2nd School and conference on

Spin-based quantum information processing

PROGRAM AND ABSTRACTS

UNI BASEL

Universität Konstanz

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2nd School and Conference on

Spin-based quantum information processing

Steigenberger Inselhotel, Konstanz, Germany

Monday, August 18

08:00 -	Registration
Opening 08:45 - 09:00	**Guido Burkard** and **Daniel Loss**
School Lecture 09:00 - 10:10	**Seigo Tarucha** (*University of Tokyo*) Triple and quadruple quantum dots for making multiple qubits p. 10
10:10 - 10:40	Coffee break
School Lecture 10:40 - 11:50	**David Awschalom** (*University of Chicago*) Quantum spintronics: controlling spin and orbital dynamics in solid state defects p. 11
Conference Talk 11:50 - 12:25	**Jörg Wrachtrup** (*Univ. Stuttgart*) Precision metrology using spin qubits p. 12
12:25 - 14:30	Lunch break
Conference Talk 14:30 - 15:05	**Jonathan Finley** (*TU München*) Optical control and measurement of spins in self-assembled quantum dots p. 13
School Lecture 15:05 - 16:15	**Andrew Dzurak** (*Univ. New South Wales*) Spin Qubits in Silicon p. 14
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Invited Talks

School and Conference

Abstracts

Triple and quadruple quantum dots for making multiple qubits

Seigo Tarucha

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To date various types of 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 a double quantum dot. The necessary step for further scaling up the qubit system is to increase the number of quantum dots having a suitable charge state for qubit system and improve the qubit gate fidelity as well. We have optimized the micro-magnet technique to speed up the X and Z-rotation with a high spin-flip fidelity. In addition we have fabricated three or four tunnel coupled quantum dots in series for making three or four spin qubits. For the triple quantum dot we use two plunger gates for the two side dots to derive a charge stability diagram and establish the most suitable charge state configuration for making three spin qubits: one electron in each dot and spin blockade for the coupled center and right dot as well as for the left and center dot. We use this configuration to demonstrate c.w. electron spin resonance and Rabi oscillation for the three dots. For the quadruple quantum dot we first reach the single electron regime for each dot and furthermore demonstrate an efficient tunability of the system in this regime, with which we are able to realize the proper charge state configurations for spin blockade readout.

Quantum spintronics: controlling spin and orbital dynamics in solid state defects

F. Joseph Heremans, Lee C. Bassett, David J. Christle, Abram L. Falk, Paul V. Klimov, Greg Calusine, Christopher G. Yale, William F. Koehl, Bob B. Buckley, and David D. Awschalom

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As traditional transistor-based electronics rapidly approach the atomic scale, small amounts of disorder begin to have outsized negative effects. Surprisingly, one of the most promising pathways out of this conundrum may emerge from recent efforts to embrace defects as the basis for future quantum machines. Recently, 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 [1]. The nitrogen-vacancy (NV) center in diamond is an optically addressable, solid-state spin that has enabled gigahertz coherent control, nanofabricated spin arrays, nuclear spin 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 [2]. Using ultrafast optical pulses, we investigate the coherent orbital dynamics of the NV center excited state that occur on nanosecond to femtosecond timescales. In a similar manner, we also probe the excited state spin dynamics of the NV center and achieve rotations of the spin state on sub-nanosecond timescales. With this ultrafast pump-probe spectroscopy, we demonstrate arbitrary-axis spin rotations and controlled unitary evolution within the full spin-triplet manifold. These techniques provide a time-domain probe to investigate Hamiltonian dynamics as well as a pathway toward integrating solid-state spin qubits with photonic networks.

Alongside research efforts in diamond, an alternative approach seeks to identify and control new spin systems with an expanded set of technological capabilities, a strategy that could ultimately lead to "designer" spins with tailored properties for future quantum information processing [3]. Color centers in silicon carbide 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 [4, 5]. We present recent advances in this rapidly developing field including electrically driven spin resonance [6], coherent spin-strain coupling [7], photonic crystal cavities [8], and the control of individual spins [9] for quantum information processing.

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Precision metrology using spin qubits

Jörg Wrachtrup

3rd Physics Institute, Stuttgart University, Germany

Long coherence times and excellent coherent control are essential to precision quantum limited measurements and characteristic of spins in solid. As a result, spin qubits in diamond are excellent system for solid-based precision measurements. Using dedicated coherent control techniques, I will show the detection and imaging of few nuclear spins. Quantum non-demolition measurements can enhance the measurement sensitivity. Further, we used a quantum memory to store the phase of the sensing electron spin into nuclear spins. By this, we increased spectral resolution of those experiments to the level of a few hundred Hz.

Optical control and measurement of spins in self-assembled quantum dots

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Over recent years the mechanisms that mediate spin relaxation and decoherence in optically active, strained quantum dots (QDs) have been elucidated by a variety of beautiful optical experiments [1,2]. For both electrons and holes trapped in self-assembled dots, hyperfine coupling to the nuclear spin system sets the fundamental timescales for spin coherence at low temperatures. In this presentation we will review recent efforts in our lab in which ultrafast optical pulses are used to optically initialize, probe and control the spin state of excitons and individual charges over sub nanosecond timescales [3-5]. We demonstrate how a precisely timed sequence of ultrafast optical pulses, with a well defined polarisation state can be used to prepare arbitrary superpositions of exciton spin states, achieve ultrafast control of the spin-wavefunction without an applied magnetic field and perform high fidelity read-out the quantum state in an arbitrary basis by detecting a strong (~2-10 pA) photocurrent flowing in an external circuit connected to the dot [6]. Results show how the polarisation state of optical field can be faithfully mapped onto the exciton spin wavefunction, manipulated via geometric phase control and read out via spin-selective stimulated exciton emission or conditional biexciton absorption [3,4]. Since optical spin control takes place over sub nanosecond timescales combined quantum state preparation, control and read-out can be performed with high fidelity (>97%). Using spin storage devices, in which optically prepared electrons are prevented from tunneling out of the dot by an AlGaAs barrier, single spins can be resonantly prepared and trapped over long timescales, extending into the millisecond regime [7,8]. After all optical *electron* spin preparation using a resonant picosecond laser pulse, we switch the electric field to trap the spin and read out the instantaneous spin projection of the electron spin along the optical axis ($\langle S_z \rangle$) by performing spin-to-charge conversion using a second laser pulse and, subsequently, detect luminescence arising from cycling of an excited charged exciton transition [7]. In this way, count rates of ~500 counts / second / spin are obtained allowing us to monitor electron spin relaxation in a single dot for timescales ranging from ~ 0.2ns up to $\sim 10\mu$s for externally applied magnetic fields $-60mT \leq B_0 \leq 60mT$. At $B_0 \sim 0T$ the time dependence of $\langle S_z(t) \rangle$ is well described by theory [1], from which we extract the width of the nuclear spin distribution $\Delta_B = 12 \pm 0.6$mT, the electron g-factor (g_e=0.67) and the characteristic timescales for spin relaxation due to electron precession in the frozen hyperfine field of the dot ($T_\Delta = 1.4 \pm 0.05$ns) and the nuclear spin precession in the hyperfine field of the electron ($T_K = 310 \pm 20$ns).

We gratefully acknowledge the DFG and EU for financial support via SFB-631 and S3Nano, respectively.

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Spin Qubits in Silicon

Andrew S. Dzurak

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Spin qubits in silicon are excellent candidates for scalable quantum information processing [1] due to their long coherence times and the enormous investment in silicon MOS technology. I will discuss qubits based upon single phosphorus (P) dopant atoms in Si and also upon Si-MOS quantum dots [2]. Projective readout of such qubits had proved challenging until single-shot measurement of a single donor electron spin was demonstrated [3] using a silicon single electron transistor (Si-SET) and the process of spin-to-charge conversion. The long spin lifetimes, of order seconds, that were observed [3] opened the path to demonstration of electron and nuclear spin qubits in silicon.

Integration of an on-chip microwave transmission line enables single-electron spin resonance (ESR) of P donor electrons. This has been used to realise Rabi oscillations of an electron spin qubit, while a Hahn echo sequence reveals electron spin coherence times $T_2 > 0.2$ ms [4]. Single-shot readout of the ^{31}P nuclear spin (with fidelity $> 99.8\%$) can be obtained by monitoring the two hyperfine-split ESR lines of the P donor system. By applying (local) NMR pulses, coherent control of a nuclear spin qubit can then also be achieved, revealing coherence times $T_2 > 60$ ms in naturally occurring silicon [5].

Finally, I discuss recent experiments on both single-atom and Si-MOS quantum dot qubits in isotopically enriched ^{28}Si devices, with even longer spin coherence times reaching $T_2 = 30$ seconds [6].

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Introduction to topological error correction and computation

James Wootton

Universitaet Basel

In order to ward off the effects of decoherence in quantum systems, as required for quantum computation, methods such as quantum error correction must be employed. There has recently been a great deal of interest in topological error correction, specifically that involving the so-called surface codes. These store qubits in the collective states of many body spin systems, and detect the effects of noise acting on the system using local operators. The encoding of the qubits can be interpreted in terms of exotic quasiparticles known as anyons. Using the unique exchange properties of the anyons, the code can also be used to perform fault-tolerant quantum computation on the qubits. This talk reviews the basics of these codes and the kind of spin systems with which they may be realized.

Nuclear magnetism in semiconductor quantum dots

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Recent fast advances in device fabrication and development of sophisticated experimental techniques enabled major breakthroughs in applications of semiconductor nanostructures for control of single spins and generation of non-classical light. This research has been largely driven by the prospects for novel applications in quantum computation and quantum cryptography, for which III-V semiconductor quantum dots (QDs) present a very versatile quantum system suitable for both electrical and optical addressing. It has been found that both single spin manipulation and generation of entangled photons in a dot requires understanding and control of the magnetic environment in the dot formed by 10^4-10^5 nuclear spins of the lattice. Effectively, the task of the electron (or hole) spin qubit control escalates to the so-called 'central spin problem' where the central spin interacts with a spin bath also exhibiting internal interactions. In order to gain insight in this problem it is important to understand the nuclear spin system itself, which in our recent work has been addressed in nuclear magnetic resonance (NMR) studies of single QDs. Such nano-NMR enables new insights in the nuclear spin bath properties including its frequency spectrum, dynamics and interactions with the electron (or hole) central spin [1-5]. One of the important conclusions of this work is that strained semiconductor QDs contain a quiescent nuclear spin system with a potential to host highly coherent electron and hole spin qubits [5,6]. This property has been previously overlooked both in theory and experiment due to the lack of the experimental NMR data for highly strained semiconductor nanostructures.

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Charles M. Marcus

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SPIN QUBITS AND LONG-RANGE ENTANGLEMENT

Daniel Loss
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Starting from a brief overview of the present status of spin qubits in semiconducting nanostructures such as quantum dots and nanowires for electron and hole spins [1], I will address the fundamental challenges of scalable quantum computing architectures and propose new directions based on long-distance entanglement based on microwave cavities for electron [2] and for hole spin qubits [3], floating metallic gates [4], or ferromagnetic wires [5].

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Loss-DiVincenzo qubits in silicon and GaAs

Lieven Vandersypen

TU Delft

The canonical qubit represented by the state of a single electron spin remains one of the most attractive qubit realizations today. In the last year, our group has made progress in controlling single-spin qubits on two fronts. In gate defined GaAs/AlGaAs quantum dot arrays, we have recently demonstrated multi-qubit read-out, while multi-qubit manipulation is on-going [1]. In Si/SiGe quantum dots, we have realized highly coherent spin rotations, with a T2* almost two orders of magnitude longer than in GaAs, thanks to the largely nuclear spin free host material [2]. Moving forward, we will aim at multi-qubit circuits in Si/SiGe.

[1] M. Shafiei, T. Baart, et al., unpublished
[2] E. Kawakami, P. Scarlino, et al., arxiv:1404.5402

Several Qubit Quantum Computers with Quantum Dots

David DiVincenzo

RWTH & Forschungszentrum Jülich

In this talk I will describe several variants on the basic motif of quantum-dot qubits that could be valuable in performing optimal quantum gates in few-qubit structures, with an eye towards scalability. Here are the results to be covered:

1. For the exchange-only (triple-dot) qubit, we analyse noise sensitivity and gating approaches.
2. For single-triplet (double dot) qubits, we show how using 3-electron dots (6 electrons total) can lead to reduced charge noise sensitivity in the appropriate mode of operation.
3. We show how two ST qubits can be effectively coupled via one quantum state of, e.g., and intervening quantum dot, giving economical operation sequences for two qubit gates.
4. Adding spin-orbit interaction to the 2-electron ST qubit enables new kinds of Landau-Zener-Stueckelberg gates if the dots are of different confining strengths.

All work performed with S. Mehl.

Spin Manipulation In Triple Quantum Dots

Andy Sachrajda

National Research Council of Canada

This talk will cover recent experimental and theoretical work on two aspects of spin manipulation in triple quantum dots (i) targeting a specific qubit and (ii) non-local transfer. The triple quantum dot system is complex. It will be shown how the coherent behaviour depends on the experimental pulse characteristics. In total four coherent behaviours are observed, including the all-exchange qubit, Landau-Zener-Stückelberg oscillations and their interference. Triple quantum dots provide a good platform for demonstrating no-local transport phenomena in which an electron can be transported via a coherent superposition from one edge quantum dot to another with only a virtual change in the occupation of the center quantum dot. Two configuration scenarios will be presented, one in which the transfer is accompanied by a spin flip and one where it is not. In the configuration where the center quantum dot is always emptied it will be argued that this process involves the non-local transfer of an arbitrary spin state.

This work was collaboration between NRC, and the groups of Gloria Platero (CSIC, Madrid) and Michel Pioro-Ladrière (University of Sherbrooke)

Scale-up and Control of Spin Qubit 2D Arrays

David Reilly

The University of Sydney

Manipulating the state of a large-scale 2D spin system presents unique challenges in comparison to the few-qubit devices of today's experiments. Error correcting codes, for instance, likely require the individual control and readout of millions of qubits in order to produce a fault-tolerant and useful quantum machine. This talk will present work underway to address many of the technical challenges associated with large-scale quantum hardware, including the development of 2D arrays of spin qubits controlled by cryogenic electronics.

Explorations on the Quantum Communications for Spin Qubits

Xuedong Hu and Peihao Huang

University at Buffalo

Recent experimental and theoretical research on spin qubits in quantum dots have clearly demonstrated that spins have long coherence times and can be reliably controlled. Electron spin two-qubit gates can be performed using the strong exchange interaction between dots, which however is short-ranged. How to achieve long-range quantum communication for spin qubits remains a significant open problem in the scale-up of spin qubit architectures. Here I give an overview of the various approaches we have studied to achieve spin information transfer, such as those based on spin-photon coupling, or based on a spin bus made from a spin chain. I will then focus on a particular approach that involves the transportation of the electrons themselves, which is attractive because of its conceptual simplicity and its similarity to the conventional charge-coupled devices. I will discuss our recent work on the physics of electron spin decoherence when the quantum dot is in motion. Specifically, we find that the motion induced spin decoherence is a pure longitudinal relaxation channel, whose rate depends on the disorder in the substrate, the strength of the magnetic field, and the speed of the quantum dot motion. Our results not only show how severe a problem this decoherence could be, but also clearly indicate how to reduce the decoherence effects of electron motion.

We thank support by US ARO and NSF PIF.

Quantum control and process tomography of a semiconductor quantum dot hybrid qubit

M. A. Eriksson[1]

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Recently it was proposed theoretically that a fast and high fidelity hybrid qubit could be formed by placing three electrons into an electrostatically gated semiconductor double quantum dot [1,2]. While this qubit is formed in two quantum dots, it shares symmetries with the exchange-only qubit formed in three quantum dots [3-5]. Previously we demonstrated experimentally that short gate voltage pulses applied to a double dot in the (2,1) charge state can generate coherent oscillations to a set of several different quantum states having charge distributions of either (2,1), (1,2), or a superposition of both [6].

In this talk I discuss new results that demonstrate experimentally the formation of the three-electron hybrid qubit in a double quantum dot [7]. Initialization of the qubit is performed by tuning the gate voltages of a Si/SiGe double quantum dot so that the charge occupation is (2,1) and subsequently applying a sequence of gate voltage pulses. Measurement is performed by mapping qubit logical 0 to the (2,1) charge state and qubit logical 1 to the (1,2) charge state. We show that the state of the qubit can be manipulated to arbitrary points on the Bloch sphere, and we demonstrate both X and Z rotations. Process tomography of these gates is performed, and we extract fidelities of at least 85% for X gates and 94% for Z gates.

The work discussed here was supported in part by ARO (W911NF-12-0607). Development and maintenance of the growth facilities used for fabricating samples is supported by DOE (DE-FG02-03ER46028). This research utilized NSF-supported shared facilities at the University of Wisconsin-Madison. This work was performed in collaboration with 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, and S. N. Coppersmith.

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Suppressing qubit dephasing using real-time Hamiltonian estimation

Michael Shulman

Harvard University

Unwanted interaction between a quantum system and its fluctuating environment leads to decoherence and is the primary obstacle to establishing a scalable quantum information processing architecture. Strategies such as environmental and materials engineering, quantum error correction and dynamical decoupling can mitigate decoherence, but generally increase experimental complexity. We improve coherence in a qubit using real-time Hamiltonian parameter estimation. Using a rapidly converging Bayesian approach, we precisely measure the splitting in a singlet-triplet spin qubit faster than the surrounding nuclear bath fluctuates. We continuously adjust qubit control parameters based on this information, thereby improving the inhomogenously broadened coherence time (T2*) from tens of nanoseconds to above 2 microseconds and demonstrating the effectiveness of Hamiltonian estimation in reducing the effects of correlated noise in quantum systems. Because the technique demonstrated here is compatible with arbitrary qubit operations, it is a natural complement to quantum error correction and can be used to improve the performance of a wide variety of qubits in both metrological and quantum-information-processing applications.

Hole spin dephasing and spin-orbit coupling in Ge/Si nanowires

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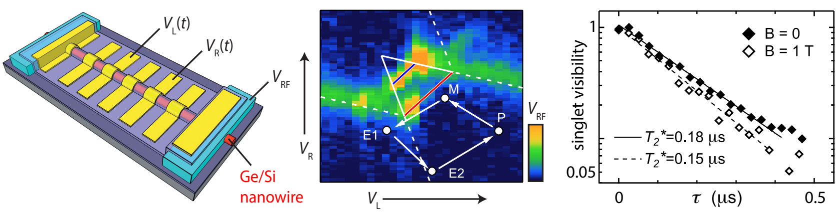
Spin states within the valence band of Ge/Si nanowires are attractive candidates for qubits. Due to the rareness of nuclear spins in Ge and Si, dephasing by uncontrolled Overhauser fields is expected to be strongly suppressed. Spin-orbit coupling is expected to be tunable in situ by transverse electric fields, and may allow fast spin manipulation and selective qubit coupling in qubit-superconducting cavity architectures [1].

By confining holes in a single quantum dot we perform transport measurements as a function of magnetic field. We observe — for the first time — antilocalization in the Coulomb blockade regime, consistent with strong spin-orbit coupling. By comparing the low-field Coulomb peak height distribution with the symplectic symmetry class of random matrix theory, we are able to place an upper bound of 25 nm on the spin-orbit length [2].

By tuning the device into a double quantum dot we manipulate and measure the spin states using fast (sub-nanosecond) gate pulses and dispersive readout using a radio-frequency LC charge sensor. We observe an inhomogeneous spin dephasing time $T_2^* \sim 0.18\ \mu$s that exceeds corresponding measurements in III-V semiconductors by more than an order of magnitude, as expected for predominantly nuclear-spin-free materials. Unlike the Gaussian dephasing previously seen in nuclear-spin-dominated materials, we observe a loss of coherence that is exponential in time, indicating the prresence of a broadband noise source [3].



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Engineering an Artificial Electron-Phonon Coupling in Ultra-Clean Nanotube Mechanical Resonators

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The coupling between electrons and phonons is at the heart of many fundamental phenomena in physics. In nature, this coupling is generally predetermined for both, molecules and solids. Tremendous advances have been made in controlling electrons and phonons in engineered nano systems, yet, control over the coupling between these degrees of freedom is still widely lacking. In this talk I will describe a new generation of carbon nanotube devices that allow us to tailor an artificial electron- phonon coupling at will. In these devices we are able to form highly-tunable single and double quantum dots at arbitrary locations along a nanotube mechanical resonator. We find that electron-phonon coupling can be turned on and off by controlling the position of a quantum dot along the resonator. Using more elaborate double quantum dots we structure the interactions in real space to couple specific electronic and phononic modes. Exploiting this tailored coupling we can measure the parity of phonons in real space and even directly image their mode shapes. Remarkably, we demonstrate tailored coupling of phonons to internal electrons in an isolated system, decoupled from the random environment of the electronic leads, a crucial step towards fully-engineered quantum coherent electron-phonon systems. These results open new vistas for engineering electron-phonon phenomena in a controlled nanoscale setting and offer important new tools for entangling the electronic and mechanical degrees of freedom at the quantum level.

Towards quantum spintronics on a silicon platform

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Quantum spintronics aims at utilizing the quantum nature of individual spins to bring new functionalities into logic circuits. Owing to a suppressed hyperfine coupling, silicon-based nanostructures can allow for long spin coherence times, a key requirement for quantum spintronics. Here I will present recent experimental progress on the confinement and control of individual holes in Si and SiGe devices, including nanotransistors fabricated with 300-mm CMOS technology. As opposed to electrons, holes own a sizable spin-orbit coupling, which can be exploited for fast coherent spin manipulation. Implications for electrically driven hole spin qubits will be discussed.

Spin-orbit Interaction and Exotic Bound States: Majorana Fermions and Parafermions

Jelena Klinovaja

Cambridge University

In my talk, I will present recent results on exotic bound states in one-dimensional condensed matter systems that have attracted wide attention due to their promise of non-Abelian statistics useful for topological quantum computing. For example, Majorana fermions can emerge in a variety of setups in which either standard or synthetic spin-orbit interaction is present. Here, I will discuss candidate materials such as semiconducting Rashba nanowires [1-2], graphene nanoribbons [3], atomic magnetic chains or magnetic semiconductors [4]. At the same time, much effort is invested in identifying systems that host even more exotic quasiparticles than Majorana fermions that obey non-Abelian statistics of the Fibonacci type. Generating such quasiparticles is a crucial step towards a more powerful braid statistics that enables universal topological quantum computing. In my talk, I will discuss time-reversal invariant parafermions. This setup consists of two quantum wires with Rashba spin-orbit interactions coupled to an s-wave superconductor, in the presence of strong electron-electron interactions [5].

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Majoranas in 1 & 2D superconducting-semiconducting devices

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Majorana fermions that can emerge in one or two dimensional solid state structures do not obey Fermi statistics. Instead they are predicted to follow non-Abelian statistics and therefore the term *fermion* might as well be dropped and simply call them *Majoranas*. We will discuss how Majoranas can arise in super-semi devices and how circuits should be designed in order to use them as qubits in schemes for topological quantum computing. The topological protection is based on the parity in the particle number. We discuss parity dynamics and show experiments demonstrating a parity lifetime of order seconds. In 2D topological quantum well devices Majoranas can arise in the edge modes near transitions between trivial and topological phases. We demonstrate edge modes in InAs/GaSb quantum wells.

Work done in collaboration with Attila Geresdi, David van Woerkom, Vlad Pribiag Fanming Qu, Arjan Beukman, Christophe Charpentier, Werner Wegscheider and others.

Spin-orbit effects in p-type QPCs

K. Ensslin, F. Nichele, S. Chesi, S. Hennel, A. Wittmann, C. Gerl, W. Wegscheider, D. Loss, T. Ihn

ETH Zürich

We present transport experiments performed in high quality quantum point contacts embedded in a GaAs two-dimensional hole gas with very strong spin-orbit interaction. This results in peculiar transport effects, such as a strong anisotropic Zeeman splitting and level dependent effective g-factor. Here we show evidences of an additional effect, namely the anti-crossing of different bands with opposite spin in an out-of-plane magnetic field. The anti-crossing is further studies as a function of in-plane magnetic field. Suppressing the anti-crossing with a large in-plane field, we determine the out-of-plane g-factor. For large subband index it reaches the theoretically predicted value of $g^* = 7.2$. The anti-crossing and the level dependent g-factors are reconciled in a model where the cubic in k_{parallel} Rashba spin-orbit interaction in hole systems plays a crucial role.

Spin dynamics in graphene quantum dots

Björn Trauzettel

Universität Würzburg, Germany

We study the dynamics of an electron spin in a graphene quantum dot which is interacting with a bath of nuclear spins via anisotropic hyperfine interaction. For a large number of nuclear spins, we employ the Nakajima-Zwanzig equation whereas, for a small number of nuclear spins, we use exact diagonalization to calculate the long-time average of the electron spin as well as its decoherence time. Interestingly, we predict remarkable long decoherence times of more than 10 ms in the limit of few nuclear spins. Finally, we explain how our system can be exploited to experimentally prove concepts of quantum thermodynamics.

Multi-photon commensuration resonances in strongly-driven few level systems

Mark Rudner

Copenhagen University

While an ideal qubit is a two-level quantum system, the physical systems in which they are implemented inevitably host more than just two states. Here we investigate the driven quantum dynamics of a three-level system, where a single level is repeatedly swept through a pair of fixed qubit levels. This setup is relevant for a variety of systems, including superconducting flux qubits, electron spin qubits, and some atomic systems. We focus on the ultra-strong driving regime, where the driving amplitude is much larger than the level spacing. Here we find a new type of multi- photon resonance, mediated by the auxiliary level, which arises when the qubit free precession period is commensurate with an even number of driving periods. In contrast to conventional multi-photon resonances, here the corresponding transition rates are insensitive to pulse shape and amplitude, depending only on the total time between level crossings. Characteristic signatures and the relevance for experiments in flux qubits and quantum dots will be discussed.

High fidelity gates, single shot correlation spectroscopy and dephasing of GaAs two-electron spin qubits

Hendrik Bluhm[1]

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While coherence measurements of two-electron spin qubits in gated GaAs quantum dots promise remarkably high gate fidelities, realizing these is nontrivial because of hardware limitations, the breakdown of the rotating wave approximation, and nonlinearity of the qubit control. We have numerically optimized single-qubit control pulses obtained based on models taking the most important experimental constraints into account [1] (Fig. 1). Using experimentally determined noise spectra [2] of both electrical and nuclear spin fluctuations, we predict fidelities as high as 99.9%. To reach these, systematic pulse errors likely will have to be eliminated based on measured error indicators. We show that this is possible using a bootstrap protocol [3].

I will also discuss measurements that indicate that the Hahn-echo dephasing time of electron spins in gated GaAs quantum dots is limited by dephasing of the nuclear Larmor precession due to quadrupolar coupling to electric fields. This effect can be eliminated by rotating the magnetic field. However, an additional echo envelope modulation that can be attrbuted to $g-$factor anisotropy appears when doing so.

Finally, I will outline a measurement technique based on correlating single shot measurements which can probe the noise spectrum seen by a qubit over a very wide frequency range [4]. It can also qualitatively test the quantumness of the environment by detecting a back-action from the qubit on the latter [5].

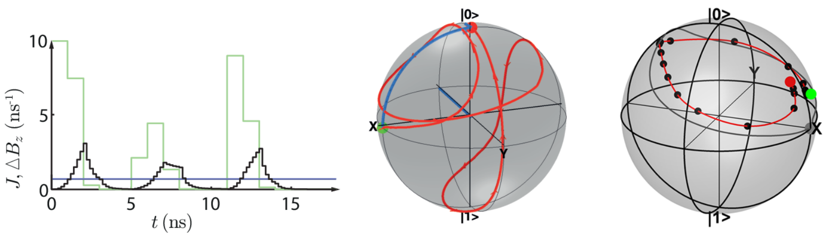

Figure 1: left and middle: Exemplary $Y_{\pi/2}$-gate with predicted fidelity $1 - \mathcal{F} = 1.5 \times 10^{-3}$. Ideal control pulses of the exchange coupling J (green) are smoothed due to finite bandwidth effects (black). The corresponding Bloch sphere trajectory (middle) is plotted for a specific initial state (green dot). Right: Preliminary experimental realization of a non-trivial identity operation and the corresponding theoretical trajectory (grey).

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Superconducting edge-mode transport in InAs/GaSb heterostructures

Arjan Beukman [1], Vlad Pribiag [1], Fanming Qu [1], Christophe Charpentier [2], Werner Wegscheider [2], Leo Kouwenhoven [1]

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Type-II InAs/GaSb heterostructures have recently attracted interest as a two-dimensional topological insulator that can be tuned between the normal and topological quantum phase by means of electrostatic gating. In proximity to a superconductor, 2D topological insulators are predicted to host Majorana zero-modes, a consequence of the helical nature of their edge conduction modes. Here we report superconductivity mediated by the edge modes of InAs/GaSb quantum wells. Using superconducting quantum interference (SQI), we demonstrate tuning between edge-dominated and bulk dominated transport regimes as a function of electrostatic gating. These experiments establish InAs/GaSb as a robust platform for further investigations of Majorana physics.

Soft decoding a quantum measurement apparatus

Bill Coish

McGill University, Montréal

Quantum measurements are commonly performed by thresholding a collection of analog detector- output signals to obtain a sequence of single-shot bit values. The intrinsic irreversibility of the mapping from analog to digital signals discards soft information associated with an a posteriori confidence that can be assigned to each bit value when a detector is well- characterized. Accounting for soft information, we show significant improvements in enhanced state detection with the quantum repetition code as well as quantum state/parameter estimation. These advantages persist in spite of non-Gaussian features of realistic readout models, experimentally relevant small numbers of qubits, and finite encoding errors. These results show useful and achievable advantages for a wide range of current experiments on quantum state tomography, parameter estimation, and qubit readout.

Quantum networks based on diamond spins: fundamental tests and long-distance teleportation

Ronald Hanson

Kavli Institute of Nanoscience, Delft University of Technology

The realization of a highly connected network of qubit registers is a central challenge for quantum information processing and long-distance quantum communication. Diamond spins associated with NV centers are promising building blocks for such a network as they combine a coherent optical interface (similar to that of trapped atomic qubits) with a local register of robust nuclear spin qubits [1]. At the same time, the excellent control of NV centers allows for testing and demonstrating fundamental concepts in physics such as qubit steering by adaptive partial measurements [2].

Here we present our latest progress towards scalable quantum networks. We have recently realized unconditional teleportation between long-lived qubits residing in independent setups [3]. The teleportation exploits entanglement between distant NV electronic spins that is generated through spin-photon entanglement and subsequent photon detection [4]. By encoding the source state in a separate qubit (a single nuclear spin) we realize a Bell state measurement that distinguishes between all four outcomes in a single shot. Analysis shows that the obtained fidelities are high enough for a loophole-free violation of Bell's inequalities. Latest results towards this goal will be given.

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Nonlinearites in electrically driven spin resonance

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The usual way to coherently control the spin of a single electron is to use electron spin resonance (ESR), i.e., to put the electron in a dc magnetic field, and apply a transversal ac magnetic field pulse. Under certain conditions, the ac magnetic field pulse can be substituted by an ac electric field pulse: the latter couples to the charge of the electron and thereby induces an oscillatory motion of the wave function. In turn, this oscillatory motion results in spin Rabi oscillations, provided that a sufficiently strong interaction between the orbital and spin degrees of freedom (e.g., spin-orbit interaction, inhomogeneous B-field, hyperfine interaction, etc) is present in the system [1,2,3].

In the talk, I will introduce a simple model of electrically driven spin resonance, in which the coupled orbital-spin dynamics arises due to a static, but spatially disordered magnetic field [4]. I will describe single- and multi-photon resonances in this model, and show that for any of these resonances, the spin Rabi frequency is a nonlinear, and moreover, a non-monotonic function of the amplitude of the ac electric field. Furthermore, for strong driving, the multi-photon Rabi frequencies become comparable to the single-photon Rabi frequency. In the context of spin-based quantum information processing, these findings highlight the availability of multi-photon resonances for qubit control with effectivity close to that of the single-photon resonance, and the possibility that increasing the drive strength might lead to a decreasing qubit-flip speed. I will argue that our simple model might be relevant for recent experiments in carbon nanotube quantum dots [5,6], where a disordered effective magnetic field is induced by the interplay of short-range potential scattering and a real magnetic field transverse to the nanotube [7,8].

This work was done in collaboration with Gábor Széchenyi. Funded by the EU Marie Curie Career Integration Grant No. CIG-293834 (CarbonQubits), and the OTKA Grant No. PD 100373. A. P. is supported by the Bolyai Scholarship of the Hungarian Academy of Sciences.

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Coherent coupling between ferromagnetic magnon and superconducting qubit

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Coherent coupling between spin ensemble and superconducting quantum circuits is now widely studied for quantum memories and microwave-to-optical quantum transducers. Recently, spin ensemble of nitrogen vacancy centers in diamond has successfully demonstrated storage and retrieval of qubit quantum states. On one hand, high spin-density materials, such as ferromagnetic insulator, are attractive for obtaining stronger coupling. Spins in ferromagnet have both exchange and dipolar interactions. Hence, spin precession under a static magnetic field is no more individual but forms rigid discrete modes, which are defined dominatly by the dipolar interaction and the boundary condition at the surface of the sample. These modes are called magnetostatic modes, and an elementary excitation of those modes, to which all the spatially distributed spins contribute, is called magnon. The uniform mode, in which all spins precess in the same phase, is specifically called Kittel mode and has been extensively studied in ferromagnetic resonance (FMR). The narrowest FMR linewidth of 0.5 MHz at 4.2 K was reported by Spencer *et al.* in yttrium iron garnet (YIG) [3], a typical ferromagnetic insulator widely applied in microwave devices.

In this talk, we demonstrate strong coupling of the Kittel mode in a spherical YIG single crystal to a three-dimensional rectangular cavity. Compared to the prior work by Huebl *et al.* [4], the Kittel mode in the sphere shows a narrower linewidth $\gamma/2\pi$ of 1.1 MHz. We observe the normal mode splitting even in the quantum regime where the number of thermally excited photons, magnons, as well as the probe microwave photon in the cavity is less than one [5]. The obtained coupling strength $g/2\pi$ and the cavity linewidth $\kappa/2\pi$ are 47 MHz and 2.7 MHz, respectively. The calculated cooperativity $4g^2/\kappa\gamma$ amounts to 3.0×10^3, which is extremely high compared to those in other hybrid system experiments. We further extend our work to coupling of the Kittel mode to a superconducting qubit. The transmon-type superconducting qubit has a large dipole antenna, and couples to the electric field of a cavity mode. We put the qubit chip together with the YIG sphere in a cavity; the qubit and the Kittel mode indirectly couples through the microwave cavity. We clearly observe *magnon vacuum Rabi splitting*, which indicates the distinct two systems coherently interact with each other. An alternative coupling scheme with which we can switch on and off the coupling will also be discussed.

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Progress in coherent optical manipulation of spins in InGaAs quantum dot ensembles

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In this contribution we will discuss recent attempts to obtain further progress in coherent manipulation of quantum dot spins, beyond orientation and rotation. The specific feature of the approach is the involvement of ensembles of self-assembled (In,Ga)As quantum dots each of which is on average charged with a single electron or hole in n- or p-doped samples, respectively. Some of the disadvantages that are connected with the inhomogeneity of such ensembles can be compensated by synchronization of the spin precession about a normal magnetic field with the periodically pulsed laser excitation used for manipulation [1].

First, we will explore the possibilities to tailor this excitation protocol which would give more flexibility for manipulating the spin ensembles. By exploiting additional pulses in combination with Pauli blocking we will demonstrate that higher harmonics in the spin precession patterns can be generated. Adjustment of the laser excitation protocol allowed us also to obtain an all-optical implementation of the CPMG protocol for extending the spin coherence. Despite the reduced control of the laser pulse properties compared to radiofrequency techniques an extension of the spin coherence time could be demonstrated.

Also all-optical spin tomography [2] could be implemented which enables one to get access to all three components of the spin ensemble magnetization. For a single ensemble of quantum dot spins the information obtained in that way is limited because after spin orientation the magnetization has only components normal to the magnetic field which can be easily accessed by Faraday rotation measurements.

However, recently we have shown that two distinct, optically oriented spin ensembles interact with each other [3]. The interaction can be described by a Heisenberg-form. This interaction which should lead also to entanglement of the spin ensembles corresponds to a precession of the spins about each other. Due to this precession a magnetization component along the magnetic field should build up which we confirm by our tomography measurements.

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Dynamic nuclear polarization and feedback in quantum dots

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Carrier spins in low dimensional semiconductor structures comprise a major research field with potential applications in spin-based electronics (spintronics) and quantum information. In quantum dots, the main source of loss of electron spin coherence is the bath of nuclear spins in the host material, leading to the view that nuclear spins are a nuisance in these systems. On the other hand, polarizing the nuclear spins can not only mitigate this effect but also produces an effective magnetic field that is used experimentally to implement coherent spin rotations. Moreover, due to the long coherence time of the nuclear spins, there exists the tantalizing possibility that the nuclear spin ensemble could be harnessed as a long-lived quantum memory. The key to unlocking this potential resource is to understand the dynamic creation of nuclear spin polarization through the carrier (electron or hole) spin and the complex multi-spin dynamics that span orders of magnitude in timescales in these systems. I will present experimental results that reveal intriguing physics and our theoretical work toward a systematic, microscopic theory of dynamic nuclear polarization.

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Coupling spins to photons

Jake Taylor

JQI, NIST

Spins in solid state state systems provide remarkable coherence properties. However, the same weak coupling to the environment also leads to weak coupling between spins, making the generation of entanglement at short- and long-distances challenging. Here I describe approaches for coupling spins to each other and to microwave and optical photons at increasing distance and time scales. In part, developments and improvements in circuit QED, using superconducting systems, enable such novel techniques for spin entanglement. Potential hybrid approaches that take the best of both coherence and long-range interacting properties suggest that combining these technologies may provide a path forward for scalable quantum information architectures.

Electron, hole and nuclear spins in an InGaAs quantum dot

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A solid-state system that mimics the properties of a few-level atom is an attractive proposition for various applications involving single photons. One example is a self-assembled quantum dot, for instance InAs quantum dots in a GaAs host. A single electron or hole trapped inside a quantum dot has a spin and can be used as a spin qubit [1]. The single spin benefits from the strong optical transition: the spin can be initialized, manipulated and subsequently read-out optically. A significant point is that spin rotations can be carried out on sub-nanosecond timescales by exploiting the large optical dipole.

The complex physics lies in the decoherence (T_2 processes) and dephasing (T_2^* processes) of the optical (exciton) and spin qubits. In the best case (high quality material at low temperature with weak resonant optical excitation), the exciton decoheres simply by radiative recombination, but the origin of the dephasing is subject to debate. In the presence of noisy nuclei, the electron spin qubit dephases rather rapidly with T_2^* times of just a few nano-seconds: this dephasing arises from the hyperfine interaction of the single electron spin with the 100,000 nuclear spins, a central spin problem. The contact part of the hyperfine interaction is strongly suppressed for a hole spin; the dipole-dipole interaction remains but in the case of a pure heavy hole state, the coupling can be strongly suppressed with an in-plane magnetic field. The extent to which a real hole spin mimics a pure heavy hole spin is also subject to debate.

Presented here are the results of experiments facilitated by the detection of resonance fluorescence from single spins in single quantum dots in very high quality material at low temperature [2]. The experiments reveal the sources of noise influencing both exciton and spin qubits and demonstrate the ability to invert the nuclear spins with frequency-swept nuclear magnetic resonance pulses following optical polarization. Specifically, the main results are: (i) determination of charge noise and spin noise spectra, exploiting a spectroscopic signature to distinguish charge noise from spin noise [2]; (ii) demonstration that nuclear spin noise (and not charge noise) is the main contributor to exciton dephasing at modest optical couplings [2]; (iii) active reduction of charge noise with a classical feedback circuit [3]; (iv) a coherent hole spin as revealed by 50 neV wide dips in a coherent population trapping experiment [4], (v) hole spin dephasing via charge noise [4], (vi) estimations of the anisotropy in the hole spin hyperfine interaction, and (vii) determination of the key parameters of the nuclear spins (temperature following optical polarization, 8 mK; indium concentration over the exciton wave function, 20%, quadrupole frequency distribution for all the main isotopes) from frequency-swept nuclear magnetic resonance [5]. Prospects for engineering spin coherence further and for enhancing the spin-photon interaction with a micro-cavity will be discussed.

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Optical k-valley state manipulation and excitonic effects in monolayer MoS_2 and WSe_2

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In strong analogy to graphene, the physical properties of transition metal dichalcogenides (TMDCs) change drastically when thinning the bulk material down to one monolayer (ML). The closely related ML materials WSe_2, MoS_2, $MoSe_2$ and WS_2 are 2D semiconductors with strong, direct optical transitions that are governed by tightly Coulomb bound electron-hole pairs (excitons). Their optoelectronic properties are directly related to the inherent crystal inversion symmetry breaking (Fig. 1a). It allows for efficient second harmonic generation (SHG) [5] and is at the origin of chiral optical selections rules, which enable efficient optical initialization of electrons in specific K-valleys in momentum space in the emerging field of *valleytronics* [1,3]. 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 non-equivalent K valleys (K_+ or K_-, respectively), see Fig. 1b [1,2]. The valley polarization is protected by the strong spin-orbit splitting in the valence and conduction band [3], leading in principle to a high stability for the valley degree of freedom [2].

Here we discuss the optical generation of valley polarization and coherence (Fig. 1c), recently demonstrated in time-integrated photoluminescence (PL) experiments up to T=300K [1,2]. We investigate the stability of the initialized valley states in time resolved experiments [4] and discuss the role of Coulomb exchange. The excited exciton spectrum is investigated in SHG spectroscopy and 2- and 1-photon absorption (Fig.1 d). We observe a clear deviation from the standard Rydberg series, which we interpret in terms of anti-screening leading to a stronger Coulomb interaction for higher excited states [5]. We extract an exciton binding energy of the order of 600 meV in ML WSe2 and demonstrate a novel mechanism for exciton alignment using below bandgap excitation [5].

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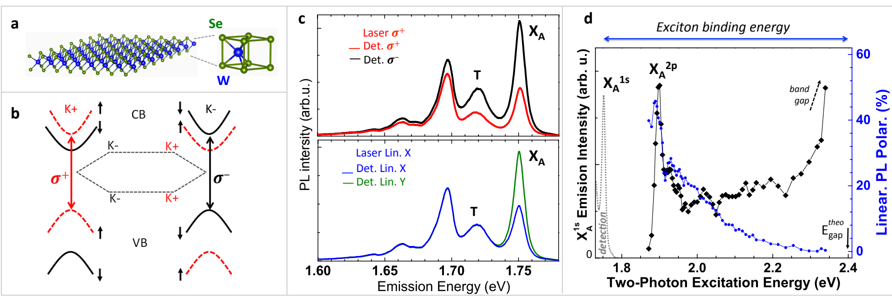

Fig. 1 a - WSe_2 ML structure; b – Chiral optical selection rules [1]; C – Top: Valley Polarization for Trion **T** and neutral Exciton X_A. Bottom: Valley coherence for X_A [4]; d – Determination of excited exciton energies (black) and Valley coherence (blue) [5]

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[3] G.B. Liu *et al* PRB **88**, 085433 (2013) & A. Kormanyos *et al* PRX **4**, 011034 (2014)
[4] D. Lagarde *et al* PRL **112**, 047401 (2014) & G. Wang *et al* arXiv:1402.6009
[5] G. Wang *et al* arXiv:1404.0056

Spin-orbit Coupling, Quantum Dots, and Qubits in Monolayer Transition Metal Dichalcogenides

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Monolayers of transition metal dichalcogenides (TMDCs) have recently emerged as a new class of materials, both of fundamental scientific interest and as potential platforms for nanoelectronic, spintronic, and optoelectronic devices. Since these atomically thin materials have a finite band gap, they offer an extremely interesting possibility: a new platform for quantum dots in truly two-dimensional materials that can be created by use of external electrical gates.

We derive an effective Hamiltonian which describes the dynamics of electrons in the conduction band of monolayer TMDCs in the presence of perpendicular electric and magnetic fields [1]. We discuss both the intrinsic and the Bychkov-Rashba spin-orbit coupling (SOC) induced by an external electric field. We identify a new term in the Hamiltonian of the Bychkov-Rashba SOC which does not exist in III-V semiconductors. A perpendicular magnetic field leads to a valley splitting of the energy states, which can be described by a valley g-factor. An important consequence of the strong intrinsic SOC is an effective out-of-plane g-factor for the electrons which differs from the free-electron g-factor. Using first-principles calculations, we give estimates of the various parameters appearing in the theory. Finally, we consider quantum dots (QDs) formed in TMDC materials and calculate the magnetic field dependence of the bound states in the QDs. We find that all states are both valley and spin split, which suggests that these QDs could be used as valley-spin filters. We explore the possibility of using spin and valley states in TMDCs as quantum bits, and conclude that due to the relatively strong intrinsic SOC the most realistic option appears to be a combined spin-valley (Kramers) qubit at low magnetic fields.

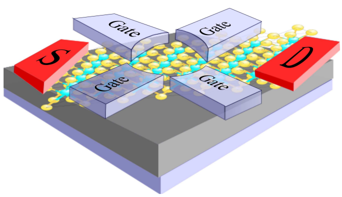

Figure 1: Schematics of a QD defined with the help of four top gates in a monolayer TMDC. S and D denotes the source and drain, respectively.

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Entanglement and teleportation in quantum dots

Parisa Fallahi

ETH Zürich

Photons play a major role in all quantum communication schemes as carriers of coherent quantum information. Establishing a quantum interface between a spin qubit and a photon, for reliable exchange of quantum information, is therefore of great importance. This is however a challenging task in solid state systems. In this talk, I will review our experiments demonstrating spin-photon entanglement and quantum teleportation between a single spin and a single photon, in InGaAs quantum dots, and will discuss their implications towards achieving quantum dot based quantum networks.

Invited Talks

Satellite Day

Abstracts

Quantum algorithms for quantum chemistry

Matthias Troyer

ETH Zürich

Architectures for Quantum Computers

Rodney Van Meter

Keio University

Recent experimental progress in qubits has brought us to the threshold of quantum computing's threshold, the fidelity level at which applying error correction makes the world better, rather than worse. It is now time for architectural studies to move from the abstract to the concrete. In this talk, I will review key architectural principles from classical computing systems and their application to large-scale systems, and end with suggestions for experimental demonstrations that are feasible with tens of qubits.

Surface code error correction

Austin Fowler

University of California, Santa Barbara

The surface code is widely considered to provide the brightest hope for large-scale fault-tolerant quantum computation. The requirements of a 2-D array of qubits with nearest neighbor interactions and gate error rates below approximately 1% are highly experimentally compatible. In this talk, I review the surface code, including recent advancements, and discuss the implications for present-day experiments.

Calibration and verification of quantum gates for spin qubits

Stephen D. Bartlett

Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney NSW 2006, Australia

Quantum tomography is considered the gold standard for fully characterising quantum systems, and in particular for characterising the quantum logic gates that form the basic elements of a quantum computer.

In the standard formulation of process tomography, a quantum process is characterised through the average statistics of an experiment wherein the unknown process is applied to a system prepared in one of a tomographically-complete set of known input states, and the output is subjected to one of a tomographically-complete set of known measurements. Generally, the input states and measurements are assumed to be pure and projective, respectively (an approximation that is quite reasonable in a range of optical and atomic systems).

This situation in many solid state implementations of qubits is complicated by two issues. First, one generally does not have access to either a tomographically-complete set of state preparations or measurements in the system; in fact typically, only preparations and measurements in a single basis (say the energy eigenbasis) can be performed directly. Tomographically complete sets can be generated using transformations (gates) that change these bases, but fully characterising these basis-changing gates through some form of tomographic methods is a bootstrapping problem [1]. The second complication is that these state preparations and measurements are often poorly approximated by pure states and projectors. In many solid state implementations of a qubit, state preparation and measurement (SPAM) errors are significantly larger than gate errors, and so one requires a full characterisation of the SPAM errors prior to performing process tomography.

A range of recent results have largely resolved these complications, and led to a method for "self-consistent" quantum process tomography that can be applied to solid-state devices [2-5]. In this tutorial, I will overview these schemes with a specific focus on their application to spin qubits.

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Long transfer of spin information using a single electron

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The recently demonstrated on-demand transfer of a single electron using surface acoustic waves in AlGaAs heterostructures [1,2] opens the route towards electronics at the single electron level and is a promising strategy to scale up the system of electron spin qubits. We will discuss the result of an experiment where the spin of an electron, initially prepared in a specific spin states in a first dot, is measured in a second dot three microns away after transfer. We will demonstrate that spin information is partially preserved during the transfer and we will discuss possible source of depolarization during the transfer and prior to the transfer.

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High quality materials for spin qubits

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A crucial requirement in future qubit applications is a reduction of dephasing processes. The origin of these dephasing processes in solid state based qubits are charge and spin fluctuations. GaAs based qubits show very promising progress but it has recently become clear that charge noise in current host structures severely limits their scalability [1]. This is somewhat surprising as the electron momentum scattering length in state of the art GaAs based heterostructures exceeds 1 mm [2], four orders of magnitude larger than the extension of the quantum dots forming the qubits.

While nuclear spin fluctuations were long the focus of dephasing studies, it has recently become clear that charge noise may be more detrimental [1]. First, it limits the fidelity of Coulomb based entangling gates [3], which are otherwise attractive because of their relatively long coupling range [4]. Second, large charge rearrangements typically require frequent device retuning, which is not practical for multi-qubit circuits. The quantum dots studied so far were all fabricated from molecular beam epitaxy (MBE) grown doped heterostructures with further processing by electron beam lithography and standard metal deposition methods, with air exposure between the processing steps. This may be one of the reasons why to date, charge fluctuations limit the scalability of qubits even in structures with very high charge carrier mobility. These fluctuations are equally relevant for self-assembled quantum dots [5, 6].

To reduce the noise in the host material, eliminating dopants and mitigating defects at surfaces and interfaces is inviting. By using undoped gate induced heterostructures, dopand noise could be eliminated. To mitigate effects from surface and interface defects, epitaxial doped semiconductor gates can be used.

Our MBE reaches very high purity due to the restrictions to the absolute necessary evaporation elements Ga, Al, In, As, Si and C. We can insert nearly all other elements of the periodic table by focused ion beams [7] in a postgrowth process which is feasible without breaking the ultrahigh-vacuum. In this way, also subsequent MBE-overgrowth is possible and thus arbitrary elements can be introduced in a laterally resolved manner in arbitrary depths.

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Steps Toward Scalability with Superconducting Qubit Systems

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Thanks to recent progress in qubit layouts, coherence times, and control techniques, the performance of superconducting qubit devices is now approaching levels at which useful error correction may be possible. One particularly attractive error-correction scheme, the surface code[1−2], is relatively tolerant of control and measurement errors, and moreover requires only nearest-neighbor qubit interactions. While the building blocks for performing error correction using this scheme have already been demonstrated in devices up to a few qubits in size[3−5], such experiments have relied on many components and techniques that are incompatible with even modest scalability; in fact, these small-scale experiments are already beginning to strain practical limits of space, time and cost.

Although a full-scale, fault-tolerant quantum computer capable of performing useful calculations remains far off, it is foreseeable that work currently underway could improve scalability sufficiently for the demonstration of a single logical qubit. There are several key areas of focus: reducing the footprint of the qubit/resonator system while finding ways to enhance coherence and reliability; designing improved quantum-limited amplifiers that eliminate the need for bulky and expensive ferrite-based circulators; developing techniques for fast tune-up and characterization of many-qubit systems; and finding more efficient ways to generate qubit control signals, likely involving custom-designed hardware.

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Posters

Abstracts

Thermopower in graphene with spin-orbit interaction

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Recently there is a great interest on the transport properties in graphene. We investigate these properties on a graphene layer in the presence of Rashba spin-orbit interaction. Quite generally, spin-orbit interactions induce spin splittings and modifications of the graphene bandstructure. We calculate within the scattering approach the linear electric and thermoelectric responses of a clean sample when the Rashba coupling is localized around a finite region. We find [1] that the thermoelectric conductance, unlike its electric counterpart, is quite sensitive to external modulations of the Fermi energy. Therefore, our results suggest that thermocurrent measurements may serve as a useful tool to detect nonhomogeneous spin-orbit interactions present in a graphene-based device. Furthermore, we find that the junction thermopower is largely dominated by an intrinsic term independently of the spin-orbit potential scattering. We discuss the possibility of cancelling the intrinsic thermopower by resolving the Seebeck coefficient in the subband space. This causes unbalanced populations of electronic modes which can be tuned with external gate voltages or applied temperature biases.

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Engineered nanodiamonds as mobile probes for high resolution sensing in fluid

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In recent years, point defects in wide-bandgap semiconductors have attracted a growing interest for applications in metrology and quantum information. In particular, the nitrogen-vacancy (NV) center in diamond has emerged as an outstanding candidate for temperature and magnetic field sensing in biological environments owing to its biocompatibility, inherent optical addressability, and unparalleled spin coherence properties at room temperature. While extensive research efforts have focused on employing nanodiamonds (NDs) as low thermal mass probes to map biological systems at the nanoscale, the challenge remains to create NDs incorporating NVs with bulk-like coherence properties and to obtain a stable three-dimensional control of the nanoparticles in fluid. In this work[1], we address these limitations by employing a fabrication process that combines the use of high quality diamond membranes and a top-down electron beam lithography technique. We obtain NV centers exhibiting consistently long spin coherence times (up to 700 μs) embedded in highly reproducible cylindrical NDs with engineered geometry. Once fabricated, the NDs can be efficiently released from the substrate into a water suspension, which is a critical step in delivering the nanoparticles to a region of interest. Additionally, we exploit the engineered geometry of our nanoparticles to demonstrate stable optical trapping within a microfluidic circuit. The achieved stability enables an experimental DC magnetic field sensitivity of $\sim 9\ \mu\mathrm{T}/\sqrt{\mathrm{Hz}}$ and paves the way towards the use of dynamical decoupling techniques to obtain ultra-high sensitivity, contactless probes in fluid. This work is supported by DARPA, AFOSR and the DIAMANT program.

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Fundamental gates for classical logic from time-independent spin Hamiltonians

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Few-body near-coherent dynamics operated in a non-adiabatic (fast) regime can offer the triple advantages of speed, minimal dissipation and logical reversibility over conventional dissipative hardware for classical logic. It therefore makes good sense to exploit the improving coherence in various physical systems to explore the coherent implementations of classical gates, especially as power consumption in classical computers becomes a prominent issue [1, 2]. All classical circuits can be composed from 3-bit Toffoli and Fredkin gates [3], so it makes sense to find ways to perform these particular gates with minimal control and low gate time. With this motivation, we explore ways to make fast, minimal control Toffoli and Fredkin gates using time independent Hamiltonians acting on three qubits, with uniform interactions. This contrasts with existing methodologies to construct Toffoli and Fredkin gates which usually involve hybrid systems, qudits, several layers of 2-qubit gates or non-uniform interactions (see e.g. [4–10]). We find that a Toffoli gate on 3 qubits using uniform Ising interactions and local fields cannot be exactly achieved, but can be achieved to within arbitrary accuracy depending on the relative strengths of the local fields and the Ising coupling. We also find an exact way in which to perform a Fredkin gate in systems where Ising and Heisenberg coupling can be achieved.

We then demonstrate how these gates could be implemented under currently realistic conditions using ion traps or bismuth dopants in silicon. Ion traps arguably represent the most controllabel quantum system currently at our disposal, so would be a natural setting to show proof-of-principle of these gates. Dopants in silicon are excellent candidates for future integration of quantum technologies with classical technologies due to the shared use of silicon, so provide an example of how we might incorporate these quantum systems into a classical computer.

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Ultrafast high fidelity heavy hole spin initialization and storage in self assembled quantum dots

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Due to their robust coherence times, single heavy hole spins in semiconductor nanostructures remain a prime candidate for the realization of optically active quibts [1]. Here, we explore how coherent two colour spectroscopy can be applied to single self assembled quantum dots to initialize and probe single spin states with fidelities >98 %, even at zero magnetic field.

Structurally, we embed InGaAs quantum dots in a photodiode structure and grow an AlGaAs barrier immediately adjacent to the quantum dots. This allows us to individually control the tunneling times of photo generated heavy holes and electrons from quantum dots to the Fermi reservoir. We optimize the tunneling rates, such that a single heavy hole spin is initalized via electron tunneling from the neutral exction state in less than 10ps. Consequently, we observe very high spin initialization fidelities above 98 % even at zero magnetic field due to the minimalized impact of the electron-hole exchange interaction[2]. In contrast, the heavy hole spin states exhibit storage times, that are increased by 3 orders of magnitude. Finally, we show that the spin storage times can be further increased by applying voltage modulations on nanoseconds timescales without reducing the heavy hole spin state fidelity.

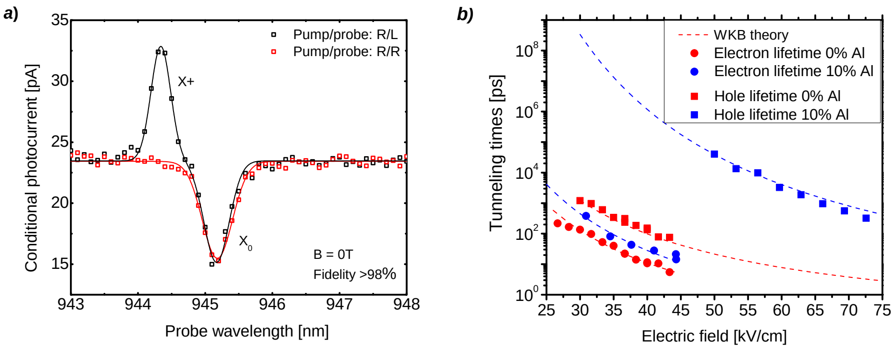

Figure 1: a)After a single heavy hole spin has been initialized via ionization of the neutal excition, the spin configuration is probed by the polarization of a second pulse(right handed R and left handed L). Plotted is the conditional absorption measured by photocurrent as a function of the wavelength of the probe pulse. Fits of the surppressed absorption yield fidelities above 98%. b)Tunneling times of electrons (red) and heavy holes (blue) for quantum dots with a 10 % AlGaAs barrier adjacent to it and without. The dashed line inidicates tunneling times expected from a WKB model.

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Entanglement Purification with the Exchange Interaction

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For the practical generation of long-distance entanglement in quantum communication networks, the concept of quantum repeaters was established [1]. The centerpiece of such a device is entanglement purification [2], for which a quantum memory is indispensable. Ideal candidates for the realization of stationary qubits acting as quantum memory are spins in solid-state systems, such as electron spins in semiconductor quantum dots (QDs) [3]. The original purification proposal [2] makes use of a bilaterally applied CNOT operation, which is, however, not directly generated by the typical interaction between spin qubits in QDs. The exchange interaction can be described by a Heisenberg Hamiltonian [3] $H_{ij}(t) = \frac{1}{4}J(t)\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$, where $\boldsymbol{\sigma}_i$ is the Pauli spin operator of the electron in QD i and $J(t)$ is the exchange energy between the two electrons. Two of these two-qubit interactions and additional single-qubit operations on both qubits are necessary to construct the CNOT gate from the Heisenberg Hamiltonian, rendering the experimental implementation more challenging. Thus, we construct a simple purification protocol [4] based solely on the one-time activation of a Heisenberg interaction leading to the $\sqrt{\text{SWAP}}$ gate (Fig. 1(a)). The protocol has the same structure as the original proposal [2], the crucial difference being that the bilateral operation is *asymmetric*, meaning Alice and Bob have to apply *different* two-qubit gates. In the optimal case, where the increase in fidelity is the largest, Alice applies a $\sqrt{\text{SWAP}}$ gate to her qubits and Bob performs the inverse $\sqrt{\text{SWAP}}$ gate, $\sqrt{\text{SWAP}}^{-1}$. The fidelity $F'(F) = \langle\Phi^+|\rho'|\Phi^+\rangle$ of the remaining qubit pair (qubits 1 and 2) turns out to be larger than the initial fidelity F provided that $\frac{1}{2} < F < 1$ (Fig. 1(b)). Following the same approach, we also find similar results for qubits coupled via XY-type and magnetic dipole-dipole interactions, e.g. superconducting qubits [5], optically coupled spin qubits [6] or nitrogen-vacancy centers in diamond [7].

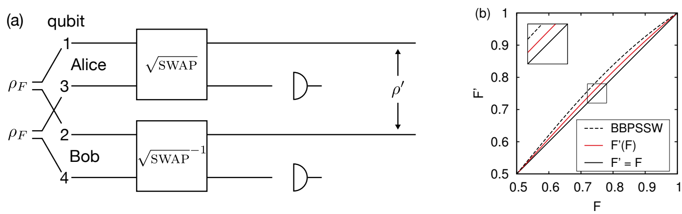

Figure 1: (a) Circuit diagram of the purification protocol directly generated from the Heisenberg Hamiltonian. (b) The fidelity F' as a function of the initial fidelity F, shown for the exchange-based purification protocol compared to the original protocol [2].

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Multi-qubit read-out of spin qubits in GaAs

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Efficient implementation and characterization of quantum information protocols requires the ability to measure multiple qubits individually and in a single-shot manner. We discuss the merits of various multi-qubit measurement strategies in dot arrays and demonstrate and implement one of them experimentally.

A succesfull demonstration of two-qubit read-out has been shown in [1]. We now demonstrate the next step by reading out three individual spin qubits formed by a linear array of three quantum dots where each electron forms a single spin qubit, see Fig. 1.

We first sequentially read out the left and right dot using standard spin-to-charge conversion [2]. Next we shuttle the centre electron to the left dot and read out its spin state thereby completing the three-qubit read-out. We are now aiming at multi-qubit operations.

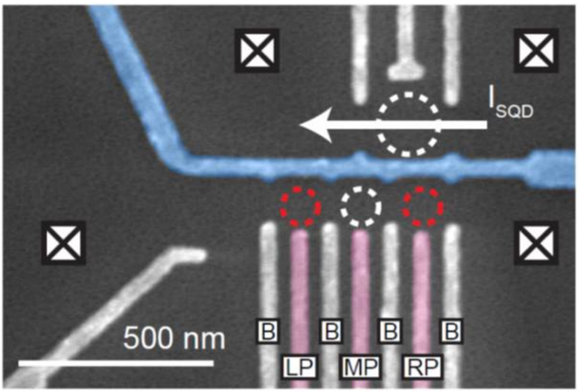

Figure 1: A linear array of three quantum dots (indicated by the three small dashed circles) forming a three qubit device. The spin state of the qubits is readout sequentially by monitoring the current I_{SQD} through the neighbouring sensing dot.

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Resolved sidebands in a strain-coupled spin-oscillator system

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Within the last years significant advances in the control of nanoscale mechanical oscillators were made and fundamental studies on the quantum-to-classical crossover as well as further progress in high precision force sensing are now within reach. One possible way to address these topics is to achieve coupling of the oscillators' mechanical motion to individual two-level systems. Of particular interest is the resolved sideband regime. It is characterized by frequency-modulated sidebands at the oscillator Eigenfrequency, which accompany transitions between the two quantum states. The resolved sideband regime is a prerequisite for sideband-cooling of a nanoscale mechanical resonator to its quantum ground state and therefore plays a significant role in generating and studying nonclassical states of mechanical motion [1, 2]. Various hybrid systems have been explored in this context, including mechanical oscillators coupled to solid state spins via magnetic fields [3, 4] or quantum dots coupled via electric or strain fields [5, 6]. However, none of these approaches has reached the resolved sideband regime so far.

Here we report on single electronic spins coupled to the motion of mechanical resonators by a novel mechanism based on crystal strain. Our device consists of single-crystalline diamond cantilevers with embedded Nitrogen-Vacancy center spins. Using optically detected electron spin resonance, we determine the so far unknown spin-strain coupling constants and demonstrate that our system resides well within the resolved sideband regime. We realize coupling strengths exceeding ten MHz under mechanical driving and show that our system has the potential to reach strong coupling in the future. Our novel hybrid system therefore forms a promising resource for future experiments on spin-based cantilever cooling and coherent spin-oscillator coupling.

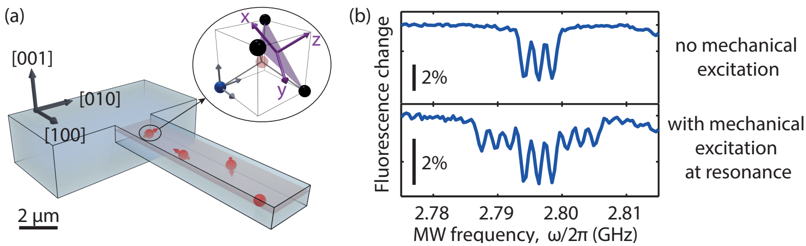

Figure 1: (a) Schematic of a diamond cantilever with shallow implanted Nitrogen-Vacancy centers. (b) Demonstration of the resolved sideband regime through optically detected electron spin resonance at an embedded NV center. If the oscillator is excited on resonance, sidebands appear around the central carrier of the NV spin transition at spacings corresponding to the oscillator Eigenfrequency.

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Microscopic models for charge dephasing in semiconductor qubits

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Charge noise is a ubiquitous source of dephasing in solid-state qubits. In typical models seeking to explain this decoherence mechanism, the charge qubit is dipole-coupled to two-level charge fluctuators distributed in the host material, at interfaces or in oxide layers. Here, we consider various microscopic mechanisms causing fluctuations in the environmental two-level systems, and study the charge qubit's coherence properties in each scenario. In light of recent experimental results reported with semiconductor qubits, we identify which noise mechanism reasonably dominates, and make testable predictions for future experiments.

Time resolved studies of hyperfine mediated electron spin relaxation in a single InGaAs quantum dot over ultra-long timescales

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It is by now well established that hyperfine coupling to the nuclear spin system dominates electron spin relaxation in quantum dots (QDs) at low temperatures [1,2]. The ensemble of interacting nuclear spins gives rise to a local effective hyperfine field B_N in which the electron spin wavefunction evolves coherently over nanosecond timescales. However, the amplitude and direction of B_N changes over $T_N \sim$1-10μs timescales due to the Knight field of the resident electron resulting in inhomogeneous spin-dephasing [2]. In this contribution we present time resolved optical studies of electron spin relaxation in a single self-assembled InGaAs QD over ultra-long timescales extending up to the $\sim \mu$s range and for externally applied magnetic fields $B_0 = 0 - 100$mT. We utilise a spin storage device in which single electron spins can be optically prepared and orientated using a resonant picosecond optical pulse and then stored in the dot over long timescales T_{store}, extending into the $\sim$ ms range [3,4]. After a well defined storage time we read out the projection of the electron spin along the optical axis by performing a spin-to-charge conversion using a second laser pulse and detect the luminescence yield arising from pumping a charged exciton transition [3-5].

Typical results of our measurements are presented in the inset of Fig.1 that shows the degree of spin polarisation $< S_z >$ as a function of B_0 for $T_{store} = 50$ns. The form of the $< S_z(B_0) >$ data can be fit using the theory of ref [1], from which we extract $\Delta_B = 13$mT, an electron spin dephasing time of T_2^* =1.4ns and an electron g-factor of $g_e = 0.62$. The main panel of Fig.1 shows typical data for the temporal evolution of the depth of the dip in the $< S_z(B_0) >$ data. As expected, $< S_z(t) >$ reduces to 3% for timescales $T_{store} \sim 2T_2^*$ and our measurements are well described by theoretical expectations. Detailed analysis of $< S_z >$ for different storage times reveal characteristic time scales for the relaxation processes due to (i) the period of the electron precession in the frozen fluctuation of the hyperfine field and (ii) the period of the nuclear spin precession in the hyperfine field of the electron.

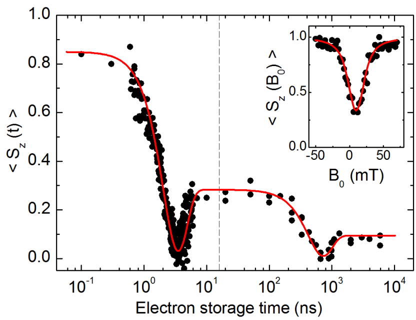

Figure 1: Temporal evolution of $< S_z >$ and comparison with the theory of ref [1]. (inset) - example data showing $< S_z >$ as a function of B_0 for $T_{store} = 50$ns. The red solid curve presents a theoretical calculation and is in very good agreement with the data [1].

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How to see individual electrons (or spins) in mesoscopic junctions

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Charge quantization is not directly measurable in mesoscopic junctions. We show that a special scheme to measure individual electrons when the Fermi sea is blocked. If it is not blocked then one has to use either weak measurement with a deconvolution of the detector noise [1] or use energy threshold detectors. The last option allows counting the capture of single electrons in the tunneling limit, which is useful in Bell tests of local realism. Such a test would have no loopholes but its ideal realization is always limited by practical side effects such as additional interaction. A generalization to single-spin detection using spin-polarized quantum point contacts is straightforward [2].

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Potentials effect on vertically coupled Silicon quantum dots

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Abstract

In order to control quantum information in the solid state [1, 2], many proposals [3, 4] have been studied. The general characteristic of these systems is the employment of exchange interaction between confined electrons in quantum dots. An important result of these studies [5] the long coherence time of an electron spin in a quantum dots [5, 3]. Previously, the exchange coupling has been studied in Silicon laterally quantum dots within quartic and biquadratic confining potential [6]. In this work we propose a computation of exchange coupling J in two vertically silicon quantum dots within the Heitler-London (HL) and Hund-Mulliken approaches. The confinement potential is modeled by three potential (quadratic, biquadratic and Gaussian). We provide a comparative study of J for these potentials as a function of interdot distance and magnetic and electric fields. The results we obtain enable us to investigate the sensitivity of the system to the choice of the confining potential at low electric and magnetic fields and at short interdot distances. These properties can be applied to the modeling experiments.

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Nanosecond transfer of a single electron between distant quantum dots

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[2]*Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, Universitätsstrasse 150, 44780 Bochum, Germany.*

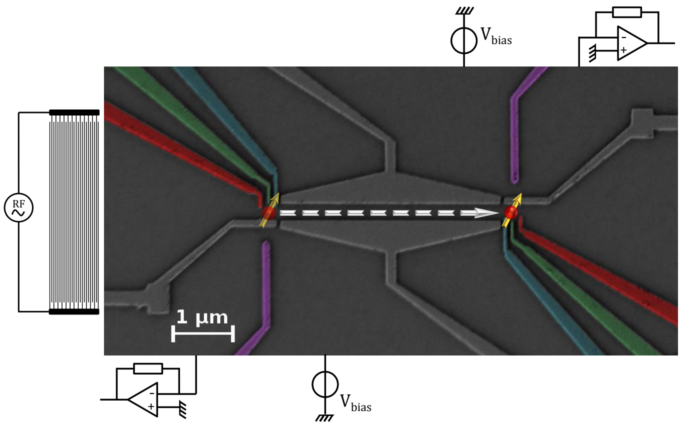

FIGURE 1 – Scanning electron microscope picture of the sample used for this work and main electronic setup.

The ability to displace controllably and on-demand a single electron on a chip is an important prerequisite for the realization of electronic circuits at the single electron level. It indeed opens the route to interconnect nodes of a spin-based quantum nanoprocessor or to perform quantum optics experiments with flying electrons. The recent demonstration of on-demand transfer of a single electron assisted by a surface acoustic wave (SAW) is a first step towards this goal [1,2].

Going one step further and proving coherent transfer of a single electron spin requires being able to work faster than the dephasing time of the system, which is around 10 nanoseconds in GaAs heterostructures [3]. To this purpose, the mechanism of injection from a static into a moving quantum dot has been extensively studied. Influence of SAW burst duration and power on the transfer efficiency has been mapped out and enables to extract the rise time of the interdigitated transducer used to generate the SAW. Furthermore by tuning the alignment between the dot and the channel potentials, a regime of high transfer efficiency can be reached where it has been shown that nanosecond triggering of the electron transfer is achievable, paving the way for future coherent transport experiments.

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Towards single-spin to microwave resonator coupling

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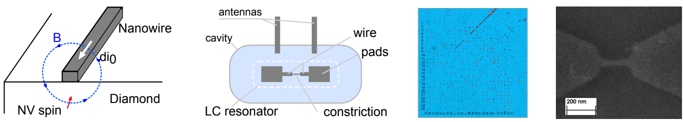
In recent years has emerged the field of hybrid quantum circuits that aims at combining the best of two worlds. On one hand, superconducting circuits are artificial atoms, which frequency and coupling to the microscopic environment can be engineered but they have relatively short coherence times. On the other hand microscopic systems, such as NV centers in diamond [1], have much longer coherence times, that can reach milliseconds or more even at room temperature. Recent experiments have shown that the reversible storage of a single microwave photon emitted by a superconducting qubit in an ensemble of NV centers is achievable, but unfortunately limited to a few hundreds of nanoseconds due to inhomogeneous broadening of the spin ensemble. [2]

Coupling only a single spin to the superconducting circuit would remove this limitation and allow for coherent manipulation of the spin via the microwave photons. With such a system we would be able to couple two distant spins via their interaction to the superconducting circuit.

Here we present our progress towards coupling a single-spin to a microwave resonator. We have concentrated our efforts on two kinds of spins, chosen for the large coherence times of their nuclear spins: NV centers in diamond and bismuth atoms in silicon [3]. Both systems present a nuclear spin of 1/2. We first aim to fabricate a high-quality factor linear superconducting resonator with a 15-nm-constriction aligned on top of the spin, implanted at 15-nm-depth in the host crystal (Fig 1). The magnetic field generated by such a nanowire will be high enough to achieve microwave detection of the spin in a few milliseconds. To obtain such a system several challenges have to be tackled: precise implantation of the spin with respect to alignment marks, accurate design and fabrication of the linear superconducting resonator to be as close as possible to the frequency of the spin and its location.



(a) (b) (c) (d)

Figure 1: Coupling between single spin and nanowire : (a)Coupling scheme between nanowire and spin implanted in host crystal, (b) Detection scheme for the superconducting resonator, (c) Implanted NV center pattern, detected by photoluminescence, (d)Nanowire fabrication in electronic lithography

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Cavity based quantum information processing in diamond

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Nitrogen-vacancy (NV) defect centres in diamond are excellent candidates for the realization of solid-state quantum networks due to their long coherence times and excellent level of control with high fidelity readout. We recently demonstrated the heralded entanglement of two NVs in two distant setups.[1] Combined with control of nuclear spins in the vicinity of NV centres [2], these results pave the way towards experimental demonstrations of protocols needed to establish quantum networks, such as entanglement distillation and quantum repeaters.

However, further advancement is hindered by the limited entanglement rates (once in approximately 10 million attempts). The main reason for such low rates is low emission probability of the required resonant photons via zero-phonon line (ZPL). Even at low temperatures only 3 % of the photons emitted by the NV centre are usable. (Figure 2.)

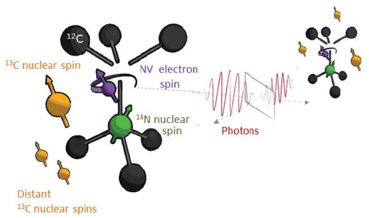

Figure 1: NV centre environment and LDE protocol.

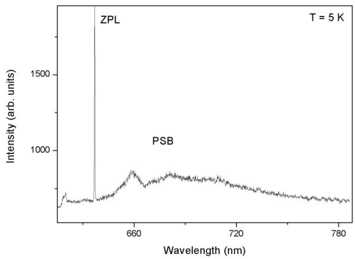

Figure 2: NV spectrum at T=5 K

Here we present our current progress in fabricating a tunable Fabry-Perot optical cavity around the NV centre. [3] Successful implementation of this design at low temperatures will provide an excellent mechanism for substantially increasing the entanglement rates by amplifying the ZPL emission of the NV centre, due to Purcell enhancement, while simultaneously improving our collection efficiency. [4]

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Impurity-induced valley relaxation in graphene

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Valley polarization, as a non-equilibrium population of one valley, is the key to using the valley degree of freedom as an information carrier. Experimental realization of valley polarization has been proposed in graphene but its applicability in electronics depends on the lifetime of the valley polarization.

In this work, we determined the relaxation time of a valley-polarized state due to charged impurities in the substrate. The valley relaxation time is calculated from Boltzmann equation using a tight-binding model taking into account screening. We find that the valley relaxation time is inversely proportional to Fermi-energy, and it grows exponentially as the graphene-impurity dinstance is increased. Unlike transport lifetime, the valley relaxation time depends on the atomic structure of the wavefunction due to large momentum transfer in intervalley scattering.

High-Fidelity Single-Qubit Gates for Two-Electron Spin Qubits[1]

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High fidelity gate operations for manipulating individual and multiple qubits in the presence of decoherence are a prerequisite for fault-tolerant quantum information processing. However, the control methods used in earlier experimental and theoretical work on semiconductor two-electron spin qubits are based on approximations which are difficult to fulfill experimentally, thus limiting the achievable fidelities.

An attractive remedy is to use control pulses found in numerical simulations that minimize the infidelity from decoherence and take the experimentally important imperfections and constraints, for example finite pulse rise times, into account. Using this approach and including experimentally determined noise spectra [2], we find pulses for singlet-triplet qubits in GaAs double quantum dots with fidelities as high as 99.9%.

Fully eliminating systematic pulse errors will likely require a calibration of the pulses on the experiment using some form of self-consistent approach. Starting with inaccurate control pulses we show that elimination of individual systematic gate errors is possible by applying a modified version of the bootstrap protocol proposed by Dobrovitski et al. [3] while still retaining the pulses high fidelities.

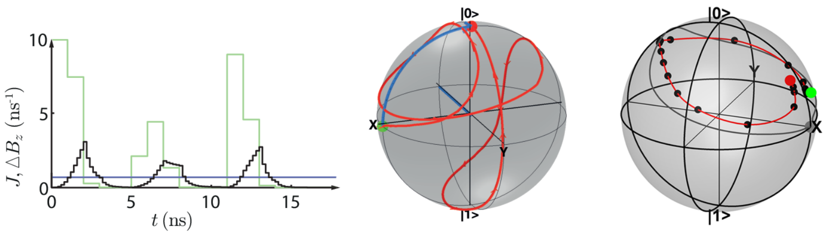

Figure 1: left and middle: Exemplary $Y_{\pi/2}$-gate with fidelity $1 - \mathcal{F} = 1.5 \times 10^{-3}$. Rectangular exchange J-pulses are shown in green, black lines show $J(t)$ accounting for finite pulse rise times and the value of the nuclear field gradient ΔB_z is shown in blue. The corresponding Bloch sphere trajectory for this pulse is plotted for a selected initial state, represented by the green dot. right: Preliminary experimental realisation of a non-trivial identity operation around the z-axis. The theoretical time evolution of the gate is depicted by the grey trace.

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Dynamics of entanglement of two electron spins interacting with nuclear spin baths

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In semiconductor quantum dot spin qubits the interaction with the nuclear bath is the main source of decoherence [1]. Creation and control of entangled states of two spins is now experimentally possible [2], and the hyperfine (hf) interaction with the nuclei is expected to be the main mechanism leading to disentanglement. We present a theoretical overview of hyperfine-induced entanglement dynamics in double quantum dots. We consider various realistic states of the nuclear reservoir: a thermal equilibrium state, a narrowed state (with well-defined longitudinal component of the Overhauser field) in each dot [3], and a correlated state in which the interdot difference of the longitudinal Overhauser field is fixed. Furthermore, apart from the case of free evolution of the state of two electron spins, we consider a spin echo sequence with the π pulses applied simultaneously to the two electron spin qubits.

We present calculations performed using the uniform hf coupling model (a "box wave-function" approximation), and exact calculations with two nuclear species are used to establish the timescale on which the uniform coupling approach is applicable. We also compare the results at higher fields with calculations done using the effective Hamiltonian theory [4]. When nuclear environments are in thermal equilibrium, the entanglement decays on timescale of $\sim T_2^*$ [5]. The narrowing of the nuclear state leads to a magnetic-field dependent characteristic time of disentanglement, while the entanglement echo signal for a single nuclear species bath shows very little magnetic field dependence for fields much larger than the characteristic magnitude of the Overhauser fields. For a bath consisting of multiple nuclear species (i.e. for III-V quantum dots) the entanglement echo signal oscillates similarly to the single-qubit echo signal [4,6].

This research is supported by funds of Polish National Science Centre (NCN), grant no. DEC-2012/07/B/ST3/03616.

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Embedding a Cooper pair splitter in a microwave cavity

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Distant entangled electrons would be of great interest in the context of quantum information. It has been suggested to make use of natural spin entanglement in superconductors by splitting a Cooper pair into two different electronic orbitals. It is possible to implement such a Cooper pair splitter in a carbon nanotube based double quantum dot architecture [1].
Conductance measurements demonstrated splitting of Cooper pairs but were not able to probe their coherence.
I will present recent experimental development to embed our Cooper pair splitter in a microwave cavity. We aim to access the quantum coherence of the split pair by performing the spectroscopy of the device coupled to the microwave cavity using a two tone measurement scheme [2, 3].

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Non-markovian weak measurement of a spin-1/2 system

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In many real quantum systems a measurement much less invasive than described by the projection postulate is performed by weakly coupling a detector for a finite time. We investigate a generalized measurement scheme by positive operator-valued measures (POVM) in the weak coupling limit with a focus on a non-Markovian interaction. This scheme can be applied e.g. to the weak measurement of a spin-1/2 system. We discuss the resulting quasiprobabilities, in particular the possible violation of weak positivity by second-order correlation functions and its possible use as quantum resource in single-spin read-out.

Decoherence of Coupled Two-Spin Systems

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The decoherence of a single qubit due to interactions with a bosonic thermal environment can be properly described using a quantum master equation in the Born-Markov approximation, and has been extensively studied [1]. However, many of the most promising proposals for quantum computation rely on hybrid coupled spin systems, where one spin is used for storage and the other for manipulation [2–4]. Knowledge of how multiple-spins systems behave when coupled to an external environment is also necessary for scaling up to multi-qubit processors.

The decoherence of coupled two-spin systems such as that shown in Figure 1 cannot be described adequately by collective Lindblad operators acting on the whole system. Nor can it be fully understood by treating the decoherence of each spin separately. In the separable case, all the cross-terms containing coherences between the two spins are lost. However, cross-terms with a small frequency difference do not oscillate rapidly, and as such cannot be neglected under the rotating wave approximation.

We move beyond the above approximations by using partial secularisation to keep terms associated with small energy changes, and investigate the extent to which the absorption spectrum resembles that resulting from either collective or independent decay operators. We show that keeping these cross-terms can have a profound effect on the steady state correlations between the two spins. The resulting equation of motion is not necessarily in Lindblad form, and we discuss its range of validity. The results are applied to TetraAlkylPhenyleneDiamine-ZnPorphyrin-Fullerene (TAPD-ZnP-C60)(Figure 2), a promising dimer molecule for spin-based quantum computing.

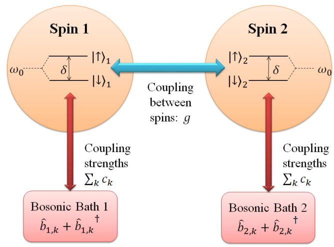

Figure 1: A coupled two-spin system with individual reservoirs.

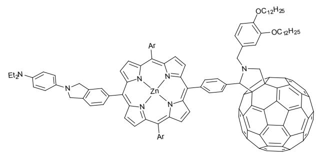

Figure 2: TAPD-ZnP-C60, a triad molecule with potential applications in hybrid quantum computing (image courtesy of N. Panjwani).

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Longitudinal Resistance Quantization and Density Gradients in the Integer and Fractional Quantum Hall Effect

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We present quantum transport measurements on van-der Pauw samples in high-mobility GaAs 2D electron gases at low temperatures. In the integer quantum Hall regime, we find a long sequence of flat plateaus of longitudinal resistance R_{xx} alternating sharply between zero and finite resistance values. Further, we observe a striking B-field asymmetry giving essentially $R_{xx} = 0$ for one sign of B, except for negative $\frac{dR_{xy}}{dB}$ regions such as reentrant integer states. Finally, fractional quantum Hall states appear smeared and poorly developed or absent. All of these signatures can be understood with charge density gradients across the sample [1,2], as confirmed by R_{xy} data. An edge-state model including gradients can neatly account for the novel sequence of R_{xx} plateaus, including exact quantization at fractional resistance values. The activation energies are surprisingly small, allowing experimental observation only at the lowest temperatures and in ultra-clean samples. Density gradients can be reduced with improved wafer growth (rotation) and smaller distances between ohmic contacts. Nevertheless, our results show that R_{xx} can easily be misleading, characterizing gradients rather than quantum Hall gaps, thus fundamentally jeopardizing R_{xx} as the predominant probe of integer and fractional quantum Hall states.

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Probing Quantum and Classical Baths via Correlation Measurements of Spinqubits

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Investigations of quantum mechanical effects in macroscopic systems are of great interest to shed light onto the question where and how the transition to the classical world appears. It is also of practical relevance to determine if a bath dephasing a qubit can be described classically or requires a quantum mechanical treatment. We propose two measurement schemes to help answer these questions and show experimentally that the dynamics of a bath of nuclear spins in GaAs quantum dots can be explained semi-classically.

The first measurement procedure we propose unambiguously detects quantum back action via correlation measurements [1]. We consider a bath coupled to a single qubit where the presence of back action leads to a dependence of correlations of subsequent initialization-evolution-readout cycles on how the qubit is manipulated in between. We analyze the realistic case of an electron spin coupled to 10^6 nuclear spins and conclude that back action from the qubit onto the nuclear spin bath should be detectable.

A similar technique can be used to extract the classical noise spectrum affecting the qubit and relies on correlating single-shot measurement outcomes of successive free induction decays [2]. This method only requires qubit initialization and readout with a moderate fidelity and also allows independent tuning of both the overall sensitivity and the frequency region over which it is sensitive. Thus, it is possible to maintain a good detection contrast over a very wide frequency range, filling the frequency gap between direct and pulse-sequence-based noise spectroscopy.

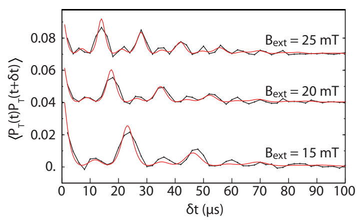

Figure 1: Correlation of triplet probabilities after Landau-Zener sweeps across the S-T_+ transition for different external magnetic fields (data in black and model in red).

Correlation measurements can also help investigate the dynamics of the transverse Overhauser field arising from the nuclear spin bath. We correlate measurements of single Landau-Zener sweeps across the S-T_+ transition of two gate-defined quantum dots, and show that the results can be understood in terms of a semi-classical model. Specifically, we observe oscillations consistent with the relative Larmor precession of the nuclear spin species in GaAs (Fig. 1). We predict that in the presence of spin orbit coupling (SOI), oscillations with the absolute Larmor frequencies are expected and could be used to quantify SOI.

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Electrical Quantum Manipulation of Valley Pseudospins in Gapped Graphene for Information Processing

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The rise of graphene opens a door to the qubit implementation for potential applications in quantum computing and quantum communications.[1-3] Such an implementation is based on the electron degree of freedom in gapped graphene known as valley pseudospin - an analogy of electron spin. In this presentation, we employ the Schrodinger theory (the low-energy effective theory of electrons in gapped graphene) as the framework, and examine i) the characteristics of a valley pseudospin, especially the analogy as well as the contrast between a pseudospin and an electron spin, ii) the novel mechanism of valley-orbit interaction (VOI), and iii) the VOI-based electrical manipulation of valley pseudospin. Based on the mechanism of VOI, several interesting, electrically controllable valleytronic devices are proposed, including qubits [1-3], FETs[4], and filters[5]. Proposals of these various devices will be presented.

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Single-spin manipulation in a double quantum dot with micromagnet

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The manipulation of single spins in double quantum dots by making use of the exchange interaction and a highly inhomogeneous magnetic field was discussed in [W. A. Coish and D. Loss, Phys. Rev. B **75**, 161302 (2007)]. However, such large inhomogeneity is difficult to achieve through the slanting field of a micromagnet in current designs of lateral double dots. Therefore, we examine an analogous spin manipulation scheme directly applicable to a realistic GaAs double dot setup and estimate typical gate times realized at the singlet-triplet anticrossing induced by the inhomogeneous micromagnet field. We discuss the optimization of single-spin gates through suitable choices of detuning pulses and an improved geometry for the micromagnet and double-dot configuration. We also examine the effect of several dephasing sources, as in particular the Overhauser field induced by nuclear spins and charge noise from the electric gates, and characterize the timescale and analytical form of the resulting decay of coherence. Our results suggest that this scheme is a promising approach for the realization of fast single-spin operations.

Engineering the coupling between molecular nanomagnets for quantum simulation

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[3] *The Lewis Magnetism Laboratory, School of Chemistry, The University of Manchester*
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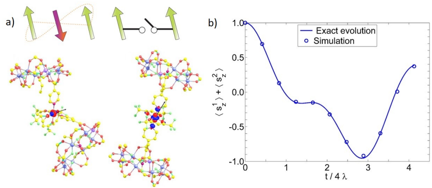

The physical implementation of quantum simulators is a major technological target of current research. Suitably engineered supramolecular complexes of molecular nanomagnets (MNMs) have been theoretically proposed as excellent candidates [1,2]. Here we report the synthesis and the theoretical study [3] of a family of antiferromagnetic Cr_7Ni rings linked through Ni complexes and we show that these can be exploited for proof-of-principle experiments of quantum simulation. Qubits are encoded in the Cr_7Ni ground multiplet, which behaves at low temperature as an effective S=1/2. The Ni ion interposed between the qubits is used as a switch of the effective qubit-qubit interaction, thus allowing us to implement single-and two-qubit gates. The magnetic couplings and crystal field anisotropy are engineered by coordination chemistry in order to fit the requirements of the scheme. Several Cr_7Ni-Ni-Cr_7Ni variants with different geometry (Fig. a) are studied by means of a recently-developed [4] DFT approach. This method is based on the explicit inclusion of strong correlation effects in a generalized Hubbard model, which is constructed using localized orbitals to describe the $3d$ electrons of the transition metal ions. The hopping and screened Coulomb integrals are calculated self-consistently by means of LDA and constrained LDA methods. Finally, the Spin Hamiltonian (SH) is obtained by means of a canonical transformation. In this way, no assumption on the form of the final SH is needed and all the interactions are deduced systematically. The extracted magnetic parameters are used to simulate with high fidelity quantum gates and quantum simulation algorithms, such as the oscillations of the magnetization in the prototypical Transverse-field Ising model, reported in Fig. b and compared with the exact result.

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Coupled shallow donor/silicon SET device in the few electrons regime.

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[1] *Univ. Grenoble Alpes, INAC-SPSMS, F-38000 Grenoble, France and CEA, INAC-SPSMS, F-38054 Grenoble, France*

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We have fabricated a silicon-single electron transistor (SET) electrostatically coupled with a single Phosphorus shallow donor. Using two control gate voltages we tuned independently the ionization of the donor and the number of electrons in the SET.

The samples, fabricated on 300 mm SOI wafers, are similar to those described in refs. [1,2]. An 8 nm thick and 42 nm-wide silicon nanowire was etched from the SOI film and covered at its centre by a 44 nm long TiN-polysilicon gate isolated by a SiO_2-HfSiON layer. This top gate (V_g) covers three sides of the silicon channel. A 145 nm thick buried oxide separates the channel from the silicon substrate, which can be biased (V_b). 25nm thick Si_3N_4 spacers separate the gate from the highly doped Source-Drain regions. The silicon nanowire regions below the two spacers form two tunnel barriers which isolate a SET below the gate from the S-D electrodes. The central part of the channel contains a few P donors which are intentionally implanted at $5 \cdot 10^{23}$ m^{-3}.

Fig. 1 shows the differential source-drain conductance as function of front and back gate voltages. Coulomb blockade oscillations correspond to the addition of electrons in the SET.

Around $V_G \simeq 0.43$ V the Coulomb oscillation pattern is shifted by the ionization of a single P donor located near the front oxide [3].

We thank support from the EU under projects TOLOP and SISPIN.

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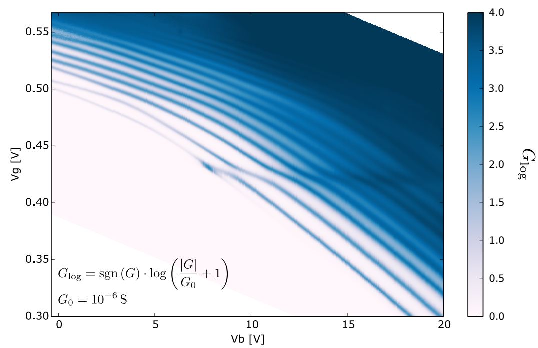

Figure 1: Differential source-drain conductance as a function of front and back gate voltages at T=4.2K

Quantum error correction with solid-state spins

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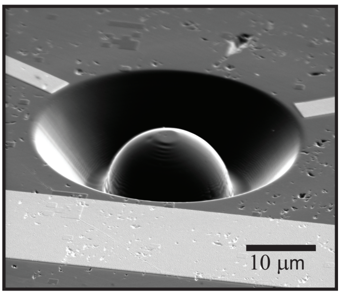
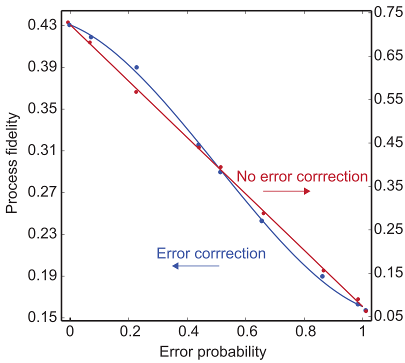
Because quantum states inevitably suffer from errors, scalable quantum computing requires quantum error correction. The information of a single qubit is encoded in multiple physical qubits. Errors are detected by comparing these qubits and are subsequently corrected. Here we present the implementation of a quantum-error-correction protocol with individual solid-state spins[1].

We realize multi-qubit encoding by a new method to control carbon-13 spins in the surrounding spin bath of a nitrogen-vacancy (NV) colour centre [2]. We selectively initialize and control these spins using the NV electron spin and construct high-fidelity single- and two-qubit gates. This method transforms weakly coupled nuclear spins from a source of decoherence into a reliable resource. With these new capabilities we implement a three-qubit quantum-error-correction protocol and demonstrate the robustness of the encoded state to single-qubit errors.

Our results enable control of multiqubit registers, which together with long-distance communication between two NV centres [3] and parity measurements [4] paves the way towards extended error-correction codes, complex error-corrected algorithms and network-based surface codes [5].





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Phonon Interactions and "Jellybean" Couplers for Singlet-Triplet Qubits

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Following the demonstration of the entanglement of two spin qubits via the electrostatic coupling of two GaAs quantum dots [1], a quest has begun to enhance the strength and controllability of the entangling interactions between singlet-triplet qubits. The methods proposed to achieve long range qubit coupling include floating metallic gates [2], magnetic dipole interactions with a ferromagnet [3] and Ruderman-Kittel-Kasuya-Yosida exchange [4]. Here, we investigate an architecture which enables the coupling of two singlet-triplet qubits via an intermediary quantum dot. This architecture theoretically accomodates the implementation of gating sequences for CNOT operations [5]. We also present signatures of phonon interactions with spin qubits [6], exploring geometric and energetic regimes which can be accessed to mitigate unwanted phonon interactions during qubit manipulations.

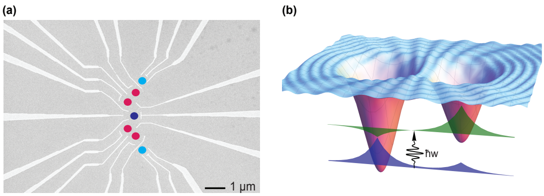

Figure 1: a) SEM of device with "jellybean" coupler. b) Double well potential of quantum dots.

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Optimal post-processing for a generic single-shot qubit readout

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McGill University

We analyze three different post-processing methods applied to a single-shot qubit readout: the average-signal (boxcar filter), peak-signal, and maximum-likelihood methods. In contrast to previous work, we account for a stochastic turn-on time t_i associated with the leading edge of a pulse signaling one of the qubit states. This model is relevant to spin-qubit readouts based on spin-to-charge conversion and would be generically reached in the limit of large signal-to-noise ratio r for several other physical systems, including fluorescence-based readouts of ion-trap qubits and nitrogen-vacancy center spins. We find that the peak-signal method outperforms the boxcar filter significantly when t_i is stochastic, but is only marginally better for deterministic t_i. We generalize the theoretically optimal maximum-likelihood method to stochastic t_i and show numerically that a stochastic turn-on time t_i will always result in a larger single-shot error rate. Based on this observation, we propose a general strategy to improve the quality of single-shot readouts by forcing t_i to be deterministic.

Observation of quantum jumps of a single quantum dot spin using sub-microsecond single-shot optical readout

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Single-shot read-out of individual qubits is typically the slowest process among the elementary single- and two-qubit operations required for quantum information processing. Moreover, in the case of electron spin in optically active quantum dots, the optical read-out operation also flips the spin, thus setting an upper limit to the available measurement time [1]. As a consequence, with the exception of a scheme based on finely adjusted coupled quantum dots that partially avoids measurement induced spin flips [2], single shot measurement of the electron spin has not been realized to date.

Here we demonstrate single-shot measurement of the electron state by using cavity-enhanced resonance fluorescence from spin-dependent recycling transitions in a single charged InGaAs quantum dot (QD) in Faraday geometry (with the magnetic field parallel to the growth direction). The photon collection efficiency of 0.34% that we achieve allows us to obtain an average number of photons above unity in a sub-microsecond time window, leading to a measurement fidelity exceeding 80%. This result corresponds to an enhancement of the spin read-out time by almost three orders of magnitude as compared to the prior measurements on coupled QDs.

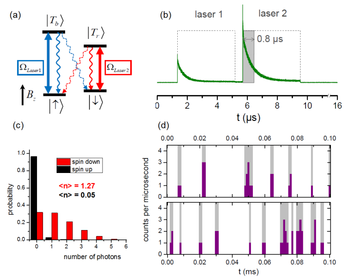

Figure 1: (a) energy diagram of the QD in Faraday geometry. (b) time-resolved average counts using the laser scheme depicted on (a). (c) photon histogram in the time range of 800 ns corresponding to the grey area on (b), after the spin is prepared to the up state (black columns) or down state (red columns). (d) quantum jumps in continuous read-out.

This achievement allows us to observe the quantum jumps of the electron spin state when monitoring continuously. In our case the jumps are mainly induced by the read-out laser (for the transition from bright to dark state) as well as by a weak repumping laser resonant with the weakly allowed diagonal transition (for the transition from dark to bright state). We use the experimentally determined waiting time distribution [3] and second order correlation function to fully characterize the incoherent spin jump dynamics. The waiting time function presents a bi-exponential shape with two very different time constants that allow for a clear discrimination between bright and dark periods.

Embedding the quantum dot in a photonic nanostructure could increase the collection efficiency by a factor of 10, allowing the single-shot measurement time to be reduced to below 20 nanoseconds and the fidelity to reach 97%.

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Exchange coupling between localized vacancy states in graphene nanoflakes

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Graphene nanoflakes are interesting because electrons are naturally confined in these quasi zero-dimensional structures, thus eluding the need for a bandgap. Vacancies inside the graphene lattice lead to localized states and the spins of two such localized states may be used for spintronics. We perform a tight-binding description on the entire system and include a perpendicular magnetic field via Peierls' phase. By virtue of a Schrieffer-Wolff transformation on the bonding and antibonding states, we extract the tunnel coupling strength between the localized states. The tunnel coupling strength allows us to estimate the exchange coupling, which governs the dynamics of singlet-triplet spintronics.

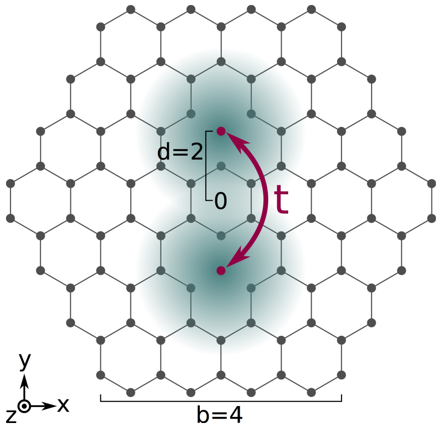

Figure 1: (Color online) Sketch of a hexagonal graphene nano flake. The flake is specified by the number of benzene rings per edge, b, and the distance d (in units of the atomic distance $a = 1.42$ Å) of the vacancies, located at $\vec{r}_{vac} = (0, \pm y)$, from the cartesian origin in the flake center. The sketched island has a $(b = 4, d = 2)$ configuration. The vacancies (red dots) give rise to localized states (green shade) with a hopping t between them. A magnetic field $\vec{B} \parallel \vec{e}_z$ can be applied perpendicularly to the flake plane.

28Si enriched in situ to 99.9998 % for quantum information devices

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National Institute of Standards and Technology

We are depositing epitaxial thin films of 28Si enriched in situ in support of quantum information devices. Highly enriched 28Si is a critical material for quantum computing as removal of 29Si spins provides a non-interacting medium for qubits such as 31P donors which have long electron and nuclear coherence (T2) times even up to room temperature of seconds and minutes respectively. 31P donors can also be addressed optically via hyperfine transitions unlike in natural Si where such transitions are unresolvable. Starting with natural abundance silane, we have used mass filtered ion beam deposition to produce 28Si films enriched to $>$ 99.9998%. The residual 29Si isotope fraction of $<$ 1 ppm is 40 times less than previously reported 28Si devices with 31P atoms controlled with optical addressing. We have demonstrated growth of crystalline 28Si films and are pursuing characterization of their structural properties using in situ reflection high energy electron diffraction (RHEED), in situ scanning tunneling microscopy (STM), and transmission electron microscopy (TEM). Secondary ion mass spectrometry (SIMS) is used to determine enrichment of crystalline 28Si films. As we move away from a silane source towards a solid sputtering source, enrichment may be improved further and the use of additional materials such as Ge can become possible. Numerous experimental systems can take advantage of 28Si as a medium for qubits including STM based hydrogen lithography devices, single donors coupled to single electron transistors, and quantum wells. We have demonstrated the ability to produce isotope heterostructures with applications including fully enriched 28Si/28Si74Ge quantum wells. The importance of 28Si to quantum information systems and the scarcity of such material make clear the critical need for an alternate source of 28Si such as the one we demonstrate.

Nuclear Spins of Ionized Donors in Silicon

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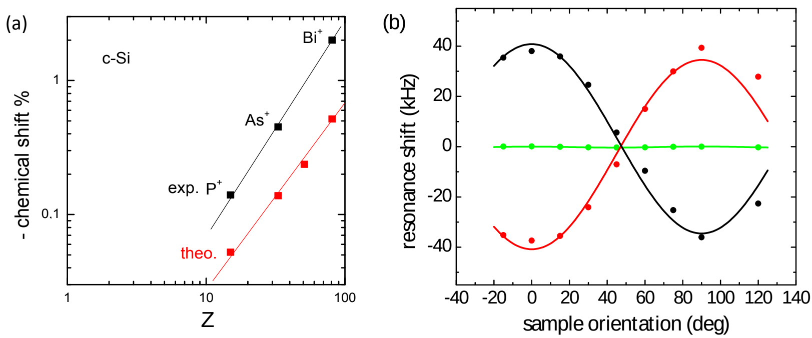
Since the first proposal by Kane [1], spins of group V donors in silicon have been treated as promising candidates for the realization of solid state spin qubits. In addition to the advantages provided by the very advanced silicon technology, these systems benefit from very long coherence times, which exceed minutes in isotopically controlled ^{28}Si. This is the case in particular for the nuclear spins of ionized donor atoms which are well isolated from their surroundings such that coherence on the timescale of 40 minutes can be reached even at room temperature [2]. Electrical read-out methods can provide a very high sensitivity for the detection of the spin state of donors and have been realized down to the single spin limit [3]. However, while the weak interaction of the ionized donors with their surroundings leads to the very slow decoherence, it also limits the possibilities to tune the resonance frequencies of particular donors for addressing them separately. For nuclear spins $I > 1/2$, we demonstrate that this can be achieved by the quadrupole interaction of the ionized donors with electrical field gradients which are, e.g., induced by strain in the Si crystal.



We present the electrical detection of ionized nuclear spins for several group-V donors in Si, which is realized by exploiting spin-dependent recombination processes with paramagnetic defects in the vicinity of the donors [4]. The chemical shift to the resonance frequency is discussed and compared with theory [Fig. 1 (a)]. Furthermore, measurements on ionized arsenic donors in strained Si are shown which demonstrate the shift of the NMR frequency due to the quadrupole effect [Fig. 1 (b)]. In addition, the use of piezo-electric actuators to achieve a controllable local strain and provide the ability to address specific nuclear spins out of an ensemble will be discussed.

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Small nuclear spin environments in graphene quantum dots

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Graphene based quantum dots (QD) constitute interesting systems for both quantum computation and the physics of quantum information. An electron spin confined to such a QD is in contact with a bath of nuclear spins via an anisotropic hyperfine interaction (HI). Since the HI is the most important interaction, the spins form a star-like system with the electron spin in its center. Most interestingly, isotopic purifcation allows to change the ratio of spin carrying ^{13}C with respect to spinless ^{12}C and, hence, to control the number K of nuclear spins. In order to complement previous studies of the anisotropic HI in graphene for large bath sizes [1,2], we investigate the spin dynamics for a small number of nuclear spins by means of exact diagonalization [3]. Considering random initial states of the spin system and different configurations of the nuclei within the dot, we find ultra long relaxation times of the electron spin of more than 10 ms for certain parameters. Based on this knowledge of the dynamics, we hope to identify experimentally accessible observables for testing predictions of quantum information theory and quantum thermodynamics.

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Using Spin Formalism to Design Quantum Energy Harvestors

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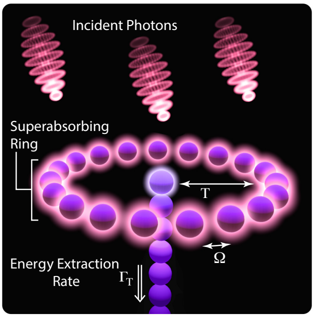
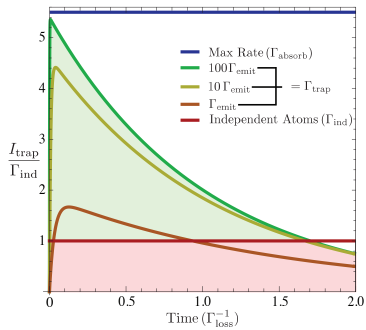
The techniques and models originally developed for complex spin systems can provide a rich formalism for the design of quantum control protocols in optical systems. Here we discuss two applications: engineering superabsorption in coupled systems and exploiting optical ratchet states to escape detailed balance in photon emission and absorption.

The Dicke model of superradiance describes a signature quantum effect: N atoms collectively emit light at a rate proportional to N^2 [1, 2]. Here we show that this phenomenon can, surprisingly, be inverted [3]; we use spin language to describe a set of interacting atoms and demonstrate that by combining several well-established quantum control techniques [4] it is possible to enhance the rate of absorption over emission. We show both analytically and numerically that net superabsorption can be sustained in certain simple nanostructures (see Fig. 1). Potential applications of this effect include photon detection, enhanced light energy harvesting and light-based power transmission.

Optically excited states, which can absorb more photons, but do not emit, would provide a way of overcoming the principle of detailed balance in photon emission and absorption, and enable the implementation of simple photon storage buffers. Employing the mathematical tools for coupled spin chains, we extract the necessary symmetries and properties of optical systems for achieving these desirable optical 'ratchet' states.



(a)



(b)

Figure 1: (a) Ring structure that could exhibit superabsorption. (b) Energy extraction rate from a ring, compared to that for the same number of individual absorbers. Energy is extracted to a trap and a range of extraction rates are displayed. Green regions indicate a superabsorptive advantage.

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Spin resonance on a ^{31}P double quantum dot in silicon

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The dynamics of single spins in ^{31}P:Si has been under intense investigation[1-3] due to their prospective use as qubits (or quantum bits) in a quantum computer[4]. The next step is the experimental demonstration of coupled ^{31}P donors[5] to investigate two electron spin dynamics. To further the understanding of interacting ^{31}P donors in silicon we fabricate a double quantum dot molecule using scanning-tunneling microscopy (STM) lithography[5] for EDSR (electrically detected spin resonance) at the atomic scale. A continuous-wave ESR experiment has been shown to lift the Pauli-spin blockade via mixing of the singlet and zero-spin triplet state of the quantum dots[6,7]. We measure the tunnel coupling between the two quantum dots and describe how using the hyperfine interaction, we can control transport using ESR. We compare the results from experiments with theoretical models using the density matrix formalism in Liouville space.

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Coulomb Blockade and Transport Mechanisms in Ultrathin Nanofabricated Silicon Quantum Dots

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The scaling of transistors and the recent interest in spin-based quantum information have motivated the development of various silicon quantum dots. In this work, we demonstrate an ultrathin intrinsic silicon nanocrystal field effect transistor (Fig. 1a) where quantum effects are ubiquitous. The precision of our fabrication technology allows to thin devices down to a few atoms in thickness, where the bandgap is enlarged threefold by quantum confinement. Such a large gap allows a band-to-band transport mechanism to be identified for the first time in quantum dot devices [1]. A single electron transistor behavior is observed with large addition energy Coulomb diamonds (Fig. 1c, 1d) and an extremely large diamond caused by the silicon bandgap (Fig. 1b), allowing a 10^4 on/off current ratio at room temperature [2]. This work suggests a path to overcome doping distribution problems in ultimately scaled transistors, deterministic fabrication of semiconductor quantum dots without gate-defined tunnel barriers as well as a practical way to engineer the band structure of silicon to achieve a direct bandgap, which is important for many photonic applications.

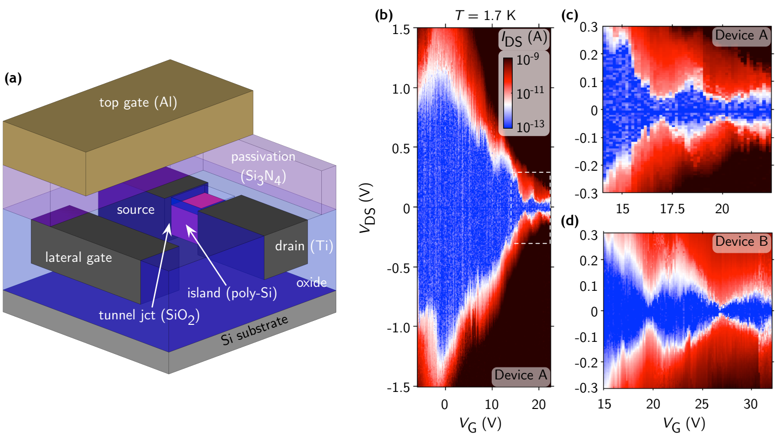

Figure 1. (a) Schematic of the nanocrystal field effect transistor. (b-d) Source-drain current I_{DS} as a function of source-drain voltage V_{DS} and gate voltage V_{G} showing large-addition-energy Coulomb diamonds.

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Virtual fluctuations with real implications: Renormalization-induced torques in spin-qubit control and readout

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Qubit manipulation and readout involve an intentional coupling to an environment, which acts in a two-fold way: Aside from inducing transitions and dissipation, it is also renormalizes the coherent evolution of the qubit. The latter manifests as a renormalization-induced torque [1] that we show to enable fast single-spin operations [2] and to evoke an inextricable coherent backaction in a weak spin-qubit measurement [3].
Regarding spin control, we consider a single-spin quantum dot tunnel-coupled to two ferromagnetic leads with nearly antiparallel, but slightly noncollinear magnetizations. Such a spin-valve setup features a spin resonance in the stationary dI/dV_b stability diagram in the Coulomb blockade regime where sequential transport is suppressed [2]. The resonance signals a lifting of the spin-valve effect by an electrically controllable spin precession. The latter is engendered by the well-known spintronic exchange field arising from virtual fluctuations [1]. To gain evidence for the underdamped precession of a *single* spin, we suggest to probe the time-averaged current in a gate-pulsing scheme that offers control over the precession axis by the pulse amplitude and the precession angle by the pulse duration.
Nurtured by the insights from nanospintronic transport, we find renormalization effects also to be relevant to spin-qubit readout [3]. We investigate a conductance measurement of a sensor quantum dot detecting the state of a spin qubit by spin-to-charge conversion [4]. We show that the capacitvively coupled system of qubit plus sensor quantum dot must be treated as a joint quantum system that evolves coherently during a weak, continuous measurement process. Although this system is entriely nonmagnetic, the ensemble-averaged evolution exhibits many similarities to that of the spin-valve setup, including torques terms acting on the qubit Bloch vector. We show that these torque terms significantly affect the predictions for the conductance signal. Basically, if the electron on the detector has time to probe the qubit, then it also has time to fluctuate and thereby renormalize the system parameters.

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Electronic Structure of the Silicon Vacancy Color Center in Diamond

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The negatively charged silicon vacancy (SiV) color center in diamond is currently of great interest which resulted in recent demonstration of resonant excitation [1,2], in research on its stability in small nanodiamonds suitable for cell-imaging [3] and finally in quantum information applications, such as quantum-key distribution [4]. However, the electronic structure of the SiV center, which manifests in a four line fine structure at low temperatures, has so far remained elusive.

To elucidate the electronic structure of the SiV, we study the fine structure splitting of single SiV centers in a high magnetic field [5]. The single centers have been created using ion implantation in a high quality single crystalline diamond. As a reference, a CVD-film containing an ensemble of SiV centers with low crystal strain is investigated. The similarity of spectra of single centers and low strain ensemble proves our ability to fabricate almost perfect SiVs, free of crystal strain and revealing the true nature of the defect's electronic properties.

We simulate these properties using a group-theoretical approach comprising spin-orbit coupling, the Jahn-Teller effect and the Zeeman interaction present in our experiment. Our model allows a calculation of the orbital and spin parts of the electronic wave functions and explains polarization measurements on single color centers [5]. Through the implementation of an effective strain Hamiltonian, we extend our model to strongly strained emitters in nanodiamonds and discuss the influence of strain onto the electronic states.

This profound understanding of the internal level structure of the SiV paves the road to access the spin of these defects. As a first application, we show a spin-selective optical excitation in the excited state [1]: We excite resonantly electronic states belonging to the $m_S = \pm 1/2$ manifolds and subsequently measure resonance fluorescence spectra. The resulting spectra prove that we can clearly distinguish between the two opposite spin projections. We discuss how this experiment relates to the theoretical model established above, and again take into account the cases of low and high crystal strain. These experiments are a first step towards spin manipulation and readout in this promising solid-state defect.

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Ultrafast optical probe of orbital and spin dynamics in a single spin in diamond

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Optically addressable atomic-scale defects in semiconductors are promising building blocks for quantum devices, but precise quantum control requires a detailed understanding of their dynamics, which is difficult to obtain with currently available techniques. Here we use picosecond resonant pulses of light to probe the coherent orbital and spin dynamics of one such defect, the nitrogen-vacancy (NV) center in diamond, over timescales spanning six orders of magnitude.

We use ultrafast pump-probe techniques to investigate the NV center's orbital-doublet, spin-triplet excited state that becomes stable and optically coherent with the ground state at cryogenic temperatures ($T < 20\,K$). Coupling this technique with optical polarization selection rules, we are able to probe coherent orbital dynamics of the NV center's excited state [1]. The experiments reveal dynamics which occur on femtosecond to nanosecond timescales due to the interplay amongst these three orbital levels. Additionally, this all-optical technique allows for a method of dynamically manipulating the spin state of the NV center by exploiting excited state structure. By studying the spin dynamics of the NV center using coherent pulses of light, we achieve rotations of the spin state at sub-nanosecond timescales and by tuning the excited-state spin Hamiltonian with a magnetic field, we demonstrate arbitrary-axis spin rotations and controlled unitary evolution of the spin state. Extending to the full excited state manifold, we develop a time-domain quantum tomography technique to precisely map the NV centers excited state Hamiltonian [1]. These techniques generalize to other optical addressable systems and can be used as powerful tool to characterize and control qubits in other defect systems. This work is supported by the AFOSR and NSF.

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Quantum limit for nuclear spin polarization in semiconductor quantum dots

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One of main sources of decoherence for spin qubits confined in semiconductor quantum dots comes from hyperfine interaction of the electron spin with the nuclear spins. By polarizing the nuclear spins to 100% it is possible to extend coherence times [1]. Moreover, highly polarized nuclear states are also desirable as a quantum memory to store the coherent state of of the electron spin [2], since the nuclear polarization can persist for minutes in the dark (in absence of an electron in the dot). Despite huge breakthroughs in coherent control of nuclear spin polarization, switching its direction, observing reversal behavior and controlling only certain group of nuclear spins [3], a close to 100% polarized nuclear state has yet to be reported.

A recent experiment [E. A. Chekhovich *et al.*, Phys. Rev. Lett. **104**, 066804 (2010)] has demonstrated that high nuclear spin polarization (65 %) can be achieved in self-assembled quantum dots by exploiting an optically forbidden transition between a heavy hole and a trion state. However, a fully polarized state could not be achieved as predicted by classical rate equations.

We take into account the quantum nature of the nuclear spins and use a fully quantum mechanical master equation describing the joint time evolution of the electronic and nuclear degrees of freedom. We show that the pumping saturation is a consequence of the collective nuclear spin dynamics. By studying both cases of homogeneous and inhomogeneous hyperfine coupling constants, we show that the simpler case of homogeneous coupling qualitatively describes all physical phenomena. The inhomogeneous case is more close to experimental conditions and provides quantitative agreement with the experiment. We also investigate in more detail the variation in the degree of maximal possible polarization depending on the distribution of the electron wave function inside of the quantum dot relative to the lattice using a shell model. Our findings show that variations in the maximal degree of polarization depend on the chemical composition of the quantum dot and the distribution of the electron wave function inside of the quantum dot [4].

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Nonequilibrium spin current through interacting quantum dots

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We develop a theory for charge and spin current between two canted magnetic leads tunneling through a quantum dot with an arbitrary local interaction. For a noncollinear magnetic configuration, we calculate equilibrium and nonequilibrium current biased by voltage or temperature difference or driven by magnetic pumping. We are able to explicitly separate the equilibrium and nonequilibrium contributions to the current, both of which can be written in terms of the full retarded Green's function of the dot. Taking the specific example of a single-level quantum dot with large on-site Coulomb interaction, we calculate the total spin current near the Kondo regime, which we find to be generally enhanced in magnitude as compared to the noninteracting case.

Measurements of the distribution of dissipated heat in a quantum dot driven out of thermodynamic equilibrium

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By split-gate technique, we define a quantum dot in a GaAs/AlGaAs heterostructure and observe real-time single-electron tunneling to and from the connected lead with a nearby quantum point contact. Starting in thermodynamic equilibrium, we apply a well-defined periodic drive voltage on the plunger gate. In this way we measure the distribution of work performed on the energetically highest dot electron and the heat dissipated in the lead during a given subinterval of each cycle. These distributions are compared to master equation calculations and the Jarzynski equation [1], which states that the ensemble average of the exponential of the work W done on the system is related to the exponential of the difference in free energy ΔF between the starting and end point of the drive, measured in equilibrium: $< e^{-\frac{W}{k_B T}} >= e^{-\frac{\Delta F}{k_B T}}$, with k_B the Boltzmann constant and T the bath temperature. For a quantitative analysis, it is important to accurately know the tunnel rates in the range of the drive voltage. In order to measure them fast but still with a good precision also far away from the Fermi energy, a feedback mechanism is implemented.

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Conductance Quantization in Zigzag Graphene Nanoribbons Fabricated by a Remote Hydrogen Plasma

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We investigate the anisotropic etching of a remote hydrogen plasma on graphite samples and graphene flakes in dependence of various parameters such as gas pressure, plasma-sample distance and substrate [1]. Intrinsic defects (graphite) or intentionally predefined holes (graphene) evolve into hexagonal etch pits during plasma exposure, confirming the anisotropy of the etch. The gas pressure and the sample-plasma distance have a similar influence on the etching process for all types of samples, increasing the etch rate for lower pressures and distances. Single layer graphene samples interact differently with the plasma compared to bilayer and multilayer samples, and the choice of the substrate heavily influences the etching for single layer graphene samples.

Further, we present electrical transport measurements performed on 200 nm wide zigzag graphene nanoribbons on a hBN substrate [2], fabricated with the anisotropic etch mentioned above in the downstream region of a cold H-plasma. We observe clear plateaus of quantized conductance at integer values of e^2/h when sweeping the global back gate [3]. Temperatures ranging from 1.2 K up to 80 K were investigated, and the plateaus were visible over the whole temperature range. Similarly, the plateaus were seen up to large source-drain voltage biases exceeding 10 mV. Finally, we also studied the dependence on magnetic field. The appearance of quantized conductance plateaus is a first clear indication of very high-quality graphene nanoribbons produced with a remote hydrogen plasma on hBN substrates.

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Breakdown of Surface Code Error Correction Due to Coupling to a Bosonic Bath

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We consider a surface code suffering decoherence due to coupling to a bath of bosonic modes at finite temperature and study the time available before the unavoidable breakdown of error correction occurs as a function of coupling and bath parameters. We derive an exact expression for the error rate on each individual qubit of the code, taking spatial and temporal correlations between the errors into account. We investigate numerically how different kinds of spatial correlations between errors in the surface code affect its threshold error rate. This allows us to derive the maximal duration of each quantum error correction period by studying when the single-qubit error rate reaches the corresponding threshold. At the time when error correction breaks down, the error rate in the code can be dominated by the direct coupling of each qubit to the bath, by mediated subluminal interactions, or by mediated superluminal interactions. For a 2D Ohmic bath, the time available per quantum error correction period vanishes in the thermodynamic limit of a large code size L due to induced superluminal interactions, though it does so only like $1/\sqrt{\log L}$. For all other bath types considered, this time remains finite as $L \to \infty$.

Effect of atomic disorder on transport in 2D MoS2

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The effect of atomic-scale disorder (defects, adatoms, substitutional atoms) on the properties of monolayers of MoS2 is studied. The different types of short-range disorder is found to result in a significant coupling between the conduction band valleys at K and K'. This hence becomes an important limiting factor for the attainable mobility in 2D MoS2 and is furthermore of importance for valleytronics applications which rely on a well-defined valley quantum number.

Towards single-shot spin read-out with a dielectric antenna

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An optically-active spin qubit can be initialized, manipulated and read-out entirely with optical techniques [1]. Example systems include a self-assembled quantum dot and the NV centre in diamond. The read-out depends on a spin-dependent emission rate. The read-out laser pulse can induce a back-action on the spin. Avoiding back-action in a single-shot process typically demands a short measurement time and hence a high photon collection efficiency yet this is hard to achieve with an unstructured semiconductor on account of the high refractive index. We report here progress on improving the photon collection efficiency from optically-active spins. The main concept is to use a high index solid immersion lens, a gallium phosphide (GaP) half-sphere ($n = 3.1$) as part of a dielectric antenna [2]. The potential advantages are broadband performance, minimal and non-invasive processing, directed emission along with a (small) Purcell enhancement of the radiative emission rate [2,3,4]. The challenge with respect to the GaP lens is that the tolerance to imperfections decreases as the refractive index increases.

The performance of a GaP solid immersion lens was evaluated in a microscopy experiment. Close-to-diffraction-limited resolution is achieved at wavelength $\lambda = 925$ nm using a numerical aperture NA$= 0.68$: the lateral extent of the point spread function is $\Delta x = 230$ nm. The collection efficiency of a singly-charged quantum dot embedded in a bulk semiconductor is compared without a solid immersion lens, with a zirconium dioxide solid immersion lens and with a GaP solid immersion lens. These results are very promising for the realization of a semiconductor membrane-based antenna structure [4]. Diamond membranes were fabricated and bonded directly to the flat surface of a GaP solid immersion lens. After plasma etching the membranes are just a few hundred nanometers thick. The key difference to the semiconductor experiment is that the refractive index of the diamond active layer ($n = 2.4$) is lower than the refractive index of the GaP lens, potentially resulting in almost complete uni-directional emission [4]. Emission from the diamond membranes exhibits thickness-dependent ring patterns in the back focal plane. The intensity profile is in excellent agreement with theoretical expectations predicting a collection efficiency $> 90\%$. Further confirmation comes from the high count rate on a single NV centre, which is close to 2 MHz. With respect to the count rate of single NV centres in electronic grade diamond material measured with the same set up, this corresponds to an enhancement by a factor of ~ 24. We also demonstrate a spin-dependent emission intensity and Hahn echo times ≥ 100 μs demonstrating that the attractive NV spin properties survive the membrane fabrication and antenna construction.

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Pulsed EPR on a dilute oriented ensemble of molecular nanomagnets

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The study of coherent electron spin dynamics in molecular nanomagnets (MNMs) has recently become the subject of intense research. This is inspired in part by proposals for quantum information processing, exploiting, for example, the large total spins, internal degrees of freedom, and molecular scale[1]. Pulsed EPR allows direct measurement of spin coherence, with such studies on Cr_7M heterometallic rings revealing phase memory times on the order of μs at a few kelvin[2,3].

By working with a dilute sample, we can minimise decoherence arising from intermolecular dipolar interactions. Furthermore, since various proposals for MNMs depend on coherent manipulation of an anisotropic spin multiplet, with orientation dependent transition energies, in order to maximise the range of quantum information experiments that may be performed, we require alignment of our MNMs. In the present work, we dope a Cr_7Zn MNM into a diamagnetic and isostructural host, Ga_7Zn. This allows pulsed X-band EPR on single crystals at low magnetic fields, including relaxation and nutation experiments on the $S = 3/2$ ground state[4] (see Figure 1).

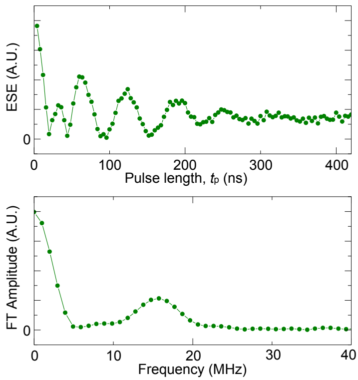

Figure 1: Nutation experiment at $T = 4.5$ K with Fourier transform of the nutation.

In addition, we present progress in the study of MNM based dimers. This includes the asymmetric $N@C_{60}$-Cr_7Ni, a variable temperature study of which reveals the phase memory time of the highly coherent N spin to provide a direct probe of the magnetisation dynamics of the Cr_7Ni MNM. Study, through the traditional EPR technique of double electron-electron resonance (DEER), of various symmetric dimers allows us also to identify an example of such a dimer that is suitable for the implementation of two quit algorithms.

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Circuit QED with Hole-Spin Qubits in Ge/Si Nanowire Quantum Dots

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We propose a setup for universal and electrically controlled quantum information processing with hole spins in Ge/Si core/shell nanowire quantum dots (NW QDs) [1]. 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] 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, so single- and two-qubit gates can be operated independently. Remarkably, we find that idle qubits are insensitive to charge noise and phonons, and we discuss strategies for enhancing noise-limited gate fidelities.

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Phonon-mediated decay of singlet-triplet qubits in double quantum dots

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We study theoretically the phonon-induced relaxation (T_1) and decoherence times (T_2) of singlet-triplet qubits in lateral GaAs double quantum dots (DQDs). When the DQD is biased, Pauli exclusion enables strong dephasing via two-phonon processes. This mechanism requires neither hyperfine nor spin-orbit interaction and yields $T_2 \ll T_1$, in contrast to previous calculations of phonon-limited lifetimes. When the DQD is unbiased, we find $T_2 \simeq 2T_1$ and much longer lifetimes than in the biased DQD. For typical setups, the decoherence and relaxation rates due to one-phonon processes are proportional to the temperature T, whereas the rates due to two-phonon processes reveal a transition from T^2 to higher powers as T is decreased. Remarkably, both T_1 and T_2 exhibit a maximum when the external magnetic field is applied along a certain axis within the plane of the two-dimensional electron gas. We compare our results with recent experiments and analyze the dependence of T_1 and T_2 on system properties such as the detuning, the spin-orbit parameters, the hyperfine coupling, and the orientation of the DQD and the applied magnetic field with respect to the main crystallographic axes.

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Evidence for Helical Nuclear Spin Order and Tunneling Spectroscopy in GaAs Quantum Wires

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We present transport measurements of cleaved edge overgrowth GaAs quantum wires. The conductance of the first mode reaches $2e^2/h$ at high temperatures T $\geq$ 10 K, as expected. As T is lowered, the conductance is gradually reduced to $1e^2/h$, becoming T independent at T $\leq$ 0.1 K, while the device cools far below 0.1 K. 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 2 suggests lifting of the electron spin degeneracy in the absence of B. Our results are consistent with theoretical predictions for helical nuclear magnetism in the Luttinger liquid regime and give first evidence for a helical nuclear spin order in GaAs quantum wires [1].

Tunneling spectroscopy in the double wire system allows probing of the energy dispersion of the wire modes and thus is a very potent tool [2]. We present spectroscopy data from the same GaAs double quantum wires described above and we investigate finite-size quantum interference fringes [3] in different parameter regimes and wire configurations, in pursuit of further signatures of helical nuclear spin order.

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Design of a probe mounted nuclear demagnetization stage for experiments at ultra-low temperatures with rapid sample changing

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The commercial production of dilution refrigerators over the past 20 years has given researchers worldwide easy access to the milli-Kelvin regime. The lowest temperatures achieved by this technology are just below 2 mK [1] [2]. For lower temperatures adiabatic nuclear demagnetization techniques have been used [3] [4], but presently there are no "off the shelf" commercial solutions which provide this technology. The temperature range below 2mK remains in the realm of specialist research groups.

The possibility of reaching this temperature range in nanostructures could reveal new physical phenomena such as novel ordering transitions in 2DEG's [5] and increased coherence times in spin qubits [6].

Recent experiments have shown the feasibility of using demagnetization techniques on a fixed nuclear stage inside a cryogen-free dilution refrigerator [7]. Here we present the initial design and construction of a commercial cryogen-free system for obtaining ultra-low temperatures via adiabatic nuclear demagnetization. In our design the nuclear refrigerant ($PrNi_5$) is mounted on a top loading cold-insertable probe, allowing for rapid sample changing. The demagnetization solenoid remains mounted within the cryostat. The dilution refrigerator operates with a base temperature below 8 mK and a cooling power of 1400 μW at 120 mK. The large plates used in the construction of this cryostat provide a low-vibration platform which will minimize possible heat leaks into the nuclear stage. We also show the predicted performance characteristics of our design and speculate on future developments.

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Distributing entanglement through noisy spin chains in diamond

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Individual nitrogen-vacancy (NV^-) defects in diamond have emerged as one of the most promising candidates for a solid state qubit, since they operate at high temperature and can be initialised and measured optically [1]. However, different NV^- centres must be widely separated if individual optical addressing is to be possible, and so generating strong enough interactions between them is a difficult problem.

A recent proposal addresses this problem by introducing an architecture where distant NV^- centres are connected by chains of implanted nitrogen impurity spins [see Fig. 1 (a)] [2], and global microwave fields are all that is needed to drive the computation. We here focus on inevitable errors and imperfections occurring in such an architecture [3]. We find that the expected level of spin decoherence in the NV- severely limits the power of the spin chain bus; for the foreseeable future the achievable gate fidelity may thus fall short of that required for fault-tolerant quantum computing. Fortunately, we also discover that the chain can still function in the more modest capacity of distribution of noisy entanglement. This opens the possibility of employing distillation protocols to purify the transmitted entanglement over several runs, and thus design a quantum computer based on the paradigm of *distributed* quantum information processing.

We go on to investigate spin chain disorder, finding that any weak links in a one dimensional spin chain cause distribution times to increase markedly. We discuss whether this can be overcome using different geometries for the spin bus. We conclude by discussing the prospects for immediate experimental testing of our ideas.

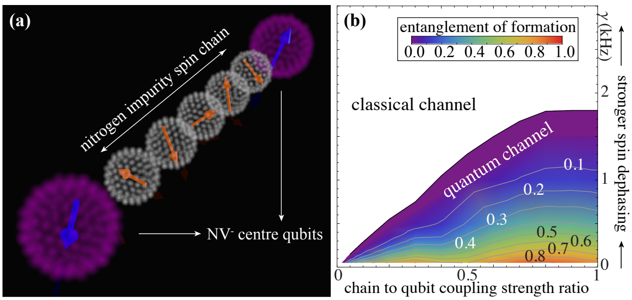

Figure 1: a: two NV^- colour centres connected by a chain of five (optically inactive) nitrogen impurity spins. b: the channel's capacity for exchanging quantum information vanishes for larger spin dephasing rates. The x axis shows the (tuneable) NV^- centre to N impurity spin coupling strength in units of the inter-chain N-N couplings.

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Experimental estimation of average fidelity of a Clifford gate on a 7-qubit NMR quantum processor

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The common approach of characterizing a given quantum gate via quantum process tomography (QPT) requires exponential number of experiments. Therefore, estimating the average fidelity of the quantum gate by QPT is not practical for large-scale systems. However, by using twirling method and some basic knowledge of probability theory, we can significantly reduce the number of experiments for certifying Clifford gates. In this work, we show how to certify a 7-qubit Clifford gate by merely repeating ≈1600 experiments to reach 99% confidence, and demonstrate our proposal in an NMR quantum processor. The Clifford gate we certified is of great importance in quantum computing as it can generate highest-order coherence from a single coherence state. In experiment, the average fidelity of this gate is over 87% after eliminating the decoherence effect, and a high-fidelity pseudo-pure state has been prepared based on this Clifford gate. This method for certifying Clifford gates is efficient and scalable, and can be extended to other quantum systems without significant changes.

Mechanical driving of nitrogen-vacancy center spins in diamond

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We directly couple nitrogen-vacancy (NV) center spins and cavity phonons by driving spin transitions with mechanically-generated harmonic strain [1]. The spin-phonon interaction that mediates this coupling has recently attracted a great deal of attention, both experimentally [1,2,3] and in theoretical works [4,5]. Here, we present the use of a bulk-mode acoustic resonator fabricated from single-crystal diamond [Fig. 1(a)] to exert non-axial ac stress on the NV centers within the substrate. By tuning the $m_s = +1 \leftrightarrow m_s = -1$ spin state splitting into resonance with a GHz frequency mechanical mode, we observe mechanically driven spin transitions [Fig. 1(b)] and coherent Rabi oscillations of the $\Delta m_s = \pm 2$ spin transition—a transition that is forbidden by the magnetic dipole selection rule. These direct spin-phonon interactions provide a new opportunity for quantum control and could have applications in hybrid quantum systems and quantum optomechanics.

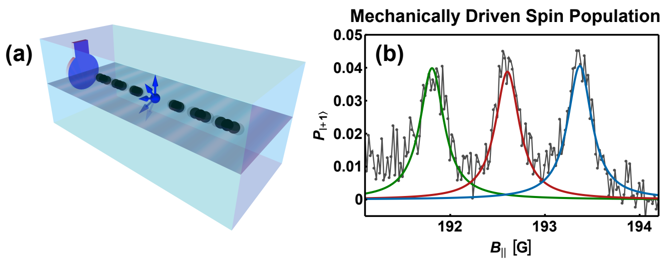

Figure 1: (a) Device schematic. A bulk-mode acoustic resonator drives NV center spin transitions; (b) Spectrum of spin population mechanically driven into the $|(m_s =) + 1\rangle$ spin state via direct spin-phonon interactions.

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Coupling Surface Acoustic Waves to Spin Ensembles

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There is great interest within the physics community in novel hybrid quantum systems. Recent work by George et al. [1] showed how the energy splittings of Mn^{2+} impurity ions in wurtzite ZnO can be controlled by an external electric field due to crystal anisotropy, and transitions can thus be electrically driven. More recently, Klimov et al. [2] demonstrated electrically driven spin resonance in a similar system, silicon carbide color centers, by applying AC voltage to electrodes patterned directly on the crystal. We work with Mn^{2+} ions in ZnO with the aim to couple them to superconducting circuits. As ZnO is strongly piezoelectric, one can also excite surface acoustic waves (SAWs). SAWs are an interesting addition to a superconducting circuit as the sound waves travel many orders of magnitude slower than electromagnetic waves. In recent unpublished work by Gustafsson et al. [3], SAWs were coupled to a transmon superconducting qubit.

We propose to make a high-Q SAW resonator on a ZnO crystal with dilute Mn^{2+} impurities and couple the waves to the Mn^{2+} spin ensemble through the electric field accompanying the SAW. To this end, we are studying SAW delay lines and resonators on bulk ZnO and will show our latest results.

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Quantum Hall Resonators for Coupling Spin Qubits

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Non-dissipative, directional edge magnetoplasmons (EMPs)[1] arising in the quantum Hall effect have potential to couple distant spin qubits. This quantum bus approach would alleviate the crowding of gates and dense wiring connections needed to operate multiple spin qubits in close proximity. Towards this goal, we demonstrate quantum Hall resonator devices that can sustain EMPs of the frequency needed for qubit coupling. The resonators are circular disks of two-dimensional electron gas, defined in GaAs/AlGaAs by wet etching. The microwave response of the resonator (see figure), probed via an on-chip coplanar transmission line and cryogenic amplifier, reveals strong features corresponding to plasmon excitations of the edge-states and their dispersion with magnetic field. This microwave technique also offers a means of probing exotic quantum Hall states beyond standard transport measurements[2], opening the possibility of coupling spin qubits to long-lived topological states.

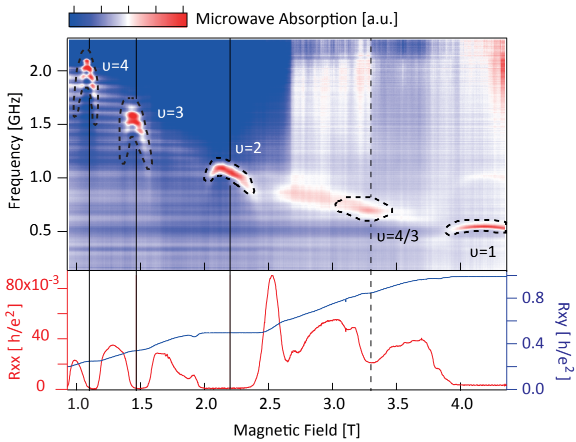

Figure 1: S21 microwave absorption spectrum of hall droplet (top frame) and transport data (bottom frame) as a function of swept magnetic field. Vertical solid (dashed) lines indicate integer (fractional) filling factors. Black dashed outlines are guides to the eye.

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Tunable g factor and phonon-mediated hole spin relaxation in Ge/Si nanowire quantum dots

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In our work [1], we theoretically consider g factor and spin lifetimes of holes in a longitudinal Ge/Si core/shell nanowire quantum dot that is exposed to external magnetic and electric fields (see Fig. 1). For the ground states, we find a large anisotropy of the g factor which is highly tunable by applying electric fields. This tunability depends strongly on the direction of the electric field with respect to the magnetic field. We calculate the single-phonon hole spin relaxation times T_1 for zero and small electric fields and propose an optimal setup in which very large T_1 of the order of tens of milliseconds can be reached. Increasing the relative shell thickness or the longitudinal confinement length prolongs T_1 further. In the absence of electric fields, the dephasing vanishes and the decoherence time T_2 is determined by $T_2 = 2T_1$.

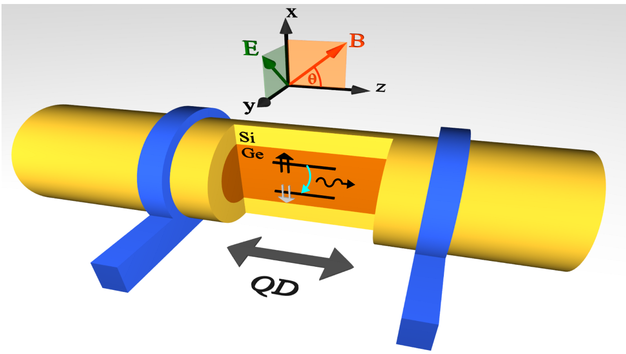

Figure 1: Sketch of a Ge/Si core/shell nanowire aligned with the z-axis of the coordinate system. Electric gates (blue) induce confinement and define a quantum dot. The electric field $\boldsymbol{E}$ lies perpendicular to the wire in the xy-plane and the magnetic field $\boldsymbol{B}$ lies in the xz-plane.

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Tunnel-Junction Thermometry down to 4 mK

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A wide range of phenomena in solid state physics contain small energy scales and are therefore only accessible at very low temperatures. To achieve low temperatures in nanoelectronic devices, we use a dilution refrigerator with a home-built parallel network of nuclear Cu refrigerators [1], equipped with multiple shielding and filtering stages. Here, we present measurements on a normal-metal / insulator / superconductor (NIS) junction which we use as an electron thermometer [2]. The IV-curve maps the convolution of the Fermi-Dirac distribution of the normal metal with the superconducting BCS density of states. To obtain temperature, we extract the size of the thermally broadened gap, which depends linearly on temperature for a wide range of temperatures [3]. To achieve a reliable calibration, variations in the magnetic stray field on the order of a few Gauss have to be corrected. We observe excellent agreement of the mixing chamber temperature and the NIS thermometer between 100 and 10 mK. When using the nuclear refrigerators to cool the Cu stage below 1 mK, the NIS temperature saturates at ~ 4 mK.

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Connecting quantum dots on micron scales: 2 approaches.

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While qubit manipulation has been intensely studied, scalably connecting many qubits is also of great importance. We consider two methods to connect qubits over μm scales. Surface acoustic waves (SAWs) are coherent phonons that, in a piezoelectric material, provide a confining potential capable of trapping and transporting electrons while preserving spin and charge coherence [1,2]. We show that individual electrons may be transported from one quantum dot along a depleted channel to a second quantum dot and returned with transfer fidelities greater than 90% [3]. Larger dot separations can be trivially achieved with longer channels which may allow "local" integration of qubit control infrastructure.

An alternative way to entangle is to allow neighbouring qubits to capacitively couple [4]. Expanding this to an array requires spacing out the qubits [5]. We have extended Ref. [5] to the coupling of multiple qubits as would be required in a two dimensional array. While adding a second coupler in parallel Fig. 1(d)(ii) reduces the initial couplers strength (i) by 40% a coupler on the opposite side (iii) gives enhanced screening and an increase of 10% over initial coupling. Additionally, the coupling of next-to-nearest-neighbour couplers can be varied up to 25% of the direct coupler-coupling strength.

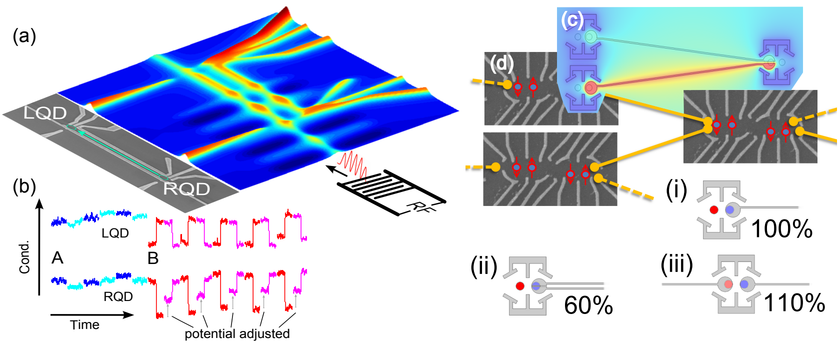

Figure 1: (a) Illustration of SAW moving from R to LQD, (b) Charge detector traces demonstrating SAW transfer. (c) Simulation of floating electrostatic couplers between three qubits. (d) Schematic of 2D qubit array connected with floating couplers allowing easier access for control voltages (light grey surface gates) (i-iii) effect of additional couplers on direct coupling strength.

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Helical nuclear spin order in two-subband quantum wires

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In quantum wires, the hyperfine coupling between conduction electrons and nuclear spins can lead to a (partial) ordering of both of them at low temperatures. By an interaction-enhanced mechanism, the nuclear spin order, caused by RKKY exchange, acts back onto the electrons and gaps out part of their spectrum. In wires with two subbands characterized by distinct Fermi momenta k_{F1} and k_{F2}, the nuclear spins form a superposition of two helices with pitches π/k_{F1} and π/k_{F2}, thus exhibiting a beating pattern. This order results in a reduction of the electronic conductance in two steps upon lowering the temperature.

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Using a two-electron spin qubit to detect flying electrons

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In quantum optic experiments with flying electrons, the flying electrons are so far detected via current measurement, summing up the contribution of millions of electron transfers between two contact pads and electron correlations are encrypted in the current noise. This represents an important limitation for the investigation of quantum correlations in experiments with flying electrons. To go beyond average measurements, it is necessary to detect an individual flying electron passing by a detector, a very difficult task to tackle with conventional detectors. However, quantum systems have been identified as extremely sensitive systems to external perturbations and potentially good detectors.
Here, we investigate experimentally the coupling between a two-electron spin qubit defined in a AlGaAs-GaAs heterostructure and individual electrons propagating in the edge states of the Quantum Hall regime. We use two different ways to inject electrons into the edge state: either by a quantum point contact or a fast tunable quantum dot. We demonstrate that the qubit is an ultrasensitive and fast charge detector with the potential to allow single shot detection of a single flying electron. This work opens the route towards quantum electron optics at the single electron level above the Fermi sea.

Electric-Field Control of Josephson Spin Currents in Bose-Einstein Condensates of Magnons Using Berry Phase

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We present the microscopic theory on the Josephson effects in Bose-Einstein condensates (BECs) of magnons. [1,2] We start from a microscopic spin model that we map onto a Gross-Pitaevskii Hamiltonian and derive the two-state model [3,4] of the magnon BEC Josephson junction. Next, we focus on the influence of the Aharonov-Casher (A-C) phase[5] (the geometric phase obtained by magnons moving in an electric field) on the Josephson effects. We show how to obtain the alternating-current Josephson effect as well macroscopic quantum self-trapping in a magnon BEC. [6] Then, we illustrate how to control the direct-current Josephson effect [7] electrically using the A-C phase. Finally, we point out the possibility for the experimental realization of persistent spin currents [8] in a ring-like setup similar to that used in a superconducting quantum interference device (SQUID), namely magnon-SQUID.

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Micro-magnet stray field simulations for spin qubit manipulation

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Manipulation by electron spin resonance requires alternating magnetic fields, which are challenging to be localized to only a single spin[1]. In contrast alternating electric fields can be generated readily by electrostatic gates and can be localized easier to address individual qubits. Recent electric dipole spin resonance (EDSR) experiments have shown that alternating electric fields can be coupled to the electron spin either by (I) spin-orbit coupling, (II) nuclear hyperfine interaction or (III) a micro-magnets stray field across the quantum dot[2, 3]. For materials having low spin-orbit coupling and hyperfine coupling, e.g. isotopically purified ^{28}Si or ^{12}C, only the third coupling mechanism will result in a MHz Rabi frequency. The advantage of e.g. ^{28}Si/SiGe quantum dots are their low spin-orbit coupling and hyperfine coupling[4, 5]. The decoupling from the solid state environment leads to long relaxation time T_1 and dephasing times T_2. Thus lower gate errors can be expected compared to III/V semiconductors. However, by fabrication of a micro-magnet on the sample, random magnetic fluctuations appear. Thus the impact of the dynamics of the micro-magnet's stray field on T_1 and T_2 has to be taken into account and compared to the achievable Rabi frequency.

We report on simulations to optimize the geometry of a micro-magnet on top of a realistic electrostatically defined, tunnel-coupled double quantum dot (DQD) occupied by two electron spins representing two qubits. The goals are to maximize the spin Rabi frequency, have addressability to a single spin and being robust against fabrication misalignments. We further simulate the required magnitude of the external magnetic field and thus the excitation frequency. Finally, we estimate T_1 and T_2 purely due to thermal fluctuations of the micro-magnet magnetization at typical operation temperature ($\sim 30\,\text{mK}$). Under realistic experimental conditions, we find a robust gradient magnetic field of at least 1.5 mT/nm. In silicon with effective electron g-factor of ≈ 2 this results in a Rabi-frequencies in the 100 MHz regime at an external magnetic field of 500 mT and an excitation frequency of 17.5 GHz for silicon DQDs. Fluctuations of the micro-magnet's magnetization limits the spin relaxation time for polycrystalline cobalt to the order of seconds, but several tens of seconds for single crystalline cobalt, while the contribution to pure spin dephasing is negligible in both cases.

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Spin polarization without magnetic field in a spin-orbit-coupled quantum point contact

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Practical implementation of spintronics devices requires realization of a source of spin polarized current that would operate in the absence of magnetic field. In semiconductor nanostructures the electron spin can be altered electrically by spin-orbit interaction [1,2]. In the present work we theoretically investigate a system of quantum point contact – a constriction introduced in quantum channel that in the presence of spin-orbit coupling can serve as a source of spin polarized current [3]. Spin-orbit interaction acts as an effective magnetic field and splits the spin subbands of the propagating electron. We explain that due to lateral confinement of the quantum point contact the subbands become mixed and as a result the degree of spin polarization of some modes is reduced. When the electron propagates through the narrowing the transmission of the input modes whose spin do not match the dominating spin polarization in the constriction is damped. This in turn leads to non-zero spin polarization of – initially spin-degenerate – electron current flowing out from the quantum point contact. We find that the polarization is obtained in a wide range of Fermi energies and quantum point contact potential. The spontaneous spin polarization appears particularly strong in the low energy part of the dispersion relation and on the last conductance step $G_0 \leq 2e^2/h$. The latter result corresponds with breaking of the spin symmetry that leads to formation of nonzero magnetic moment in the constriction that is considered [4] as responsible for formation of $G \simeq 0.7G_0$ anomalous plateau present in the experimental data [5].

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Majorana modes in smooth normal-superconductor nanowire junctions

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Institute for Cross-Disciplinary Physics and Complex Systems

A numerical method to obtain the spectrum of smooth normal-superconductor junctions in nanowires, able to host Majorana zero modes, is presented. Softness in the potential and superconductor interfaces yields opposite effects on the protection of Majorana modes. While a soft potential is a hindrance for protection, a soft superconductor gap transition greatly favors it. Our method also points out the possibility of extended Majorana states when propagating modes are active far from the junction, although this requires equal incident fluxes in all open channels.

A simple yet accurate theory for bulk donors in Si: exchange coupling and Stark effect

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We present and analyze a multi-valley effective mass theory (EMT) describing donors in Silicon [1], accounting for anisotropy of the Si conduction band and central cell corrections due to the impurity potential. Within the usual EMT envelope approximations, we are able to fit experimental orbital binding energies and the hyperfine coupling of the donor electron to the nucleus, with just two parameters that only depend on the chemical species of the doping (P, As, Bi).

Such simple theory unveils a unique physical insight into the electronic behaviour of dopants and is used for fast computation of accurate values for two key quantities in the framework of Si quantum computing: the exchange coupling J between two nearby donor electrons, and the one-electron hyperfine and g-factor shifts induced by an external electric field F. The former is maybe the most known and straightforward channel to implement two-qubit operations when using electron spins as the computational degrees of freedom [2,3]; the Stark effect is expected to be an unavoidable feature of any real-world Si quantum computer, since external fields must be applied and carefully tuned in order to execute any controlled logical operation.

While experimental measurements of the inter-donor exchange coupling are still lacking, we predict that the spread of possible values it can take is not as broad as expected from previous calculations [4,5] (Fig. 1), where the computed exchange varied dramatically on the sub-nanometer scale of the relative positioning d of the nuclei. It follows that the precision with which donors must be placed to achieve a certain error tolerance in two-qubit operations is not as great an experimental obstacle as was earlier assumed.

Furthermore, we compare the Stark shifted hyperfine coupling A (Fig. 2) and g-factor of the donor electron to recent experimental measurements [6], and find close agreement.

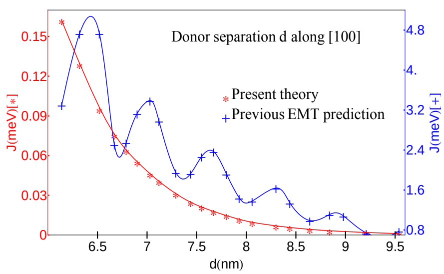

Figure 1

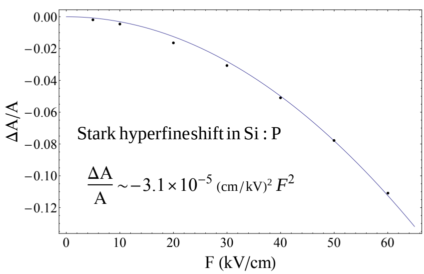

Figure 2

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Silicon-vacancy centre in diamond: Optical signatures of spin

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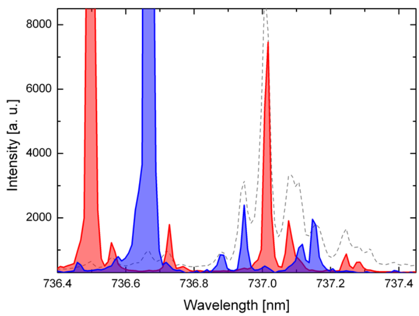
Colour centres in diamond have become a versatile toolbox for various applications, including quantum information processing [1], metrology [2] and biomarking [3]. The negatively charged nitrogen-vacancy centre is the most studied one for such applications, thanks to its spin triplet ground state. As a candidate for similar applications, the negatively charged silicon-vacancy (SiV^-) centre has the advantage of a very low electron-phonon coupling, leading to about 80% of the emission being concentrated into a spectrally narrow (down to 0.7 nm) zero-phonon line at 737 nm even at room temperature [4], making it a promising single photon source. The next challenge is to determine whether the SiV^- centre possesses an optically accessible electronic spin degree of freedom for quantum information processing purposes.

We have investigated the response of the SiV^- centre to a magnetic field up to 7 T, evidencing in the fluorescence spectrum a splitting of the optical transitions consistent with a spin S=1/2 system [5]. In order to get a direct access to the population dynamics of the energy levels, we have implemented resonant excitation of the different transitions under magnetic field. We have this way evidenced the selective excitation of two complementary transition groups in the fluorescence spectrum (as seen in Figure), revealing an optically accessible spin S=1/2 [6]. Future steps towards coherent control of confined spins and spin-photon entanglement include probing of the spin coherence through optically detected magnetic resonance or coherent population trapping.



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Interplay of spin-orbit and hyperfine interactions in dynamical nuclear polarization in semiconductor quantum dots

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We explore the interplay of spin-orbit and hyperfine effects in nuclear state preparation schemes in two-electron double quantum dots in $In_xGa_{1-x}As$. The quantity of utmost interest is the resulting electron spin decoherence time T_2^* in dependence of the number of sweeps through the electron spin singlet S triplet T_+ anti-crossing. Decoherence of the singlet-triplet qubit is caused by the difference field induced by the nuclear spins. We study the case where a singlet $S(2,0)$ is initialized, in which both electrons are in the left dot. Subsequently, the system is driven repeatedly through the anti-crossing and back using linear electrical bias sweeps. Our model describes the passage through the anti-crossing with a large number of equally spaced, step-like parameter increments. We develop a numerical method describing the nuclear spins fully quantum mechanically, which allows us to track their dynamics. Both Rashba and Dresselhaus spin-orbit terms do depend on the angle θ between the [110] crystallographic axis and the axis that connects the centers of two quantum dots. Our results show that the suppression of decoherence (and therefore the enhancement of T_2^*) is inversely proportional to the strength of the spin-orbit interaction, which is tuned by varying the angle θ Fig. 1.

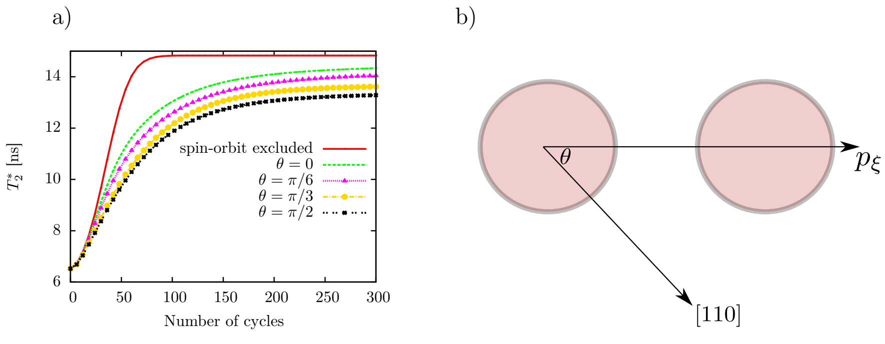

Figure 1: a) Qubit decoherence time in $In_{0.2}Ga_{0.8}As$ as a function of number of cycles over the anti-crossing for different values of the angle θ and therefore different strengths of spin-orbit. b) θ is the angle between the [110] crystallographic axis and the interdot connection axis.

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Universal phase diagram of quantum dissipative many-body systems

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The interplay between quantum dissipation and interactions in quantum many-body systems can give rise to a wealth of novel phenomena.

The one-dimensional coplanar rotor model (also known as quantum phase model) is a paradigmatic model for studying quantum phase transitions with dissipative coupling to an external bath. It can represent, for instance, the superconducting phases of BCS condensates in a one-dimensional chain of superconducting islands connected by Josephson junctions and shunt resistances [1]. At zero temperature, a quantum phase transition occurs by tuning the interaction strength between the phases [2,3]. When the system is coupled to the environment, the common accepted scenario is that the dissipation suppresses the quantum fluctuations and, therefore, enhances the classical ground state characterised by long-range order [4,5].

Contrary to previous studies, I focus on a system which is coupled to the environment with a dissipative interaction designed in way to reduce the quantum fluctuations of the conjugate variables of the local phases [6]. I will show that this anomalous dissipation leads to a reversed behaviour of the phase diagram: Increasing the dissipation causes a stabilisation of the disordered quantum ground state.

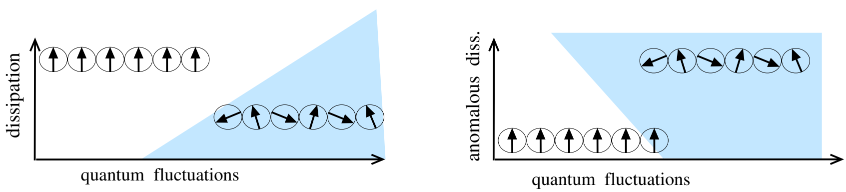

Figure 1: Phase diagram for the 1D quantum phase model with dissipative coupling. **Left:** standard dissipative coupling. **Right:** Anomalous dissipative coupling.

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Nuclear Spin Diffusion Mediated by Heavy Hole Hyperfine Non-Collinear Interactions

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Enormous progress has been made in initializing, manipulating, and reading out the state of a single spin confined in semiconductor quantum dots [1,2]. However, these developments are still not sufficient to implement a functional spin-based quantum computer. In III-V semiconductor quantum dots, a major obstacle originates from the hyperfine interaction between the electron or hole spin and the host nuclear spins [3]. This interaction results in very short decoherence times on the order of tens of nanoseconds. Although it was predicted that nuclear spin polarization can improve spin coherence, the required degrees of nuclear polarization have never been reached experimentally. The inability to achieve a maximally polarized nuclear state shows that our understanding of the hyperfine mediated dynamics is still incomplete.

Here, we show that the effective hyperfine interaction between heavy hole states, described with p-symmetric Bloch functions, and nuclear spins leads to a diffusion mechanism which limits optical pumping of nuclear spins in neutral quantum dots [4]. Diffusion is allowed through the effective heavy hole hyperfine non-collinear interaction. Although the strength of the latter is relatively small compared to the strength of the previously found Ising-like interaction [5,6], it leads to non-trivial dynamics due to the presence of dark excitons. The longer the system stays in the dark states the more efficient diffusion becomes. Ironically, dark excitons are populated via the electron hyperfine interaction during the optical pumping. In contrast to earlier theories, we find that non-collinear interactions influence the nuclear spin dynamics even when the laser frequency is on resonance with the optically allowed electronic transition [7].

Our results not only provide an explanation for the experimentally observed low degrees of nuclear spin polarization, but they also offer an alternative explanation to the results found by Chekhovich *et al.* [8].

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Quantum dots in Ge-Si core-shell nanowires

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Group IV semiconductor nanowires have been established as a versatile platform for low-temperature charge transport experiments in single and double quantum dots [1, 2, 3]. Since group-IV materials have predominantly spin-zero nuclei, high spin decoherence times are expected in such systems, an essential step towards quantum computers [4].

Here, we study monocrystalline Ge nanowires with a thin Si shell where the type-2 band alignment between Si and Ge induces free holes in the Ge core without using gates or any form of doping [5, 6]. Wires are deposited on top of an array of bottom gates separated by a dielectric layer to control the potential landscape within the wire, creating a fully tunable single or double quantum dot. Compared to using a top-gated design, the use of bottom gates avoids exposure of the active area of the nanowire to the potentially destructive effects of e-beam lithography. Ohmic Ti/Pd source-drain contacts are applied while a backgate is realized by using a p++ doped substrate.

Preliminary transport measurements at 4.2 K show low contact resistances (<5 kΩ) while both the global back gate and individual bottom gates can be used to pinch-off the nanowire. This bodes well for the creation electrostatically defined quantum dots in the nanowires.

Furthermore, theoretical calculations for Ge-Si nanowires predict a strongly anisotropic g-factor as well as a large and tuneable spin-orbit coupling [7, 8]. The latter enables manipulation of spin states in the quantum dots by means of electrical instead of magnetic fields, a major technological advantage.

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Hybrid spin and valley quantum computing with singlet-triplet qubits

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The existence of non-equivalent energy minima, so-called valleys, in the electronic band structure of silicon, graphene, or other materials is often assumed to be a problem for quantum computing with electron spins in quantum dots as proposed by Loss and DiVincenzo [1] because the exchange interaction is different in the presence of an additional degree of freedom. We show that combining spin and valley states in the subspace spanned by the singlet S and the triplet T_0 directly provides a scheme for universal quantum computing [2]. When both, spin and valley S-T_0 qubits are stored in the same double quantum dot a universal two qubit gate can be performed by applying the exchange interaction [3]. Single-qubit operations of the spin S-T_0 qubit can be achieved in a non-valley-degenerate double dot by the exchange interaction and a gradient in the Zeeman splitting [4]. For valley S-T_0 qubits this can work in the same way when the spins are polarized. For the necessary switching between the single-qubit and two-qubit operation mode, we consider the valley-dependent hopping between a spin-only and a spin-and-valley quantum dot while the largest term in the Hamiltonian is the valley splitting. Our calculations reveal that for different values of the hopping parameter and the detuning, fidelities for the spin-only SWAP operation close to one can be achieved.

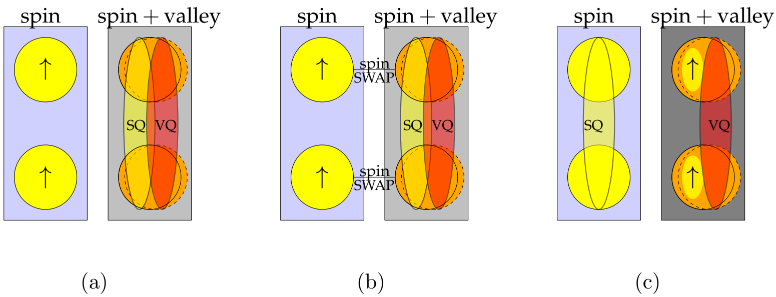

Figure 1: Building block of the proposed quantum register, composed of quantum dots with spin degree of freedom only (single circles) and those with spin and valley degree of freedom (double circles). (a) A universal two-qubit gate can be applied by exchange interaction when spin and valley qubits are stored in the same double quantum dot. (b) The spin-only SWAP operation interchanges the spin qubit with the polarized spins in the spin-only quantum dots. (c) After this separation, single-qubit operations can be performed by exchange interaction and a gradient in the Zeeman splitting of spin and valley.

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Universal Quantum Computing with spin and valley in singlet-triplet qubits

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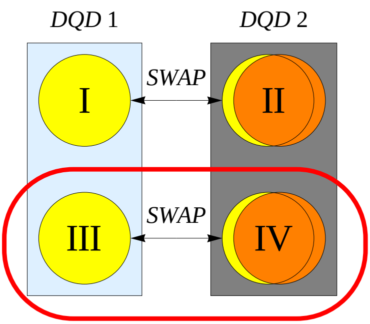
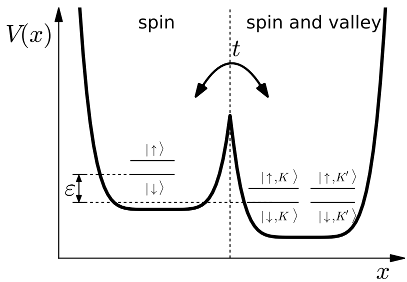
Spin-based quantum computing [1] in graphene [2], silicon and other materials with an additional degree of freedom called "valley" in double quantum dots (DQD) is often considered difficult because the exchange interaction is disturbed by the valley degeneracy. In this work we present a possibility for universal quantum computing in such systems. We use two different kinds of DQDs as the building block for a quantum register, where DQD 1 only has spin degeneracy and DQD 2 has spin and valley, as shown in Fig. 1a. As logical qubits we use the singlet and triplet states of spin (yellow) and valley (orange) in DQD 2. The two-qubit gates are directly given by exchange interaction between QD "II" and "IV" [3]. The single qubit gates are realized by swapping the spin qubit in DQD 2 with polarized spin states in DQD 1, hence separating the two qubits. The seperated qubits can then be controlled by a gradient in Zeeman-splitting and exchange interaction. Therefore we need two spin-only SWAP-gates between "I" and "II" and between "III" and "IV". Exchange interaction – described by a Hamiltonian as illustrated in Fig. 1b – and controllable valley splitting provides the spin-only SWAP-gate in the singlet-triplet subspace, enabling universal quantum processing [4,5]. Crafting many building blocks to a register allows for universal quantum computing.



(a) Building block of quantum register proposed in this work. The yellow circles represent the spin qubits whereas the orange circles indicate the valley qubits.



(b) Graphical model of the used Hamiltonian with the spin states $|\uparrow\rangle, |\downarrow\rangle$ and the valley states $|K\rangle, |K'\rangle$. Only the two QDs marked in red in Fig. 1a are considered [5].

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Adiabatic Tracking of Quantum Many-Body Dynamics in Spin Chains

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(Dated: April 10, 2014)

We propose working recipes for engineering transitionless quantum driving of many-body systems under realistic experimental conditions. We extend thereby the applicability realm of the recently proposed method of Opatrný and Mølmer for partial suppression of nonadiabatic transitions in few-body systems [New J. Phys. **16**, 015025 (2014)] toward large many-particle ones subject to both computational and experimental restrictions. Our numerical method is capable of circumventing practical challenges for realizing shortcuts to many-body adiabaticity, i.e., the difficulty in finding the optimal counterdiabatic operators and the exponential growth of the size of the many-body Hilbert space. The results promise feasible experimental protocols for an efficient control of the real-time dynamics of a wide variety of driven many-body systems including paradigmatic spin chain models. In particular, they suggest the possibility of efficient emulation of the supplementary Berry Hamiltonian with only a *quadratic* (or effectively even *linear*) scaling of the experimental resources with the number of particles. Our scheme at the same time yields numerical machinery for identifying critical points of a driven many-body system upon undergoing a quantum phase transition.

Magnetic Field induced Oscillations of Photon Echoes in Semiconductor Nanostructures

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The interaction with a short laser pulse resonantly excites negatively charged excitons (trions) from an ensemble of localized electrons in a n-type CdTe/(Cd,Mg)Te semiconductor quantum well (QW). The resulting polarization undergoes a fast dephasing due to inhomogeneous broadening in the sample. However, it can be reversed using echo-techniques as long as the optical coherence is preserved.

The ground (electron) and the excited (trion) states are the doublets characterized by the electron ($S = \pm 1/2$) and hole ($J = \pm 3/2$) spin projections, respectively. In our experiment the first circularly polarized pulse at $t = 0$ induces a coherent superposition of the optically accessible electron and trion states $S = +1/2$ and $J = +3/2$ according to the selection rules. A second pulse at $t = \tau_{12}$ conjugates the phase for each dipole so that rephasing produces a photon echo (PE) at $t = 2\tau_{12}$. As shown in Figure 1(a), the application of a transverse magnetic field induces oscillations into the echo-amplitude due to coherence transfer provided by Larmor precession of the electron spin in the ground state [1].

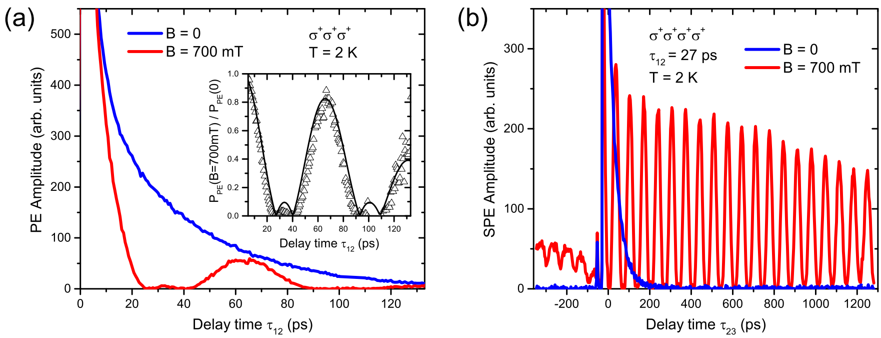

Figure 1: (a) Magnetic field induced oscillation of the photon echo amplitude as a function of the time delay τ_{12}. (b) Appearance of the stimulated photon echo from the QW at time delay $\tau_{23} > 1$ ns at application of transverse magnetic field 700 mT for $\tau_{12} = 27$ ps.

Figure 1(b) shows the results for three-pulse stimulated photon echoes (SPE) where the measurements were performed as a function of the time delay τ_{23} between the second and third pulse. Larmor precession of the electron spin in a transverse magnetic field causes oscillations and a gain of the SPE amplitude for $\tau_{23} > 1$ ns.

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Long-range transfer of spin qubits

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Quantum mechanics allows for superpositions of indirectly coupled states even if the intermediate states are far in energy. This is done via higher-order transitions in which the energetically forbidden intermediate states are only virtually occupied. These transitions have been recently detected in the form of long-range charge transport through quantum dot chains[1,2,3]. We present the first evidence of long-range transfer of a spin qubit in a triple quantum dot [3]. This process is detected via a very narrow resonance in the current through the system at the degeneracy point of three-electron charge configurations (2,0,1) and (1,0,2). There, an electron is delocalized between the two dots without ever occupying the center dot. The mechanism takes advantage of Pauli's exclusion principle which prevents two electrons with the same spin from occupying the same orbital: Of the two electrons forming a spin singlet in one (say the leftmost) dot, only the one with a spin opposite to that of the electron in the other edge dot will be allowed to tunnel. The emptiness of the centre dot warranties the conservation of the spin of the tunneling electron. An important aspect of our results is that the electron which is left alone in the left dot has the same spin state of the electron initially alone on the right. Thus, the long-range electron tunneling between edges enables the long-range transfer of an arbitrary spin state $|\Psi\rangle$ (the qubit) in the opposite direction: $|\uparrow\downarrow\rangle_{\rm L}\otimes|0\rangle_{\rm C}\otimes|\psi\rangle_{\rm R} \rightarrow |\psi\rangle_{\rm L}\otimes|0\rangle_{\rm C}\otimes|\uparrow\downarrow\rangle_{\rm R}$, as sketched in figure 1. Our work opens the way to low decoherence transport of qubits essential for quantum information architectures.

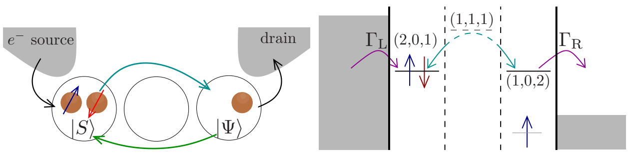

Figure 1: Schematic description of the long range spin transfer in a triple quantum dot. A singlet in one of the dots allows for the long-range transfer of an arbitrary spin in the opposite dot.

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Electrical control of a long-lived spin qubit in a Si/SiGe quantum dot

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Nanofabricated quantum bits permit large-scale integration but usually suffer from short coherence times due to interactions with their solid-state environment.The outstanding challenge is to engineer the environment so that it minimally affects the qubit,but still allows qubit control and scalability. Here we demonstrate a long-lived single-electron spin qubit in a Si/SiGe quantum dot with all-electrical two-axis control. The spin is driven by resonant microwave electric fields in a transverse magnetic field gradient from a local micromagnet, and the spin state is read out in single-shot mode. Electron spin resonance occurs at two closely spaced frequencies, which we attribute to two valley states. Thanks to the weak hyperfine coupling in silicon, Ramsey and Hahn echo decay timescales of 1us and 40us, respectively, are observed. This is almost two orders of magnitude longer than the intrinsic timescales in III-V quantum dots, while gate operation times are comparable to those achieved in GaAs. This places the single-qubit rotations in the fault-tolerant regime and strongly raises the prospects of quantum information processing based on quantum dots [1].

[1]arXiv:1404.5402

Precise ultra fast single qubit control using optimal control pulses

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Ultra fast (compared to the Larmor frequency) and accurate quantum operations are required in many modern scientific areas - like quantum information, quantum metrology and magnetometry. These operations are often realized as rectangular radio frequency pulses. However the accuracy of the population transfer is limited if the Rabi frequency is comparable with the transition frequency due to the breakdown of the rotating wave approximation (RWA). In this strong driving regime the Rabi frequency would be high, but the oscillations become anharmonic [2] and a full population transfer can not be achieved. Here the experimental implementation of optimal control pulses is shown, which do not suffer these limitations. As a test system the electron spin associated with a single nitrogen-vacancy center in diamond [3,4,5] is used and the pulses were optimized via the Chopped Random Basis (CRAB) algorithm [6,7]. We realized the most commonly used quantum operations - the $\pi/2$-pulse and the π-pulse with fidelities of $F^{exp}_{\pi/2} = 0.95 \pm 0.01$ and $F^{exp}_{\pi} = 0.99 \pm 0.016$ respectively, in an excellent agreement with the theoretical predictions. In figure 1 the arbitrary trajectory of the spin magnetization of the π-pulse on the Bloch sphere is illustrated. Moreover, we demonstrate magnetic resonance experiments both in the rotating and lab frames and that we can "switch" between these two. Since our technique is general, it could find a wide application in quantum computing, quantum optics and broadband magnetometry.

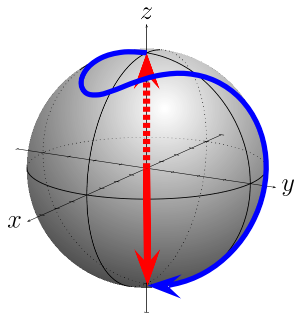

Figure 1: Trajectory of the spin magnetization during the optimal π-pulse on the Bloch sphere.

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Parafermions in Condensed Matter Physics

Constantin Schrade

University of Basel

We use numerical and analytical techniques to understand the mechanisms that drive a system into a state that harbours exotic parafermionic zero modes. Due to their non-abelian statistics the Parafermions may play an important role as building blocks for a fault-tolerant quantum computer.

Detection of spin entanglement via spin-charge separation in crossed Tomonaga-Luttinger liquids

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[2] *Scottish Universities Physics Alliance, University of St Andrews, UK*
[3] *Departamento de Física Teórica de la Materia Condensada, Condensed Matter Physics Center (IFIMAC), and Instituto Nicolás Cabrera, UAM, Spain*
[4] *Interactive Research Center of Science, Tokyo Institute of Technology, Japan*

We investigate tunneling between two spinful Tomonaga-Luttinger liquids (TLL) realized, e.g., as two crossed nanowires or quantum Hall edge states [1]. When injecting into each TLL one electron of an opposite spin pair, the dc-current measured after the crossing differs for singlet, triplet or product states (Fig. 1). This is a striking new non-Fermi liquid feature because the (mean) current in a non-interacting beam splitter is insensitive to spin-entanglement [2-4]. It can be understood in terms of collective excitations subject to spin-charge separation. This behavior may offer an easier alternative to traditional entanglement detection schemes based on current noise, which we show to be suppressed by the interactions.

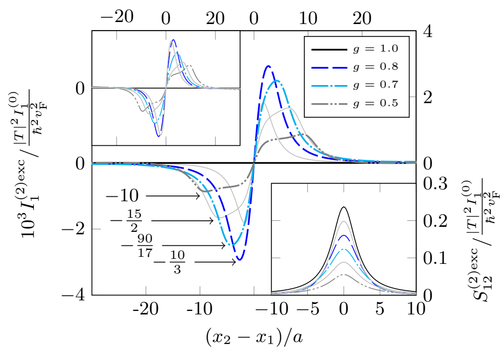

Fig. 1: **Entanglement induced contributions to the tunnel current** in conductor 1 and to the zero-frequency current cross-correlations between conductor 1 and conductor 2 (right inset) for different interaction strengths (Luttinger parameters) g and injection points $x_{1,2}$ away from the tunnel junction of the beam splitter. The contribution to the tunnel current is non-zero if $x_1 \neq x_2$ because spin-charge separation induces an asymmetry between the two possible directions of tunneling. The arrow tips indicate the positions of the maxima, which can be estimated analytically. The entanglement part of the current noise is finite only if the spins meet at the junction. For further details see Ref. [1].

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Steady-State Entanglement in the Nuclear Spin Dynamics of a Double Quantum Dot

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We propose a scheme for the deterministic generation of steady-state entanglement between the two nuclear spin ensembles in an electrically defined double quantum dot. Due to quantum interference in the collective coupling to the electronic degrees of freedom, the nuclear system is actively driven into a two-mode squeezed-like target state. The entanglement build-up is accompanied by a self-polarization of the nuclear spins towards large Overhauser field gradients. Moreover, the feedback between the electronic and nuclear dynamics leads to multi-stability and criticality in the steady-state solutions. We investigate this effect using analytical and numerical techniques, and demonstrate its robustness under various types of imperfections.

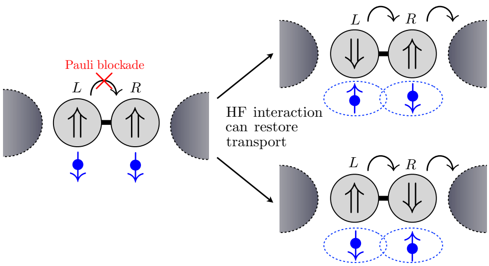

Figure 1: Schematic illustration of nuclear entanglement generation via electron transport. Whenever the Pauli-blockade is lifted via the HF interaction with the nuclear spins (blue), a nuclear flip can occur either in the left or the right quantum dot and no which-way information is leaked. This can lead to dissipative entanglement generation between the two nuclear spin ensembles.

[1] M. J. A. Schuetz, E. M. Kessler, L. M. K. Vandersypen, J. I. Cirac, G. Giedke, Phys. Rev. Lett. **111**, 246802 (2013).
[2] M. J. A. Schuetz, E. M. Kessler, L. M. K. Vandersypen, J. I. Cirac, G. Giedke, arXiv:1403.6145 (unpublished).

Single hole transport in SiGe self-assembled nanocrystals

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P-type SiGe nanostructures have been recently proposed as promising candidates for the realization of fast spin qubits [1], due to (i) the long spin coherence times expected for group IV semiconductors with low hyperfine interaction and (ii) the strong valence-band spin-orbit coupling. A few experimental works have recently addressed the potential of SiGe nanostructures as spins qubits hosting systems [2-3].

In our group we study self-assembled nanostructures made by direct growth of Ge on Si substrates by molecular-beam epitaxy, via the Stranski-Krastanow (SK) growth mode. This method results in self-assembled crystalline islands of various size and geometry, as shown in Fig. 1. Due to the dissimilar size, strain and chemical composition, each island gives rise to a different confinement potential.

Recent magneto-transport experiments on single dome islands have revealed an interesting combination of properties. In particular, highly anisotropic and tunable g-factors have been measured as well as a strong and tunable spin-orbit coupling [4-7].
Our aim is now to move towards the realization of double dot devices and charge detectors which will open the way to measure the spin relaxation and coherences times of holes in SiGe nanostructures. Here we will present our fabrication strategies, developments and recent progress in the fabrication of single and double SK quantum dots, and report first quantum transport measurements.

Figure 1: High resolution ultra-high vacuum scanning tunneling microscope (STM) images showing a) a hut cluster (50x32x3nm^3), b) a pyramid (50x50x7nm^3) and c) a dome island (50x50x10nm^3), formed after the deposition of Ge onto a Si(001) surface [8]. The size of the islands can be adjusted by the growth parameters.

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Sensing and atomic-scale structure analysis of single nuclear spin clusters in diamond

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Single-molecule nuclear magnetic resonance is a great challenge in the field of magnetic resonance spectroscopy and has important applications in chemical analysis and in quantum computing. Recently, it has become possible to tackle this challenge.Through decoherence measurement of nitrogen-vacancy centers under dynamical decoupling control, the sensing of single $^{13}\mathbf{C}$ at nanometer distance has been realized. A step towards the ultimate goal of structure analysis of single molecules would be direct measurement of the interactions within single nuclear spin clusters. Here we sense a single $^{13}\mathbf{C}$-$^{13}\mathbf{C}$ nuclear spin dimer located about 1 nm from the NV center and characterize the interaction ($\sim$ 690Hz) between the two nuclear spins. This was achieved by measuring NV center spin decoherence under various orders of dynamical decoupling control at room temperature. From the measured interaction we derived the spatial configuration of the dimer with atomic-scale resolution. These results indicate that central spin decoherence under dynamical decoupling control may be useful for NMR structure analysis of single molecules, in combination with advanced material surface engineering.

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Dispersive discrimination of electron spin states in Coulomb-confined silicon double quantum dots

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We use radio frequency reflectometry to investigate a double quantum dot device patterned by the placement of phosphorus donors in silicon with scanning tunnelling microscope lithography. The measurement is sensitive to the tunnelling of electrons between the quantum dots and the leads, as well as directly between the two quantum dots. The inter-dot tunnelling is spin dependent, as the tunnelling of spin triplets is forbidden by the Pauli exclusion principle. The change of the rf signal in response to both electric and magnetic fields can be used to extract the tunnel coupling energy (93 ueV) and the dependence of the exchange energy on the electric field between the dots. Electron singlet-triplet readout and control of the exchange energy in a donor-based system represent the first experimental steps toward implementing the Kane model of quantum computation.

Singlet-triplet qubit entanglement in the double charge resonant regime

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Spin qubits encoded in two-electron singlet and triplet states of a double quantum dot are rapidly controllable via electric fields [1–4], as has been demonstrated in the context of both single-qubit manipulation [5] and two-qubit entanglement [6, 7]. However, achieving robust gating in the presence of decoherence due to charge noise remains a major challenge [8]. We investigate an approach for entangling two singlet-triplet qubits in adjacent double dots via capacitive coupling [Fig. 1(a)], focusing specifically on the case where large energy detunings between the (1,1) and (0,2) charge configurations exist simultaneously for both dots. The interplay of these large detunings and the inter-qubit Coulomb interaction energy gives rise to the "double charge resonant" regime, in which the $|1111\rangle$ and $|0202\rangle$ configurations are exactly or nearly degenerate [Fig. 1(b)]. In this regime, charge relaxation due to electron-phonon interaction is suppressed by the absence of a dipole matrix element coupling the $|1111\rangle$ and $|0202\rangle$ states. Furthermore, a controlled-phase gate may be realized by combining time evolution in the presence of single-qubit exchange and two-qubit Coulomb interaction with single-qubit π pulses that swap (1,1) singlet and triplet states using, e.g., magnetic gradients. We analyze the fidelity of this entangling gate in the presence of charge fluctuations in the single-qubit detunings and identify parameter regimes that optimize the fidelity.

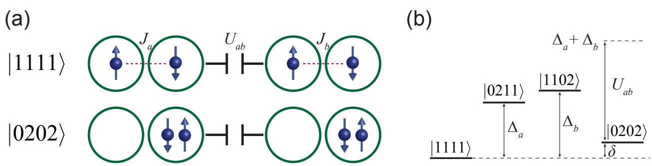

FIG. 1: (a) Illustration of capacitively coupled double quantum dots in the charge states $|1111\rangle$ and $|0202\rangle$. (b) Schematic energy level diagram for the charge states involved in our calculation.

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Ground state cooling of a carbon nano-mechanical resonator using spin-polarized current

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We study the non-equilibrium regime of a mechanical resonator at low temperature realized with a suspended carbon nanotube quantum dot contacted to two ferromagnets [1]. Due to spin-orbit interaction [2,3] and/or an external magnetic gradient [4], the spin on the dot couples directly to the flexural eigenmodes. Accordingly, the nanomechanical motion induces inelastic spin-flips of the tunneling electrons and modifies the I-V characteristics. The feed-back action of the spin-polarized current on the state of the oscillator causes either heating or active cooling of the mechanical modes. Maximal cooling is achieved at resonant transport when the energy splitting between two dot levels of opposite spin equals the resonator frequency. Even for weak electron-resonator coupling and moderate polarizations we can achieve ground state cooling.

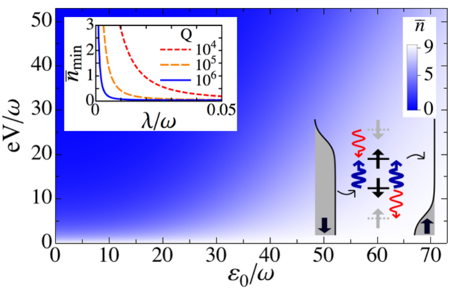

Figure 1: Phonon occupation as function of the bias voltage V and gate voltage ε_0. We consider the resonant regime when the energy splitting of the energy levels on the dot equals the frequency ω of the oscillator. The temperature of the oscillator is set to $k_B T = 10\omega$ corresponding to the white color, the quality factor is $Q = 10^5$ and the spin-vibration coupling constant is $\lambda/\omega = 0.01$. Inset left: the minimum occupation $\bar{n}_{\min}$ at $\varepsilon_0 = 0$ as a function of the spin-vibration coupling constant λ for different quality factors. Inset right: schematic behavior of the energy levels and of the inelastic resonant spin-flip tunneling.

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Accelerated 2D nuclear spin spectroscopy using matrix completion

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In experiments measurement time is always a valuable resource and each improvement which reduces it is important. Here we present a novel application for correlation spectroscopy (COSY) measurements[1] based on the matrix completion method which significantly shortens the time for obtaining a 2D spectrum. As a test system for the demonstration we use a single nitrogen-vacancy (NV) center in diamond[2].

To verify the used algorithm we perform at first a 2D COSY measurement yielding a full rank matrix. The NV's electron spin is coupled to the neighboring nuclei with different coupling strengths which are resolved in the Fourier transform of the measured matrix. By taking randomly only few tens of percent of the matrix entry of the collected data we reconstruct a low-rank approximation matrix by means of matrix completion. The completion method itself is a singular value thresholding algorithm (SVT) which is based on singular value decomposition (SVD)[3]. Finally the reconstructed and the actual matrix are compared in real and Fourier space to confirm the quality of the matrix completion method.

We can show that only about ten percent of the matrix is needed to gain nearly the same information in Fourier space. As a consequence the measurement time is reduces by a factor of 10.

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Accumulation of spin anisotropy in a nanoparticle in the mesoscopic Stoner regime

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Spin anisotropy has lately turned out to be a quantity similar to charge and spin-dipole moment, i.e., it can be transported and stored [1-5]. For a thermally biased spin-valve, a pure spin-anisotropy current without spin and charge current has been predicted [4]. Here, we discuss theoretically the possibility to concentrate a large spin-anisotropy together with a strongly suppressed spin-dipole moment and without charge accumulation. Our system is a nanoparticle weakly tunnel coupled to two ferromagnetic leads [6]. The accumulation of spin-quadrupole moment in our isotropic system indicates the nonequilibrium generation of a spin anisotropy. We demonstrate that a positive spin-quadrupole moment indicating easy-axis anisotropy can be generated by abruptly switching off the bias voltage for parallel magnetizations of the leads. A negative quadrupole moment indicating easy-plane anisotropy can be generated by applying an oscillating bias voltage for both parallel and antiparallel magnetizations.

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Circuit QED with Semiconductor Single-Electron Charge Qubits

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We present a hybrid quantum system in which a double quantum dot (DQD) acting as a two level system interacts with a single photonic mode of a microwave cavity. The gate defined semiconductor double quantum dot, which can be operated in the single electron regime, is capacitively coupled to a superconducting coplanar waveguide resonator. Employing the quantum dot system as a charge qubit coupling strengths of about 50 MHz were achieved [1-3]. A model describing the interaction with a Jaynes-Cummings Hamiltonian permits the extraction of the qubit decoherence rates and the tunnel coupling between the two quantum dots [4]. Because the dephasing rates of the qubits significantly exceed the coupling strength in all cited work [5], strong coupling to the resonator has not been realized, yet.

We investigated the origin of the large dephasing rates by evaluating the charge noise acting on the quantum dot using the microwave resonator. The result is consistent with previous results obtained with quantum point contact charge detectors on similar heterostructures and suggests that charge noise is the main source of dephasing in our system [6].

We also present our current efforts to study the photon emission of the DQD into the resonator. We investigate the power spectral density and second order correlations of emitted microwave photons.

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Current hot spot in the spin-valley blockade in carbon nanotubes

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Carbon nanotube double quantum dots are promising candidates for a solid-state platform of quantum-information processing. In the ground state of the nanotube the physical qubit is a Kramers doublet, which involves two states with antiparallel alignment of spin and valley.

We present a theoretical study of the spin-valley blockade transport effect in a double quantum dot defined in a bent carbon nanotube. We find that intervalley scattering due to short-range impurities completely lifts the spin-valley blockade and induces a large leakage current in a certain confined range of the external magnetic field vector. This current hot spot emerges due to different effective magnetic fields acting on the spin-valley qubit states of the two quantum dots.

We discuss the implications for blockade-based schemes for qubit initialization/readout, and motion sensing of nanotube-based mechanical resonators.

Long-distance entanglement of mobile electron soliton spin qubits in gated semiconductor nanodevices

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The ability to couple and entangle distant spin qubits within the quantum register seems to be essential ingredient for realization of scalable quantum computer architecture. Here we propose and simulate nanodevice which allows for coupling spatially separated electron spin qubits and consequently for generating spin entangled states of distant electrons.

Proposed device is based on gated semiconductor nanowire in which two electrons are confined. According to the theoretical investigations [1,2] in such a systems the charge density associated with the presence of an electrons in the quantum wire induces a response potential of the electron gas in the metallic gates which in turns lead to lateral confinement of the charged particle wave function - so called self focusing mechanism [1]. As a result electrons can be self trapped under the metal in form of a stable Gaussian wave packets which have the soliton like properties [1]. Such electron solitons can be transported between different part of the nanodevice by application low static voltages to the top metal electrodes [2].

The proposed nanodevice act as follows. Initially each of the electrons is confined in spatially separated quantum dot (defined under certain metal electrodes which covers nanowire) and electrons are prepared with opposite spins. Then the electron solitons are transported to the quantum dot in which both the electrons are trapped. Confined electron solitons periodically collide with each other. Due to the exchange interaction electrons swap some fraction of their spins during each collision and consequently $\sqrt{\mathrm{SWAP}}$ gate is realized which is essentials for entangling spin qubits. After the maximally entangled spin state is obtained (which we confirm by calculating Wootters concurrence), electron solitons are transported to the initial spatially separated positions.

We show how proposed long distant entanglement scheme can be integrated with recently proposed nanodevices acting as a ultrafast (sub nanoseconds) single quantum logic gates on an electron [3] and a hole spin qubits [4,5]. Furthermore we present a proposal of scalable multi qubit architecture - 2D lattice of spin qubits [5] on which single quantum logic gates can be applied in selective manner and where long distant spin qubits can be coupled.

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Dynamic Nuclear Polarization Feedback scheme using hyperfine-mediated Electron Dipole Spin Resonance

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In many electron spin qubit systems coherent control is impaired by the fluctuating nuclear spin bath of the host material. Here we present a feedback mechanism using electron dipole spin resonance (EDSR) to stabilize the nuclear magnetic field for a two-electron spin qubit in a GaAs double quantum dot. Former experiments have shown dynamic nuclear polarization with feedback to significantly prolong T_2^* [2, 3]. The effectiveness was limited by the pump rate of the pumping mechanism used, but a quantitative analysis has not been performed. We present a model relating the achievable amount of narrowing to the pump and diffusion rates and find good agreement with the data. Solving the spin diffusion equation results in a noise correlator of $\langle \Delta B^2 \rangle = \frac{S_\eta}{2\gamma_{pump}}$, where S_η is the noise spectrum of Langevin forces driving diffusion (figure 1b) and γ_{pump} the pump rate, both of which are experimentally accessible. To overcome the limitation of the scheme used previously, we propose a different polarization scheme based on the work of Laird [1], who measured a high spin-flip rate of up to $10^6 s^{-1}$ for transitions driven by hyperfine-mediated EDSR. Sequentially applying two oscillating electric fields with slightly different frequencies close to the resonance results in a pumping curve with a stable fixed point, shown in figure 1a. Our model predicts that T_2^* values on the microsecond scale can be achieved.

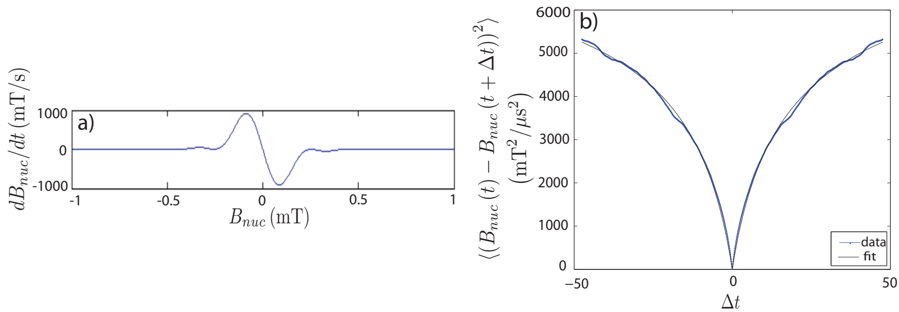

Figure 1: (a) Simulated pump curve of the nuclear magnetic field arising from applying two oscillating electric fields with a frequency difference of 6.4 MHz. The maximum pump rate is more than an order of magnitude larger than that measured in Ref. [2]. (b) Measured noise correlator of Overhauser field fluctuations. It's slope near $\Delta t = 0$ can be used to predict the amount of narrowing.

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Electron-hole entanglement in a quantum spin-hall insulator

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Entanglement is the most exclusive property of the quantum theory of many-body systems, which is manifested through nonlocal correlations that cannot be explained by any local hidden-variable theory. This unique feature of quantum mechanics allows for various new applications, such as quantum computation, quantum teleportation, and quantum cryptography. There are a number of schemes proposed for creating entangled states in solid-state systems, the vast majority focusing on entangling the spin degrees of freedom, as they are usually more robust against decoherence than their orbital counterparts. Remarkably, the set-up in Ref. [1] stands alone in that it proves that entangled electron-hole pairs can be produced via tunneling in the absence of any interactions between the consituents. While this setup was employing the quantum Hall edge states as electron beams, we show that a quantum spin Hall insulator bar instead can supersede the quantum Hall system to both efficiently produce and detect entangled electron-hole pairs in the absence of any interactions and, importantly, without fine tuning of the tunneling characteristics [2]. This may provide a viable route to producing spin entanglement in the absence of any correlations and pairing, where spin-to-charge conversion is enabled by the helical edge structure of a quantum spin Hall insulator.

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Long-Distance Entanglement of Spin Qubits via Ferromagnet

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We propose a mechanism of coherent coupling between distant spin qubits interacting dipolarly with a ferromagnet. We derive an effective two-spin interaction Hamiltonian and find a regime where the dynamics is coherent. Finally, we present a sequence for the implementation of the entangling controlled-NOT gate and estimate the corresponding operation time to be a few tens of nanoseconds. A particularly promising application of our proposal is to atomistic spin qubits such as silicon-based qubits and nitrogen-vacancy centers in diamond to which existing coupling schemes do not apply.

Anomalous sequence of quantum Hall states revealing tunable Lifshitz transition in bilayer graphene

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Bilayer graphene (BLG) is one of the most tunable materials: not only the Fermi energy can easily be changed with an electric field, but one can also tune the band structure from un-gapped to gapped via the application of a displacement field D (Fig. 1a) [1-3].

In high quality BLG, the approximation of a parabolic dispersion relation is not sufficient to describe the system in the low energy limit: the skew interlayer hopping γ_3 plays an important role and gives rise to trigonal warping with the presence of 4 massless Dirac cones [1]. Exposing high quality devices to high displacement fields leads to observable consequences of the situation displayed in Fig. 1b: as a function of energy, the constant energy contour gets broken, from a singly-connected Fermi contour to three separated Fermi lakes (see insets). This change in the topology of the Fermi contour is called a Lifshitz transition.

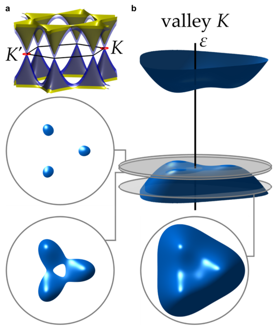

Figure 1: a) Band structure of BLG. b) Low energy dispersion of a gapped trigonally warped BLG.

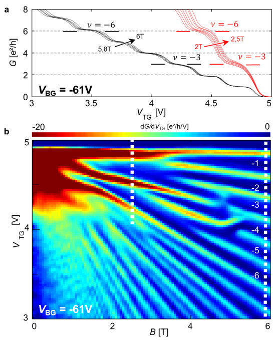

Figure 2: a) Sequence of plateaus observed at low (red) and high fields (black). b) Measured LL spectrum: around $5T$, a crossing of LLs is seen.

Using the quantum Hall effect as a probe in a dual-gated BLG device under the influence of a high displacement field allows us to observe a very rich Landau level (LL) spectrum (Fig. 2a-b) with three distinct regimes. At high magnetic field (Fig. 2a, black conductance cuts), all the degeneracies are lifted, while at low fields (Fig. 2a, red conductance cuts), only filling factors -3 and -6 remain. In-between, the LL spectrum exhibits a crossing. Analysing these different features and comparing them to the calculated LL spectrum, we were able to relate these three regimes with the three contours displayed in Fig. 1b (insets), thereby revealing the presence of a Lifshitz transition in this gapped BLG system.

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Quantum error correction in a solid-state hybrid spin register

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Error correction is important in classical and quantum computation. Decoherence caused by the inevitable interaction of quantum bits with their environment leads to dephasing or even relaxation. Correction of the concomitant errors is therefore a fundamental requirement for scalable quantum computation[1-7]. Although algorithms for error correction have been known for some time, experimental realizations are scarce[2-7]. Here we show quantum error correction in a heterogeneous, solid-state spin system.We demonstrate that joint initialization, projective readout and fast local and non-local gate operations can all be achieved in diamond spin systems, even under ambient conditions. High-fidelity initialization of a whole spin register (99 per cent) and single-shot readout of multiple individual nuclear spins are achieved by using the ancillary electron spin of a nitrogenvacancy defect. Implementation of a novel non-local gate generic to our electron-nuclear quantum register allows the preparation of entangled states of three nuclear spins, with fidelities exceeding 85 per cent. With these techniques, we demonstrate three-qubit phase-flip error correction. Using optimal control, all of the above operations achieve fidelities approaching those needed for fault-tolerant quantum operation, thus paving the way to large-scale quantum computation. Besides their use with diamond spin systems, our techniques can be used to improve scaling of quantum networks relying on phosphorus in silicon, quantum dots , silicon carbide or rare-earth ions in solids

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Electrical spin protection and manipulation via gate-locked spin-orbit fields

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The spin-orbit (SO) interaction in semiconductors facilitates coherent spin manipulation but inherently also causes spin relaxation. A unique situation arises when the Rashba and Dresselhaus SO fields are matched, protecting spins from relaxation [1,2]. Quantum computation and spintronic devices could benefit if such spin protection could be expanded from a single point into a broad range accessible with in-situ gate-control, making possible tunable SO rotations under protection from relaxation. Here, we demonstrate broad, independent control of all relevant SO fields in GaAs quantum wells, allowing us to tune the Rashba and Dresselhaus fields while keeping both locked to each other using gate voltages [3]. Thus, we can electrically control and simultaneously protect the spin. Our experiments employ quantum interference corrections to electrical conductivity as a sensitive probe of SO coupling. We combine transport data with numerical SO simulations to precisely quantify all SO terms [4].

At zero magnetic field, a closed-form expression for the quantum corrections to the Drude conductivity can be derived including all SO terms. Ongoing experiments aim at extracting the SO terms directly from transport measurements using this expression, and compare values with the simulated quantities.

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Influence of Nuclear Quadrupole Moments on Electron Spin Coherence in Semiconductor Quantum Dots

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We theoretically investigate the influence of the fluctuating Overhauser field on the spin of an electron confined to a quantum dot (QD)[1]. The fluctuations arise from nuclear angular momentum being exchanged between different nuclei via the magnetic dipole coupling[2–5]. We focus on the role of the nuclear electric quadrupole moments (QPMs)[6,7] which generally cause a reduction in internuclear spin transfer efficiency in the presence of electric field gradients (EFGs). The effects on the electron spin coherence time are studied by modeling an electron spin echo experiment. We find that the QPMs cause an increase in the electron spin coherence time and that an inhomogeneous distribution of the quadrupolar shift, where different nuclei have different shifts in energy, causes an even larger increase in the electron coherence time than a homogeneous distribution. Our findings are in agreement with recent experimental investigations of the nuclear spin dynamics[8]. Furthermore, adding nuclear spin polarization amplifies the effect of the inhomogeneous quadrupolar shifts and leads to a significant increase in electron coherence, even for partial polarization. The combination of partial nuclear spin polarization and inhomogeneous quadrupolar shifts provides an alternative to the experimentally challenging suggestion of full nuclear spin polarization as a method of prolonging electron coherence.

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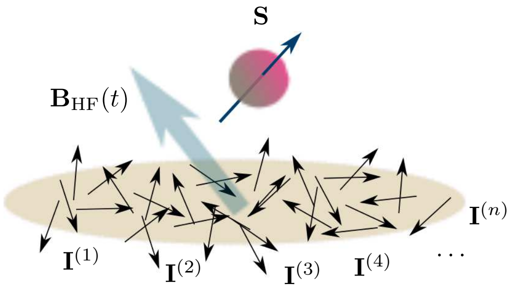

Figure 1: Illustration of the QD containing many nuclear spins (black arrows) each with corresponding operator $\mathbf{I}^{(n)}$. The nuclear spins couple to an electron spin (red ball with arrow) via the hyperfine hamiltonian and give rise of an effective magnetic field (large blue arrow). Because of the transfer of nuclear spin between different nuclei and the inhomogenous hyperfine coupling strength, the effective magnetic field is fluctuating in time and given by the stochastic vector $\mathbf{B}_{\mathrm{HF}}(t)$

Demonstration of a hybrid rare-earth ion superconducting system for quantum information processing

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Motivated by potential applications in quantum information processing (QIP), we have investigated a prototype hybrid Rare Earth (R.E) spin-superconducting resonator system. Crystals doped with R.E ions are particularly suitable for QIP applications, providing accessible spin transitions compatible with the microwave regime alongside straightforward integration with lithographically defined circuitry. Further advantages of R.E ions include narrow line-widths and exceptionally long spin coherence times [1]. Fast quantum manipulation can be achieved using methods from circuit-quantum electrodynamics (circuit-QED) - implemented using well-established superconducting micro-resonators.

We have developed a fabrication technique for local doping using ion implantation of RE's in well-defined micron-sized areas on sapphire substrates; on top of which are then patterned superconducting fractal resonators [2] made from niobium-nitride. The ion-implantation technique does not significantly degrade the quality factors of the resonators. Using an ultra-sensitive frequency feedback measurement technique called Pound locking [3], we demonstrate the coupling of the R.E ensemble to a micro-resonator, obtaining results in good agreement with modelling using the EasySpin [4] software package.

We emphasise the control of dosage and location provided by the ion-implantation technique. These variables determine the number of spins (N) in the ensemble - which increases the single-spin coupling rate by $\sqrt{N}$, allows placement of the ensemble in a region of maximal coupling, and provides manipulation of obtainable linewidths. By tuning these variables we demonstrate through modelling the potential of such a device to operate in the strong coupling regime. We further evaluate the feasibility of coupling several RE ensembles to the same resonator for future QIP applications and increased functionality.

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All-optical control of a defect spin qubit utilizing coherent dark states

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Atomic-like defects in crystals have shown great promise as spin qubits for solid-state quantum information applications. In particular, the nitrogen-vacancy (NV) center in diamond has garnered interest over the past decade due to the optical addressability and excellent coherence properties of its spin state. Typically, the NV center's spin state is initialized and readout through a spin-dependent intersystem crossing, while coherent rotations of the spin state are generated through microwave electron spin resonance techniques. Here, we discuss an alternative and more generalizable method to control the spin state of the defect by driving a lambda (Λ) system within its electronic level structure ($T<20$ K). Through time-resolved and tomographic techniques, we study optically driven processes in this system in order to develop the following arbitrary-basis protocols to all-optically control the spin state of the NV center: initialization, unitary rotation, and readout.[1]

When the transitions within a Λ system are excited resonantly, the spin becomes trapped into a dark state, a spin superposition resulting from destructive interference of the light fields. Through this dissipative process, known as coherent population trapping, we initialize the spin into any selectable dark state by adjusting the relative phase and amplitude of the driving fields. Similarly, the spin state can be read out in this chosen basis, as the transient photoluminescence emitted during the process is proportional to the projection of the spin along the selected dark state. By detuning our driving light fields, we generate unitary rotations of the spin state about any pre-selected dark state axis through stimulated Raman transitions. Combining these three protocols, we demonstrate the ability to measure NV center spin coherence using only pulses of light. This all-optical set of single qubit protocols does not rely on the NV center's intersystem crossing nor on the use of on-chip microwave antennae. As such, these techniques could enable the integration into photonic networks or spin arrays as well as the investigation of other potential solid-state qubits, not just those with similar structures to the NV center. This work is supported by the AFOSR and DARPA.

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Building quantum memory from nuclear spin in nitrogen vacancy in diamond for quantum repeater

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One of the key devices of quantum communication is quantum repeater. One of the key elements in BDCZ quantum repeater is quantum memory [1]. There are a few requirements for this memory: 1. it needs long coherence time, so quantum error correction algorithm can be performed in the quantum repeater nods ; it needs to couple to the flying qubits, i.e. photon ; 3. it needs to be stable under many times of optical illuminations. Solid states qubits especially nuclear spins in nitrogen vacancy centers (NVs) emerge as one of the candidates for this quantum memory. Here we show ^{14}N nuclear spin in NVs in low temperature fulfills the requirements as quantum memory for quantum repeater.

Nitrogen nuclear spin in NVs has been demonstrated as robust quantum memory for spin qubit operations in room temperature[2,3]. But to be able to couple to flying qubit, selective optical addressing is needed. Low temperature optically resonant excitation of spin-selective transitions and single shot readout of electron spin in low magnetic field have been realized. $M_s = \pm 1$ ground states and A1 excited state form Λ system which is the basis of many quantum devices. Entanglement between electron spin of NV and photon has been demonstrated [4]; entanglements between two NVs nearby or 3 meters apart have been shown[5,6]. Here we would show the scheme of missing pieces for making quantum repeater: transfer quantum information from photon to nuclear spin.

We also benefit from low temperature with long coherent time of this memory. Since electron spin life time is over minutes and nuclear spin is non-resonant to ^{13}C nuclear spin bath, coherent time beyond 50ms is measured in ^{13}C natural abundant sample. Under resonant laser excitation during electron spin operation, the excited state quadruple and hyperfine interaction could lead to decoherence of nuclear spin. We show those interactions are low and nuclear spin can keep its coherence over 1000 times resonant laser excitation of electron spin.

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Entanglement of nuclear spins in diamond enhanced by weak measurements and postselection

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Solid state spin systems comprised of electron and nuclear spins are very interesting quantum registers with potential room temperature applications in Quantum information processing and metrology.[1,2,3] Particularly, nuclear spins have extremely long coherence times which can reach tens of minutes.[4] The latter features, however, require ultimate decoupling from any surrounding impurity spins, which in turn makes control and read-out of these nuclear spins challenging. The prototype spin system used in our work are single nitrogen-vacancy spin defects in diamond with proximal nuclear spins.[2] We investigate the application of weak measurements in combination with post-selection to achieve heralded, high fidelity entanglement at room temperature. In addition, we are able to measure weak values of nuclear magnetic moments.

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Anisotropic g factor in InAs self-assembled quantum dots

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We investigate the wave functions, spectrum, and g-factor anisotropy of low-energy electrons confined to self-assembled, pyramidal InAs quantum dots (QDs) subject to external magnetic and electric fields. We present the construction of trial wave functions for a pyramidal geometry with hard-wall confinement. We explicitly find the ground and first excited states and show the associated probability distributions and energies. Subsequently, we use these wave functions and 8-band $\boldsymbol{k}\cdot\boldsymbol{p}$ theory to derive a Hamiltonian describing the QD states close to the valence band edge. Using a perturbative approach, we find an effective conduction band Hamiltonian describing low-energy electronic states in the QD. From this, we further extract the magnetic field dependent eigenenergies and associated g factors. We examine the g factors regarding anisotropy and behavior under small electric fields. In particular, we find strong anisotropies, with the specific shape depending strongly on the considered QD level. Our results are in good agreement with recent measurements [Takahashi *et al.*, Phys. Rev. B **87**, 161302 (2013)] and support the possibility to control a spin qubit by means of g-tensor modulation.

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Spectral characterization of deep paramagnetic defect spin states in silicon carbide

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The neutral divacancy in 4H silicon carbide has been shown to have a spin-1 ground state that can be coherently manipulated at room temperature with pulsed microwave fields [1]. All-optical initialization, manipulation, and readout of the spins could be an appealing route towards extending the range of applications in photonic networks. We present our recent efforts in all-optically addressing ensembles of such defects, looking at photoluminescence excitation (PLE), spectral-hole burning, and exploring possible lambda systems for all-optical coherent control of the spin states. As a first step towards coherent population trapping, we characterize the spin ensemble using fixed pump lasers together with a scanning probe laser near resonance with the excited state.

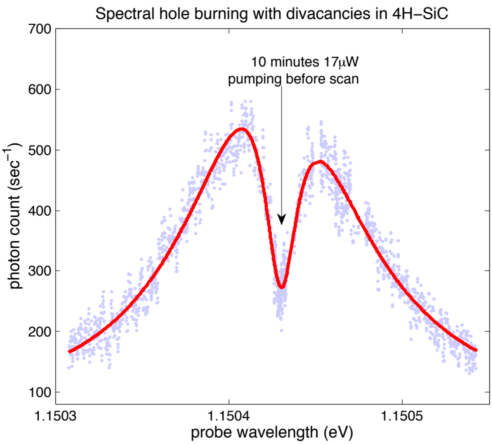

Figure 1: Spectral hole burning, in the PLE spectrum of the zero-phonon line of a divacancy ensemble in SiC.

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Correlations between Majorana Fermions Through a Superconductor

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We consider a model of ballistic quasi-one-dimensional semiconducting wire with intrinsic spin-orbit interaction placed on the surface of a bulk s-wave superconductor (SC), in the presence of an external magnetic field. This setup has been shown to give rise to a topological superconducting state in the wire, characterized by a pair of Majorana-fermion (MF) bound states formed at the two ends of the wire. Here, we demonstrate that besides the well-known direct-overlap-induced energy splitting, the two MF bound states may hybridize via elastic tunneling processes through virtual quasiparticle states in the SC, giving rise to an additional energy splitting between MF states from the same as well as from different wires.

A. A. Zyuzin, Diego Rainis, Jelena Klinovaja, and Daniel Loss, Phys. Rev. Lett. 111, 056802 (2013)

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