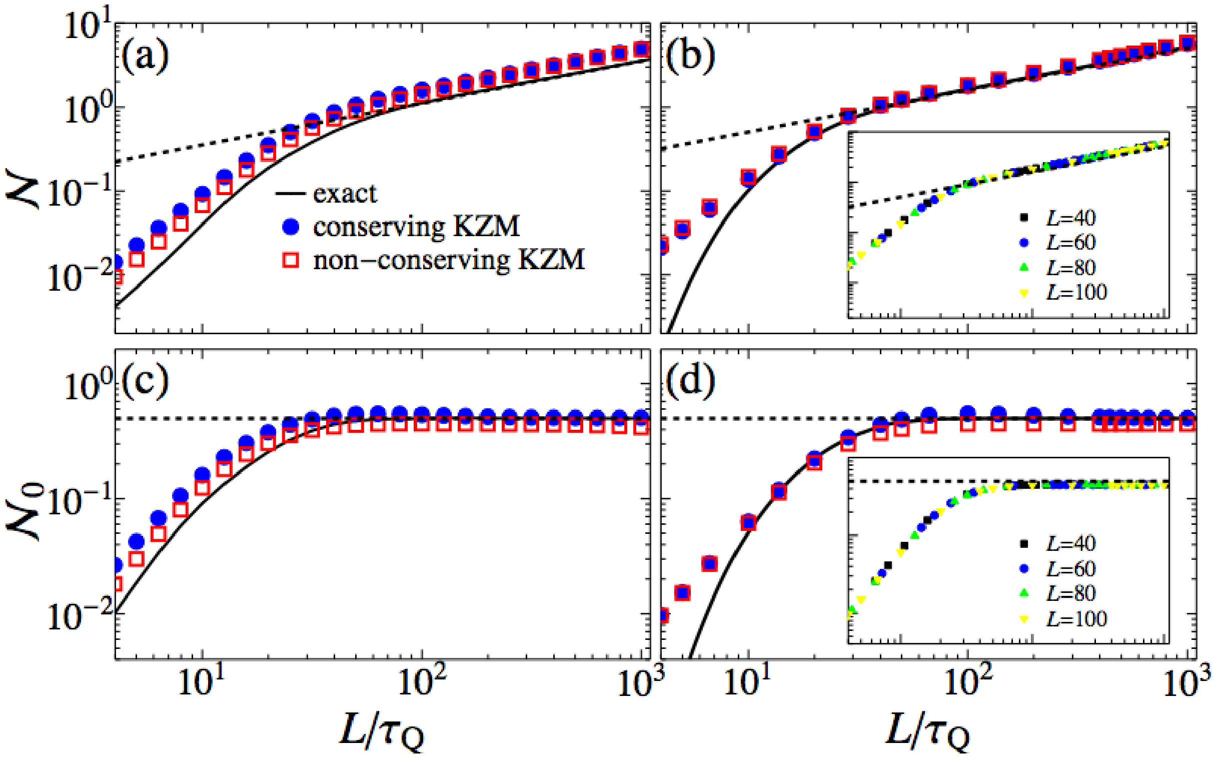
The Kibble-Zurek Mechanism in a Topological Phase Transition

Seungju Han,[1] Minchul Lee,[2] and Mahn-Soo Choi[1]
[1]*Department of Physics, Korea University, Seoul 136-701, Korea*
[2]*Department of Applied Physics, Kyung Hee University, Yongin 446-701, Korea*

Dynamical aspect of topological phase transitions can be studied in several different way. One common method is to investigate quasi-particle excitations. Our previous study [1] on the dynamical dissipation through Majorana modes in the coherent RC circuit is one example. A more direct method is to examine the quenching dynamics. The present work [2] explores this method adopting the spirit of the Kibble-Zurek mechanism (KZM).

In this work, the KZM is generalized to a class of multi-level systems and applied to study the quenching dynamics of one-dimensional (1D) topological superconductors (TS) with open ends. Unlike the periodic boundary condition, the open boundary condition, that is crucial for the zero-mode Majorana states localized at the boundaries, requires to consider many coupled levels. Our generalized KZM predictions agree well with the numerically exact results for the 1D TS. In particular, the generalized KZM explains well the Majorana-mode contribution to the topological defects, which defies utterly the traditional KZM. The inherent bound-state character and multi-level structure of the Majorana mode, who play key roles in the TS, are efficiently captured by the generalized KZM.

[1] Minchul Lee and Mahn-Soo Choi, Physical Review Letters 113, 076801 (2014).
[2] Minchul Lee, Seungju Han, and Mahn-Soo Choi, to appear in Physical Review B (2015); arXiv:1409.1753.



Quantum Hall and de Haas-van Alphen effects in edge channels confined by impurity strata

N. Bagraev[1,2], V. Grigoryev[2], L. Klyachkin[1], A. Malyarenko[1], V. Mashkov[2] and V. Romanov[2]
[1] *Ioffe Physical Technical Institute, 194021, St. Petersburg, Russia*
[2] *Peter the Great Saint Petersburg Polytechnic University, 195251, St. Petersburg, Russia*

We present the first findings of the high temperature quantum Hall, 77K, and de Haas-van Alphen, 300K, effects in silicon sandwich structure that represents the ultra-narrow, 2 nm, p-type quantum well (Si-QW), p_{2D} =3 10^{13} m^{-2}, confined by the delta barriers heavily doped with boron on the n-type Si (100) surface (Fig. 1a). These results are made possible owing to the strong suppression of the electron-electron interaction that is caused by the strata consisting of the negative U dipole boron centers which surround the Si-QW edge channels (Figs. 1b). As a result of this impurity confinement, the edge channels appear to be divided into the fragments that contain the single holes which are able to order the dipole boron centers by the RKKY interaction. Firstly, the strong diamagnetism of the impurity strata allowed the observation of the de Haas – van Alphen oscillations that appear to identify the step-by-step capture of magnetic vortices on single holes in edge channels. Secondly, this step-by-step process seems to verify the principal role of the Faraday effect in the formation of the Hall plateaus and the longitudinal "zero" resistance. These data appear to result from the small effective mass of single holes due to the additional confinement by impurity strata.

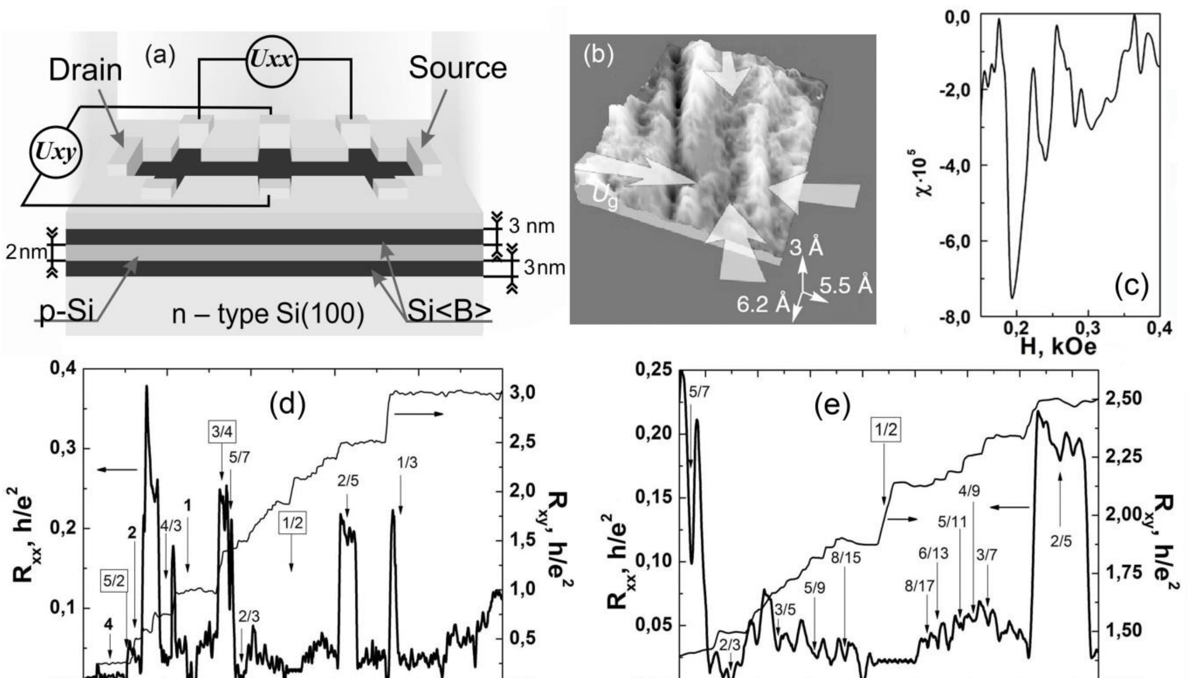


Fig. 1. (a) - Device schematic showing the perspective view of the silicon multi-terminal sandwich structure. (b) – The model and the 3D STM image of the fragment of the edge channel in the silicon sandwich that is confined by the stripes consisting of the negative U dipole boron centers. (c), (d) and (e) - The field dependences of the static magnetic susceptibility, which reveals the strong diamagnetism and the de Haas –van Alphen oscillations at room temperature (c), the Hall resistance and the magnetoresistance (d, e) at 77K in silicon sandwich.

Spin-coherent dot-cavity electronics

Michael Ferguson[1], David Oehri[1], Oded Zilberberg[1], Clemens Rössler[2], Jana Pijnenburg[2], Thomas Ihn[2], Klaus Ensslin[2], and Gianni Blatter[1]

[1]*Institute for Theoretical Physics, ETH Zurich*

[2]*Solid State Physics Laboratory, ETH Zurich*

Quantum engineering requires controllable artificial systems with quantum coherence exceeding the device size and operation time [1,2]. Controlled quantum effects can be obtained from geometrically confined low-dimensional electronic structures embedded within ultraclean materials, with prominent examples being artificial atoms (quantum dots) [3,4,5] and quantum corrals (electronic cavities) [6,7]. Combining the two structures, we have experimentally implemented a mesoscopic coupled dot–cavity system in a high-mobility two-dimensional electron gas, and obtained an extended spin-singlet state in the regime of strong dot–cavity coupling [8]. Engineering such extended quantum states presents a viable route for nonlocal spin coupling that is applicable for quantum information processing. The physics is theoretically studied using: (1) a numerical single-particle analysis of the specific 2D geometry, (2) generation of an effective many-body Hamiltonian consisting of a central dot-cavity part connected to leads, (3) ground state map of central region using exact diagonalization, (4) conductance analysis using a master equation approach, and (5) study of the competition between Kondo and gapped spin-singlet physics using self-consistent equation of motion analysis.

[1] J. A. Katine, et al., Physical Review Letters 79, 4806 (1997).
[2] J. S. Hersch, M. R. Haggerty, E. J. Heller, Physical Review Letters 83, 5342 (1999)
[3] L. P. Kouwenhoven, D. G. Austing, S. Tarucha, Reports on Progress in Physics 64, 701 (2001)
[4] D. Goldhaber-Gordon, et al., Nature 391, 156 (1998)
[5] L. P. Kouwenhoven, L. Glazman, Physics World 14, 33 (2001)
[6] M. F. Crommie, C. P. Lutz, D. M. Eigler, Nature 363, 524 (1993)
[7] H. C. Manoharan, C. P. Lutz, D. M. Eigler, Nature 403, 512 (2000)
[8] C. Rössler, et al., arXiv:1503.02928

A Dressed Spin Qubit in Silicon

Arne Laucht,[1] Rachpon Kalra,[1] Juan P. Dehollain,[1] Stephanie Simmons,[1] Juha T. Muhonen,[1] Guilherme Tosi,[1] Fahd A. Mohiyaddin,[1] Solomon Freer,[1] Fay E. Hudson,[1] Kohei M. Itoh,[2] David N. Jamieson,[3] Jeffrey C. McCallum,[3] Andrew S. Dzurak,[1] and A. Morello[1]

[1]*Centre for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, UNSW Australia, Sydney, New South Wales 2052, Australia*
[2]*School of Fundamental Science and Technology, Keio University, 3-14-1 Hiyoshi, 223-8522, Japan*
[3]*Centre for Quantum Computation and Communication Technology, School of Physics, University of Melbourne, Melbourne, Victoria 3010, Australia*

Coherent dressing of a quantum two-level system has been demonstrated on a variety of systems, including atoms [1], self-assembled quantum dots [2], and superconducting quantum bits [3]. Here, we present coherent dressing of a single electron spin bound to a phosphorus donor in silicon. We observe a Mollow triplet [1] in the excitation spectrum (see Fig. 1), use the driven spin for noise spectroscopy measurements [4], perform coherence time measurements on the driven qubit, and demonstrate full two-axis control of the driven qubit in the dressed frame with a number of different control methods.

In our work we investigate the properties of a dressed electron spin, and probe its potential for the use as quantum bit in scalable architectures where the two spin-polariton levels constitute the quantum bit. The dressed qubit can then be coherently driven with an oscillating magnetic field, an oscillating electric field, by frequency modulating the driving field, or by electrically modifying its detuning. We measure coherence times of $T_{2\rho}^{\star} = 2.4\,ms$ and $T_{2\rho} = 8\,ms$, longer than those of the undressed qubit. Furthermore, we demonstrate that the dressed spin can be driven at Rabi frequencies as high as its transition frequency, making it a model system for the breakdown of the rotating wave approximation.

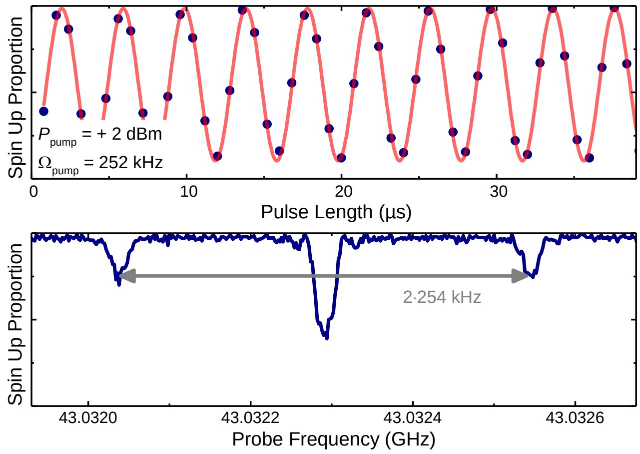


Fig. 1: Dressing a single electron spin in silicon. The upper panel shows Rabi oscillations of the resonantly driven electron spin. The Rabi frequency is $\Omega = 252\,kHz$. The lower panel shows the observation of a Mollow triplet. Here, the electron spin was coherently rotated by 21π, while a second microwave source with -26dB less power was scanned over the resonances to obtain the spectrum.

This research was funded by the ARC Centre of Excellence for Quantum Computation and Communication Technology (project number CE110001027) and the US Army Research Office (W911NF-13-1-0024).

[1] B. R. Mollow. Phys. Rev. **188**, 1969 (1969). Power Spectrum of Light Scattered by Two-Level Systems.
[2] X. Xu *et al.* Science **317**, 929 (2007). Coherent Optical Spectroscopy of a Strongly Driven Quantum Dot.
[3] M. Baur *et al.* Phys. Rev. Lett. **102**, 243602 (2009). Measurement of Autler-Townes and Mollow Transitions in a Strongly Driven Superconducting Qubit.
[4] F. Yan *et al.* Nature Comm. **4**, 2337 (2013). Rotating-frame relaxation as a noise spectrum analyser of a superconducting qubit undergoing driven evolution.

Bell's inequality violation with a single ^{31}P atom electron-nuclear spin pair

Juan P. Dehollain,[1,2] Stephanie Simmons,[1,2] Juha T. Muhonen,[1,2] Rachpon Kalra,[1,2] Arne Laucht,[1,2] Fay Hudson,[1,2] Kohei M. Itoh,[3] David N. Jamieson,[1,4] Jeffrey C. McCallum,[1,4] Andrew S. Dzurak,[1,2] and Andrea Morello[1,2]

[1] *Centre for Quantum Computation and Communication Technology*
[2] *School of Electrical Engineering and Telecommunications, UNSW, Sydney NSW 2052, Australia*
[3] *School of Fundamental Science and Technology, Keio University, 3-14-1 Hiyoshi, 223-8522, Japan*
[4] *School of Physics, University of Melbourne, Melbourne, VIC 3010, Australia*

Bell's theorem sets a boundary between the classical and quantum realms, by providing a strict proof of the existence of entangled quantum states with no classical counterpart. An experimental violation of Bell's inequality demands simultaneously high fidelities in the preparation, manipulation and measurement of multipartite quantum entangled states. For this reason the Bell signal has been tagged as a single-number benchmark for the performance of quantum computing devices [1].

Here we demonstrate deterministic, on-demand generation of two-qubit entangled states of the electron and the nuclear spin of a single phosphorus atom embedded in a silicon nanoelectronic device [2]. By sequentially reading the electron and the nucleus, we show that these entangled states violate the Bell/CHSH inequality with a Bell signal of 2.50(10). An even higher value of 2.70(9) is obtained by mapping the parity of the two-qubit state onto the nuclear spin, which allows for high-fidelity quantum non-demolition measurement (QND) of the parity. Furthermore, we complement the Bell inequality entanglement witness with full two-qubit state tomography exploiting QND measurement, which reveals that our prepared states match the target maximally entangled Bell states with >96% fidelity.

These experiments demonstrate complete control of the two-qubit Hilbert space of a phosphorus atom, and show that this system is able to maintain its simultaneously high initialization, manipulation and measurement fidelities past the single-qubit regime.

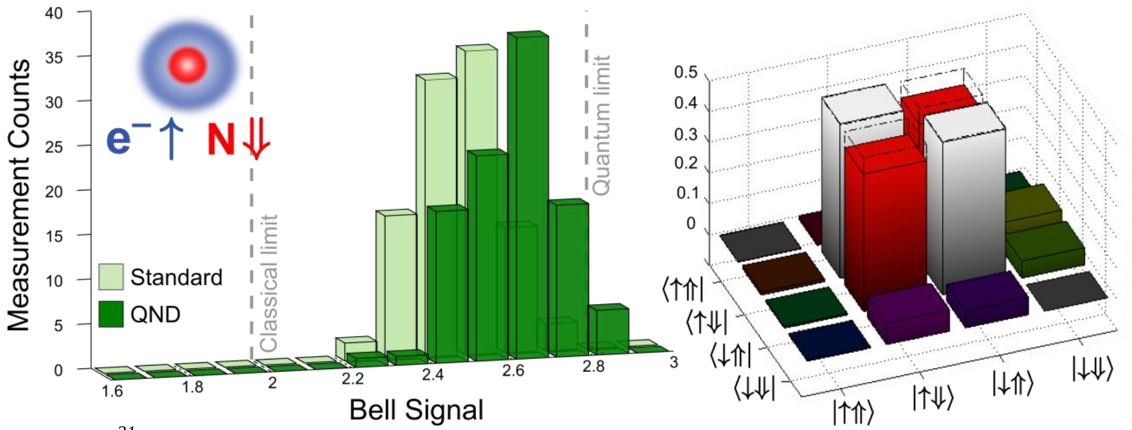


Figure 12. ^{31}P Electron-nuclear entanglement measurements. Left: Histograms of Bell signals obtained from 100 repetitions of the CHSH protocol, using sequential readout of the electron and nucleus (light) and QND parity measurement (dark). Right: Results of density matrix tomography measurement on the $\frac{1}{\sqrt{2}}(|\uparrow\Downarrow\rangle + |\downarrow\Uparrow\rangle)$ *state.*

This research was funded by the ARC Centre of Excellence for Quantum Computation and Communication Technology (project number CE110001027) and the US Army Research Office (W911NF-13-1-0024).

[1] Rowe, *et al*. Nature **409**, 791 (2001); Ansmann, *et al*. Nature **461**, 504 (2009)
[2] Muhonen, *et al*. Nat.Nano. **9**, 986 (2014)

List of Participants

Family Name	First Name	Institution
Abulizi	Gulibusitan	University of Basel
Aguado	Ramon	CSIC
Alidoust	Mohammad	University of Basel
Ando	Kazuya	Keio University
Ares	Natalia	University of Oxford
Auer	Adrian	University of Konstanz
Awschalom	David	University of Chicago
Bagraev	Nikolay	Ioffe Physical Technical Institute, St. Petersburg
Barcikowski	Zachary	UMD-NIST
Baumgartner	Andreas	University of Basel
Berezovsky	Jesse	Case Western Reserve University
Beugeling	Wouter	Technische Universität Dortmund
Beyer-Hans	Kerstin	Swiss Nanoscience Institute
Boettcher	Jens	Scienta Omicron GmbH
Bogan	Alex	University of Waterloo, National Research Council of Canada
Boross	Péter	Eötvös University, Budapest
Botzem	Tim	RWTH Aachen
Braakman	Floris	University of Basel
Bragar	Igor	Polish Academy of Sciences
Brataas	Arne	Norwegian University of Science and Technology
Brauns	Matthias	University of Twente
Broome	Matthew	University of New South Wales
Bruder	Christoph	University of Basel
Brüne	Christoph	University of Würzburg
Buchter	Arne	University of Basel
Camenzind	Leon	University of Basel
Carroll	Chris	University of St. Andrews
Cerfontaine	Pascal	RWTH Aachen
Chen	Wei	ETH Zürich
Cheng	Guanglei	University of Pittsburgh
Chesi	Stefano	Beijing CSRC
Chirolli	Luca	Imdea Nanoscience, Madrid
Choi	Mahn-Soo	Korea University
Christle	David	University of Chicago
Ciorga	Mariusz	University of Regensburg
Corna	Andrea	CEA/INAC Grenoble
Crippa	Alessandro	CNR-IMM-Laboratorio MDM
Csonka	Szabolcs	Budapest University of Techology and Economics
Cywiński	Łukasz	Polish Academy of Sciences

Dankert	André	Chalmers University of Technology
Dartiailh	Matthieu	CNRS-ENS
De Bonis	Sergio Lucio	ICFO
de Boo	Gabriele	University of New South Wales
De Franceschi	Silvano	CEA Grenoble
Dehollain	Juan Pablo	University of New South Wales
Demokritov	Sergej	University of Münster
Dorokhin	Mikhail	Nizhny Novgorod State University
Dwyer	Chris	Duke University
Eichhammer	Emanuel	Max Planck Institute for the Science of Light
Eklund	Anders	KTH Royal Institute of Technology
Eltrudis	Kevin	University of Duisburg-Essen
Ensslin	Klaus	ETH Zürich
Eriksson	Mark	University of Wisconsin-Madison
Erlingsson	Sigurdur I.	Reykjavik University
Eto	Mikio	Keio University
Fabian	Jaroslav	University of Regensburg
Fábián	Gábor	University of Basel
Ferguson	Michael	ETH Zürich
Ferreira	Aires	University of York
Ferreira Morais	Alysson	University of São Paulo
Frank	Tobias	University of Regensburg
Fuchs	Gregory	Cornell University
Fujita	Takafumi	Delft University of Technology
Ganzhorn	Marc	University of Basel
Garcia-Abadillo Uriel	Jose Carlos	Instituto de Ciencia de Materiales de Madrid (CSIC)
Gerhard	Felicitas	University of Würzburg
Ghosh	Joydeep	TU Wien
Golovach	Vitaly	University of the Basque Country
Gramich	Jörg	University of Basel
Gravert	Lars	TU Dortmund
Gül	Önder	Delft University of Technology
Han	Seungju	Korea University
Handschin	Clevin	University of Basel
Hanson	Ronald	QuTech, Delft University of Technology
Harabula	Cezar	University of Basel
Hasler	Thomas	University of Basel
Heinz	Tony	Stanford University
Hennel	Szymon	ETH Zürich
Henriques	Andre	University of São Paulo
Hoffman	Silas	University of Basel
Högl	Petra	University of Regensburg
Hong	Jinki	Korea University

Hsu	Chen-Hsuan	RIKEN
Hutter	Adrian	University of Basel
Irmer	Susanne	University of Regensburg
Itoh	Kohei	Keio University
Iwasaki	Yu	University of Tokyo
Jamonneau	Pierre	Laboratoire Aimée Coton, CNRS
Jarillo-Herrero	Pablo	MIT
Jeong	Se-Young	Pusan National University
Joo	Sungjung	Korea Institute of Standards and Science
Juenger	Christian	University of Basel
Jung	Minkyung	University of Basel
Kaldewey	Timo	University of Basel
Kally	James	Pennsylvania State University
Kalyoncu	Yemliha Bilal	University of Basel
Kanai	Shun	Tohoku University
Kanazawa	Ken	University of Tsukuba
Kancharla	Sarma	American Physical Society
Karalic	Matija	ETH Zürich
Karl	Christoph	Oxford Instruments NanoScience
Kazimierczuk	Tomasz	University of Warsaw
Kim	Sangsu	Korea University
Kim	Taeyueb	Korea University
Kiyama	Haruki	Osaka University
Klinovaja	Jelena	University of Basel
Kloeffel	Christoph	University of Basel
Kobak	Jakub	University of Warsaw
Koenraad	Paul	Eindhoven University of Technology
Kohda	Makoto	Tohoku University
Köhler	Laura	Universität zu Köln
Kolasiński	Krzysztof	AGH University of Science and Technology
Kormanyos	Andor	University of Konstanz
Kornich	Viktoriia	University of Basel
Kosaka	Hideo	Yokohama National University
Kotekar Patil	Dharmraj	INAC, CEA
Krompiewski	Stefan	Polish Academy of Sciences
Kuczmik	Thomas	University of Regensburg
Kuemmeth	Ferdinand	Niels Bohr Institute, University of Copenhagen
Kuhlmann	Andreas	University of Basel
Kukucka	Josip	Johannes Kepler University Linz
Lang	Aicha	University of Basel
Laucht	Arne	University of New South Wales
Lausecker	Elisabeth	Johannes Kepler University Linz
Lemaitre	Aristide	Laboratoire de Photonique et de Nanostructures, CNRS

Lipiński	Stanisław	Polish Academy of Sciences
Loss	Daniel	University of Basel
Luczak	Jakub	Polish Academy of Sciences
MacQuarrie	Evan	Cornell University
Majer	Johannes	TU Wien
Makk	Peter	University of Basel
Maletinsky	Patrick	University of Basel
Malinowski	Filip	Niels Bohr Institute, University of Copenhagen
Marcus	Charles	Niels Bohr Institute, University of Copenhagen
Marie	Xavier	Université de Toulouse, CNRS
Martins	Frederico	Niels Bohr Institute, University of Copenhagen
Matthiesen	Clemens	University of Cambridge
Mehlin	Andrea	University of Basel
Meyer	Ernst	University of Basel
Milivojević	Marko	University of Belgrade
Mintun	Peter	University of Chicago
Mook	Alexander	Max Planck Institute for Microstructure Physics
Morello	Andrea	University of New South Wales
Mourik	Vincent	Delft University of Technology
Mrenca	Alina	AGH University of Science and Technology
Müller	Jan	University of Cologne
Munsch	Mathieu	University of Basel
Nakamura	Yasunobu	University of Tokyo, RIKEN
Nakamura	Taketomo	University of Tokyo
Nakata	Kouki	University of Basel
Nakazawa	Kazuki	Nagoya University
Noiri	Akito	University of Tokyo
Norizuki	Naoto	Nagoya University
Oda	Shunri	Tokyo Institute of Technology
Oiwa	Akira	Osaka University
Osika	Edyta	AGH University of Science and Technology
Otsuka	Tomohiro	RIKEN
Palma	Mario	University of Basel
Palyi	Andras	Eotvos University, Budapest
Patlatiuk	Taras	University of Basel
Pawlowski	Jaroslaw	AGH UST, Krakow
Pearce	Alexander	University of Konstanz
Peddibhotla	Phani	University of Ulm
Pedrocchi	Fabio	RWTH Aachen
Peterfalvi	Csaba	University of Konstanz
Pica	Giuseppe	University of St Andrews
Pioda	Alessandro	SPECS Surface Nano Analysis GmbH
Poggio	Martino	University of Basel

Psaroudaki	Christina	University of Basel
Ramsak	Anton	University of Ljubljana
Ramsteiner	Manfred	Paul-Drude-Institut für Festkörperelektronik
Rancic	Marko	University of Konstanz
Ranjan	Vishal	University of Basel
Rehmann	Mirko	University of Basel
Rickhaus	Peter	University of Basel
Riedel	Daniel	University of Basel
Rohling	Niklas	University of Konstanz
Rohner	Dominik	University of Basel
Rossella	Francesco	NEST, Scuola Normale Superiore and CNR-NANO
Rossi	Nicola	University of Basel
Russ	Maximilian	University of Konstanz
Ryu	Jeongchun	Tohoku University
Samarth	Nitin	Penn State University
Schäpers	Thomas	Research Center Jülich
Scheller	Christian	University of Basel
Schliemann	John	University of Regensburg
Schoenenberger	Christian	University of Basel
Schrade	Constantin	University of Basel
Schreiber	Lars	JARA-Institute for Quantum Information, RWTH Aachen
Schroeter	Sarah	Institute for Theoretical Physics, Cologne
Schuetz	Martin	Max-Planck-Institute for Quantum Optics
Sekiguchi	Yuhei	Yokohama National University
Seo	Yongho	Sejong University
Serina	Marcel	University of Basel
Shields	Brendan	University of Basel
Simon	Pascal	University Paris Sud
Siusys	Aloyzas	IP PAS
Šmejkal	Libor	ASCR, Prague
Stano	Peter	RIKEN
Stepanenko	Dimitrije	Institute of Physics Belgrade
Stiehl	Gregory	Cornell University
Sverdlov	Viktor	TU Wien
Szafran	Bartlomiej	AGH University of Science and Technology
Szombati	Daniel	TU Delft
Szumniak	Pawel	University of Basel
Tagliaferri	Marco	CNR-IMM-Laboratorio MDM
Takeda	Kenta	RIKEN
Tarasenko	Sergey	Ioffe Institute
Tarucha	Seigo	University of Tokyo
Teleberg	Gustav	Oxford Instruments NanoScience
Tiwari	Rakesh	University of Basel

Tokura	Yoshinori	RIKEN
Torelli	Piero	CNR-IOM
Trif	Mircea	University Paris Sud
Truhlar	Alisha	Johannes Kepler University Linz
Tserkovnyak	Yaroslav	UCLA
Ullah	Saeed	University of São Paulo
van Beek	Ian	University of St Andrews
van der Wal	Caspar	University of Groningen
Vignale	Giovanni	University of Missouri
Vitiello	Elisa	Università degli Studi di Milano-Bicocca
Voisin	Benoit	University of New South Wales
Volk	Christian	Niel Bohr Institute, University of Copenhagen
Vukusic	Lada	Johannes Kepler University Linz
Waizner	Johannes	University of Cologne
Wang	Kai	University of Twente
Wang	Heng	University of Konstanz
Watson	Thomas	University of New South Wales
Watzinger	Hannes	Johannes Kepler University Linz
Weiss	Markus	University of Basel
Wenk	Paul	University of Regensburg
Wojcik	Pawel	AGH University of Science and Technology
Wójcik	Krzysztof	Adam Mickiewicz University, Poznań
Wolf	Michael	Case Western Reserve University
Wootton	James	University of Basel
Wrześniewski	Kacper	Adam Mickiewicz University, Poznań
Wyss	Marcus	University of Basel
Xiao	Ming	University of Science and Technology of China
Xue	Qikun	Tsinghua University
Yakimenko	Irina	Linköping University
Yamaguchi	Terufumi	Nagoya University
Yang	Guang	RIKEN
Yazdani	Ali	Princeton University
Yeats	Andrew	University of Chicago & UC Santa Barbara
Yokoyama	Tomohiro	Delft University of Technology
Yu	Liuqi	University of Basel
Zhou	Brian	University of Chicago
Zihlmann	Simon	University of Basel
Zipper	Elzbieta	University of Silesia, Katowice
Zumbühl	Dominik	University of Basel
Zwanenburg	Floris	University of Twente
Zyuzin	Alexander	University of Basel

8th International School and Conference on Spintronics and Quantum Information Technology (SPINTECH VIII)

Aug 10-13, 2015; Basel, Switzerland

	Monday Aug 10	Tuesday Aug 11
8:00-	Registration	
8:45-9:00	Opening	
9:00-10:10	Awschalom	Marcus
10:10-10:40	Coffee break	Coffee break
10:40-11:50	Tarucha	Tserkovnyak
11:50-12:25	Marie	Zumbühl
12:25-14:30	Lunch break	Lunch break Posters A
14:30-15:05	Xue	
15:05-16:15	Klinovaja	Stano Ensslin
16:15-16:45	Coffee break	Coffee break
16:45-17:55	Nakamura	Jarillo-Herrero Ando
17:55-18:05	Short break	Short break
18:05-18:40	Majer	Gül
18:40-19:15	Brüne	Chesi; Henriques
19:15-19:50		Smejkal; Mook
	19:30 welcome reception	20:30 city tour

Wednesday Aug 12	Thursday Aug 13	
Heinz	Fujita; Broome	9:00-9:35
Demokritov	Morello	9:35-10:10
Coffee break	Coffee break	10:10-10:40
Brataas	Itoh	10:40-11:15
Tokura	De Franceschi	11:15-11:50
Poggio	Eriksson; Brauns	11:50-12:25
Lunch break Posters B	Lunch break	12:25-14:30
	Vignale; Botzem	14:30-15:05
Maletinsky	Oiwa	15:05-15:40
Christle	Samarth	15:40-16:15
Coffee break	Coffee break	16:15-16:45
Yazdani	Yeats; Cheng	16:45-17:20
Meyer; Csonka	Trif	17:20-17:55
Short break	Short break	17:55-18:05
Fabian	Kohda; Schäpers	18:05-18:40
Fuchs; Hennel	Aguado; Baumgartner	18:40-19:15
20:00 conference dinner		

school lecture: 60'+10'

conference talk: 30'+5'

contributed talk: 15'+2.5'