# TT 25: Focus Session: Electron Spin Qubits in Semiconductor Quantum Dots (organized by HL)

There have been remarkable new developments in the physics of electron spins confined in semiconductor quantum dots. In articular, silicon quantum dots have come to prominence, following in steps developments in GaAs dots. Spin hot spots — parametric regions with drastically reduced spin relaxation time — have been experimentally observed in both silicon and GaAs, in accord with theoretical investigations. Furthermore, novel ways of controlling and manipulating coherent dynamics of electron and nuclear spins in quantum dots by optics have been developed. This focused session will highlight those recent developments.

Organizer: Jaroslav Fabian, Universität Regensburg, and Jonathan Finley, Walter Schottky Institut, TU München.

Time: Monday 15:00–18:45 Location: POT 051

**Topical Talk** TT 25.1 Mon 15:00 POT 051

**Single Charge Relaxation in a Silicon Double Quantum Dot** — •Jason Petta — Department of Physics, Princeton University

Silicon has a weak spin-orbit interaction and can be isotopically purified resulting in an ultra-coherent environment for semiconductor qubits. I will describe recent measurements of single electron double quantum dots formed from undoped Si/SiGe quantum wells. Photon assisted tunneling is used to probe the energy level structure of the charge qubit, revealing the presence of low lying excited states. We measure the interdot charge relaxation time $T_1$ of a single electron as a function of detuning and interdot tunnel coupling and show that it is tunable over four orders of magnitude, with a maximum of 45 $\mu s$.

TT 25.2 Mon 15:30 POT 051

**Entanglement Purification with the Exchange Interaction** — •Adrian Auer and Guido Burkard — Department of Physics, University of Konstanz, Germany

Entanglement purification techniques provide means to create qubit pairs of arbitrary high fidelity with respect to a maximally entangled state, starting from a larger number of low fidelity pairs. So-called recurrence protocols act iteratively on two or more qubit pairs to produce one pair with higher fidelity, using local unitary operations, measurements, and communication of the measurement results. In this talk, we present a purification protocol that solely uses a single pulsed Heisenberg-type exchange interaction between two qubit pairs, therefore being especially suitable for spin qubits in tunnel-coupled quantum dots. In contrast to previously known protocols, we allow for asymmetric bilateral operations where the two communication parties operate differently on their qubits. In the most efficient version of our protocol, the local two-qubit interactions correspond to the $\sqrt{\text{SWAP}}$ gate and its inverse, which are the natural entangling gates generated from a Heisenberg-type interaction. Furthermore, we show how the same fidelity gain can be reached using $XY$-type interactions.

TT 25.3 Mon 15:45 POT 051

**Reservoir-assisted coherent control of a quantum-dot spin** — •Carsten H. H. Schulte[1], Jack Hansom[1], Claire Le Gall[1], Clemens Matthiesen[1], Jacob M. Taylor[2,3], and Mete Atatüre[1] — [1]Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom — [2]Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, USA — [3]National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

The interaction of a quantum-dot electron spin with the nuclear spins of its environment has attracted a lot of attention recently [1]. In equilibrium, the stochastic polarisation of the unperturbed nuclear spin bath leads to a splitting of the electron spin states. Here, we show that this effective Zeeman splitting is smaller than the linewidth of the charged exciton transition. The transitions in the unperturbed regime represent dynamically evolving $\Lambda$-systems. Harnessing these level schemes with sub-linewidth spin splittings, we implement spin-bath enabled coherent population trapping in the absence of an external magnetic field. We verify the coherence of the created spin state by coherent dark- and bright-state basis rotation through phase control of the laser fields, yielding arbitrary spin state initialisation and spin rotation with only hyperfine-induced spin orientation. The shown sub-linewidth level splitting advantageously reduces the influence of Larmor precession in spin manipulation schemes and facilitates photonic cluster state generation by triggered photon emission [2].

[1] Urbaszek et al., Rev. Mod. Phys. 85, 79-133 (2013).

[2] Lindner et al., Phys. Rev. Lett. 103, 113602 (2009).

**Topical Talk** TT 25.4 Mon 16:00 POT 051

**Spin Qubits in Silicon** — •Andrew Dzurak — University of New South Wales, Sydney 2052, Australia

Spin qubits in silicon are excellent candidates for scalable quantum information processing [1] due to their long coherence and the enormous investment in Si-MOS technology. Projective readout had proved challenging until single-shot measurement of a single donor electron spin was demonstrated [2] using a Si-SET and spin-to-charge conversion. The high readout fidelities > 90% and spin lifetimes T1 > 6 seconds [2] observed opened a path to electron and nuclear spin qubits in Si.

On-chip ESR of the P donor electron enables Rabi oscillations of the electron spin qubit, while Hahn echo reveals coherence T2 > 0.2 ms [3]. We also achieve single-shot readout of the 31P nuclear spin with fidelity > 99.8% and apply (local) NMR pulses to demonstrate coherent control of the nuclear spin qubit, with T2 > 60 ms [4].

Finally, I discuss recent experiments on both single-atom and Si-MOS quantum dot qubits in isotopically enriched 28Si devices, with even longer spin coherence exceeding 30 seconds.

[1] D.D. Awschalom et al., Quantum Spintronics, Science 339, 1174 (2013).

[2] A. Morello et al., Single-shot readout of an electron spin in silicon, Nature 467, 687 (2010).

[3] J.J. Pla et al., A single-atom electron spin qubit in silicon, Nature 489, 541 (2012).

[4] J.J. Pla et al., High-fidelity readout and control of a nuclear spin qubit in Si, Nature 496, 334 (2013).

TT 25.5 Mon 16:30 POT 051

**Combining spin and valley singlet-triplet qubits for universal quantum computing** — •Niklas Rohling, Maximilian Russ, and Guido Burkard — Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

The valley degree of freedom in silicon or other materials is often considered to be an obstacle for quantum computing based on electron spins in quantum dots. Nevertheless, controlling the valley states opens new possibilities for quantum information processing. Combining qubits encoded in the single-triplet subspace of spin and of valley states allows for universal quantum computing because the exchange interaction directly provides a universal two-qubit gate between those qubits if they are stored in the same two-electron double quantum dot [1]. We show how spin and valley qubits can be separated in order to enable single-qubit rotations. Finally we propose explicit sequences for quantum gates in two kinds of spin-valley quantum registers.

[1] N. Rohling and G. Burkard, New Journal of Physics **14**, 083008 (2012).

TT 25.6 Mon 16:45 POT 051

**Optical detection of coherent electron spin states of silicon vacancy defects in silicon carbide** — •Matthias Widmann[1], Sang-Yun Lee[1], Nguyen Tien-Son[2], Helmut Fedder[1], Torsten Rendler[1], Adam Gali[3], Erik Janzén[2], and Jörg Wrachtrup[1,4] — [1]3. Physikalisches Institut, Universität Stuttgart — [2]Department of Physics, Chemistry and Biology, Linköping University — [3]Institute for Solid State Physics and Optics, Budapest — [4]Max-Planck Institute for Solid State Research, Stuttgart

Deep defects in wide band gap materials are promising candidates for realizing quantum information processing [QIP]. One candidate is the negatively charged nitrogen-vacancy (NV) center in diamond. NV centers can be used for realization of QIP[1] and nano-scale magnetic field sensing[2]. The diamond serving as a host material, however, is rather

hard to be implemented in existing silicon based semiconducting materials and devices. In order to circumvent this challenge, we focus on 4H silicon carbide (4H-SiC) which houses missing silicon atoms, forming the negatively charged silicon vacancies ($\mathrm{T}_V$ centers). Unlike the visible light emissions from NV centers in diamond, $\mathrm{T}_V$ centers in SiC also have the advantage of the infrared emissions around 900 nm, in which the optical attenuation is weaker in silica based fibers. We will present that single $\mathrm{T}_V$ emissions can be observed and coherent spin manipulation of both ensemble and single $\mathrm{T}_V$ centers are possible at room temperature.
[1] Neumann et al, Science, 2010, 329, 542
[2] J. R. Maze et al, Nature 455, 644-647

### Coffee break (15 min.)

**Topical Talk** TT 25.7 Mon 17:15 POT 051

**Spin Hot Spots in Quantum Dots** — •Peter Stano — RIKEN Center for Emergent Matter Science, 2-1 Hirosawa, Wako, Saitama 351-0198 Japan — Institute of Physics, Slovak Academy of Sciences, 845 11 Bratislava, Slovakia

Spin hot spots are points in parameter space which dominate spin relaxation in quantum dots. The relaxation proceeds through spin-orbit interactions and a phonon emission. In a spin hot spot the otherwise weak spin-orbit effects become non-perturbative and thus unusually strong.

The hot-spot dominance leads to a pronounced anisotropy of the relaxation rate as a function of the quantum dot and/or magnetic field orientation with respect to crystallographic axes. This behavior is very general, occurring for different electron occupations, quantum dot geometry and material composition. Of practical interest is the possibility to individually identify different types of spin-orbit interactions (e.g. Rashba vs Dresselhaus), and obtain their relative strengths in a given sample, from the relaxation rate anisotropy.[1]

The important influence that the spin hot-spots might imply on spin relaxation was first recognized in bulk metals and later in quantum dots. The theoretically predicted spin hot-spots were recently established experimentally in gated Si [2] and GaAs [3] quantum dots.
[1] P. Stano and J. Fabian, Phys. Rev. B 74, 045320 (2006).
[2] C. H. Yang, et al., Nature Comm. 4, 2069 (2013).
[3] V. Srinivasa, et al., Phys. Rev. Lett. 110, 196803 (2013).

TT 25.8 Mon 17:45 POT 051

**ESR Spin manipulation in spin light emitting diodes** — •Andreas Merz, Jan Siller, Heinz Kalt, and Michael Hetterich — Inst. für angew. Physik KIT, Karlsruhe, Germany

Electron spin resonance is one of the most promising mechanisms to enable coherent quantum information processing. In spin light emitting diodes (spin-LEDs) we are able to initialize single electron spins all electrically by injecting them through a ZnMnSe spin-aligner layer into single self-assembled InGaAs quantum dots (QDs) with up to 100% fidelity. In a 53GHz microwave (MW) cavity we are able to manipulate the 3d Mn spin system of the spin aligner resonantly and detect the spin manipulation after the injection of band electrons into the QDs. We can optically observe the effect by analyzing the circular polarization of the recombination radiation during electrical excitation of the spin-LED for the magnetic field tuned such that the MW is resonant with the spin splitting in the Mn system. Furthermore we are able to differentiate between the resonant spin heating and non-resonant lattice heating of an amplified MW pulse for longer pulse lengths and pure spin heating for sub-microsecond MW pulses. The understanding of these mechanisms plays an important role for MW spin manipulation of single electron spins in semiconductor QDs on a ns timescale.

TT 25.9 Mon 18:00 POT 051

**Optical Spin Noise of a Single Hole in a Quantum Dot** — •Ramin Dahbashi[1], Jens Hübner[1], Fabian Berski[1], Klaus Pierz[2], and Michael Oestreich[1] — [1]Institute for Solid State Physics, Leibniz Universität Hannover, Appelstr. 2, D-30167 Hannover, Germany — [2]Physikalisch Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig, Germany

We present spin noise spectroscopy (SNS) [1] at the extreme limit of single spin detection, i.e., measurements of the spin dynamics of a single heavy hole localized in a self-assembled (InGa)As quantum dot (QD) [2]. Magnetic field dependent measurements reveal a strong dependence of the heavy hole spin relaxation rate $T_1^{-1}$ on the longitudinal external magnetic field ($\propto B_z^{-3/2}$) even for very low magnetic fields up to 31 mT. At very low probe light intensities we detect an extremely long $T_1$ of $> 180$ $\mu$s at 31 mT and 5 K. The inhomogeneously broadening of a single QD SN spectrum is unveiled by the probe energy dependence of the SN power for finite light intensities. This feature is explained by charge fluctuations in the QD vicinity leading to distinct charge configurations. The corresponding fluctuations of the QD resonance energy are corroborated by a distinct probe intensity dependence of the spin lifetime. We further investigate time correlation effects of single QD SN spectra to gain insight into charging dynamics in the surrounding.
[1] Müller et al., Physica E **43**, 569 (2010).
[2] Dahbashi et al., arXiv:1306.3183 (2013).
[3] Dahbashi et al., Appl. Phys. Lett. **100**, 031906 (2012).

TT 25.10 Mon 18:15 POT 051

**Spin-orbit effects on nuclear state preparation at the $S-T_+$ anti-crossing in double quantum dots** — •Marko J. Rančić and Guido Burkard — University of Konstanz

We explore the interplay of spin-orbit and hyperfine effects on the nuclear preparation schemes in two-electron double quantum dots, e.g. in GaAs. The quantity of utmost interest is the 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 electron spin 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 $\theta$ between the [110] crystallographic and the inter-dot axis. 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 $\theta$.

TT 25.11 Mon 18:30 POT 051

**Addressing ionized $^{75}$As nuclear spin qubits in silicon using nuclear quadrupole interaction** — •Florian M. Hrubesch, David P. Franke, Markus Künzl, Andrej Voss, Felix Hoehne, Lukas Dreher, and Martin S. Brandt — Walter Schottky Institut, Technische Universität München, Am Coulombwall 4, 85748 Garching

Electrically detected electron nuclear double resonance (EDENDOR) studies have shown coherence times of $^{31}$P$^+$ nuclear spins in crystalline $^{\mathrm{nat}}$Si of 18 ms [1]. In isotopically enriched $^{28}$Si these $T_2$ times can reach up to 3 hours [2], making these nuclear spins promising candidates for quantum information storage. However, these long coherence times are caused by the nearly perfect isolation of the ionized donor nuclear spins from their environment, which hampers selective addressing with e.g. electric fields. We present EDENDOR measurements on $^{75}$As$^+$ nuclear spins in $^{\mathrm{nat}}$Si which exhibit similarly long decoherence times as $^{31}$P$^+$ nuclear spins in $^{\mathrm{nat}}$Si. By applying elastic strain, the transition frequencies involving the $|m_I| = \frac{3}{2}$ states can be shifted by about 25 kHz, while the transitions between the $|m_I| = \frac{1}{2}$ states remain virtually unaffected. This allows the selective manipulation of the nuclear spin state via magnetic resonance, which could enable the addressing of single $^{75}$As$^+$ qubits with the help of nanoscale piezoactuators positioned on top of the donors [3]. [1] L. Dreher *et al.*, Phys. Rev. Lett. 108, 027602 (2012) [2] K. Saeedi *et al.*, Science 342, 830 (2013) [3] L. Dreher *et al*, Phys. Rev. Lett. 106, 037601 (2011)