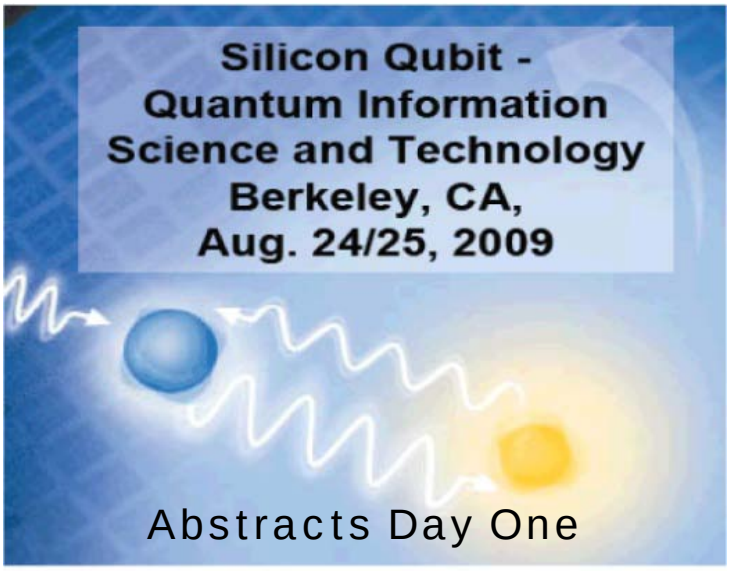

Si/SiGe Depletion -Mode and Accumulation -Mode Few -Electron Dots

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We have measured charging spectra and charge dynamics of few -electron quantum dots made using SiGe/Si heterostructures. In depletion-mode dots, electrons are confined in a single Si well by reverse -biased gates surrounding the dot, and nearby QPCs provide a means of charge sensing. We have measured charging spectra in these dots using through-dot current, and well as QPC charge sensing. We have performed excited -state spectroscopy using the lowest observed transition, and have identified an excited state with energy consistent with Zeeman splitting for an electron with a g -factor of 2.0±0.1. The lifetime for this excited state was measured at several values of magnetic field. The lifetime was 615 msec at 1 .2T, consistent with our estimate for T_1 for a single electron in these dots at this value of field. The lifetime had close to the B^7dependence on magnetic field strength expected for spin relaxation in silicon.

We have also made measurements of charging spectra and charge dynamics in an accumulation-mode SiGe dot. These dots are formed using a double-well heterostructure in which electrons are localized in the top, nominally empty, well by forward biasing a small circular gate. Charge occupancy changes in the dot are monitored by measuring current confined to a narrow channel in the bottom well. Tunneling in and out of the dots is controlled primarily by the width of the SiGe barrier in between the top and bottom wells, and is relatively insensitive to bias and dot occupancy compared to depletion dots. In these dots, w e have measured charging spectra from N=0 up to N= 13, with charging energies as high as 4.5 meV for the second electron added to the dot. Preliminary magnetospectroscopy measurements in ^{3}He system are consistent with an initial 4-electron shell, in contrast to a 2-electron shell inferred for similar III-V devices, and agree with theoretical predictions.

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Modeling Accumulation -Mode Few -Electron Quantum Dots

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Semiconductor quantum dots coupled via a controllable exchange interaction can be used to make encoded qubits comprised of two or more physical qubits. We have modeled several aspects of a coupled qubit system in the context of accumulation -mode Si/SiGe - based quantum dots, including the electronic structure of single dots and properties of exchange -coupled double dots.

Specifically, we have calculated the charging spectrum of Si/SiGe few-electron quantum dots using a combination of Poisson -Schrödinger (PS) and full configuration interaction (CI) codes. The dots are formed using a double -well heterostructure in which electrons are localized in the top, nominally empty, well by forward biasing a small circular gate. Changes in the charge occupancy of the dot are monitored by measuring the current flowing through a quantum point contact (QPC) formed in the bottom well by reversed biased gates in the vicinity of the circular gate The full three -dimensional device structure is simulated using the PS code and the electronic structure in the few electron regime is computed with the CI code using PS wavefunctions as a basis set and explicitly including both spin and valley degrees of freedom. We find good agreement with experimental results for ground state properties, in particular for the changes in addition energy, which allows us to conclude that valley degree of freedom plays an essential role in determining the electronic structure of these dots. We compare this to the case of III-V quantum dots where the valley degree of freedom is absent. We have also calculated the multi -electron excited state spectrum for both III-V and Si/SiGe accumulation-mode quantum dots and found excellent agreement with experimental data on III-V dots.

We have also calculated the properties of accumulation -mode double quantum dots that have recently been fabricated at HRL. Specifically, we have calculated the Coulomb and exchange energy for different configurations of dots sizes, separations and exchange gate geometries. These calculations suggest that sufficient exchange coupling and tunability can be achieved with accumulation mode dots to make them useful for realizing multi-qubit devices capable of demonstrating an exchange-only encoded qubit

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Pulse-gate excited-state spectroscopy in a Si/SiGe quantum dot by charge sensing

Madhu Thalakulam, C. B. Simmons, B. M. Rosemeyer, B. J. Van Bael, D. E. Savage, M. G. Lagally, M. Friesen, S. N. Coppersmith, and M. A. Eriksson.
University of Wisconsin-Madison

We discuss the manipulation and readout of excited states in a few-electron Si quantum dot using a point contact charge sensor and pulsed gate voltages. The quantum dot and the point contact are defined by the split-gate technique on a Si/SiGe heterostructure. A single dot with single electron occupancy and a double dot with one electron per dot have been achieved in the same device. We

present a new method to extract alpha, the lever-arm connecting the gate voltage and the quantum dot energy, and we use this method to measure the energy of the observed excited states. Manipulation of charge states in the dot is accomplished by applying pulse sequences to the gates defining the quantum dot, and the excited-states are identified by tunnel-rate-selective readout using the integrated point-contact charge-sensor.

This work was supported in part by ARO and LPS (W911NF-08-1-0482), by NSF (DMR-0805045), by DOD, and by DOE (DE-FG02-03ER46028). This research utilized NSF-supported shared facilities at the University of Wisconsin-Madison.

Physical mechanisms of interface-mediated intervalley coupling in Si

A.L. Saraiva, M.J. Calderón, Xuedong Hu, S. Das Sarma and Belita Koiller

The conduction band degeneracy in Si (valley-degeneracy) is known to be detrimental to spin quantum computing, for which nondegenerate ground orbital state is desirable. This degeneracy is lifted at an interface with an insulator, as the spatially abrupt change in the conduction band minimum leads to intervalley scattering. We present an effective mass study of the interface induced valley splitting in Si that provides simple criteria for optimal fabrication related conditions to maximize this splitting. We emphasize the specific role played by the interface width and the conduction band offset in the quantitative determination of the valley splitting.

Charge sensing and controllable tunnel coupling in a Si/SiGe double quantum dot

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University of Wisconsin-Madison

We report charge sensing measurements on a Si/SiGe double quantum dot. Charge sensing can be used to probe the inter-dot motion of a single electron at fixed total charge in the double dot, and we measure this motion as a function of the double dot gate voltages. The tunnel coupling between the two dots directly affects the charge localization and thus the sharpness of this inter-dot transition. We demonstrate that the tunnel coupling is an exponential function of the voltage on a single gate and show a smooth transition between two well-isolated dots, two dots so strongly coupled that they act as a single large quantum dot, and the intermediate regime. The observed tunnel coupling is a monotonic function of the voltage on the central gate, indicating that valley effects do not produce measurable oscillations or non-monotonicity in this experiment.

This work was supported in part by ARO and LPS (W91 1NF-08-1-0482), by NSF (DMR-0805045), by DOD, and by DOE (DE-FGO2-03ER46028). This research utilized NSF-supported shared facilities at the University of Wisconsin-Madison.

Singlet-triplet qubits in multivalley Si quantum dots

Dimitrie Culcer,[1] Lukasz Cywinski, [1] Qiuzi Li,[1] Xuedong Hu,[2, 3] and S. Das Sarma[1]
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Quantum dot (QD) spins are promising candidates for scalable quantum computation (QC). Electrical readout and control of single spins in QDs have proven challenging, yet GaAs double QDs, where spin blockade and charge sensors enable observation of single/two-spin dynamics, have seen impressive experimental progress. Recent experiments [1] have demonstrated quantum coherence and the use of the two-electron singlet and unpolarized triplet as a qubit, with reliable initialization, single-qubit rotation, and measurement. Yet the hyperfine interaction provides a fundamental limit to spin lifetimes in GaAs, a fact which has spurred intense research into Si QDs. Silicon is often regarded as the best semiconducting host material for spin qubits because of its excellent spin coherence properties: spin-orbit coupling is very small while the hyperfine interaction can be reduced by isotopic enrichment. The biggest obstacle to spin QC in Si is the valley degree of freedom, which I will discuss at length. At the Si/SiO_2 interface two valleys are relevant to the ground orbital state, which introduces fundamental complications in distinguishing spin and orbital degrees of freedom. Scattering at the interface lifts the valley degeneracy by producing a valley-orbit coupling Δ, yet the exact form and magnitude of Δ is generally not known a priori and is sample-dependent. With this in mind we have established the precise criteria for realizing spin qubits in Si QDs [2]. I will show that, for small Δ, a singlet-triplet qubit cannot be constructed since a number of different states may be initialized, leading to different experimental outcomes. For large valley splitting ($\Delta \sim k_B T$) the experiment is analogous to GaAs. A Zeeman field can be used to distinguish between different initialized states for any valley splitting, and sweeping a uniform magnetic field provides a useful method for estimating Δ, which is particularly useful when $\Delta < k_B T$. This work is supported by LPS-NSA.

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Electron spin coherence and manipulation in Si quantum dots

Xuedong Hu
Department of Physics, University at Buffalo, SUNY

Spins in semiconductor nanostructures are promising qubit candidates for a solid state quantum computer, and have seen some truly impressive experimental progresses in the past few years. In this talk I will report some recent calculations where we study electron properties in Si quantum dots. In particular, I will discuss recent results we obtained on the strength of hyperfine interaction for conduction electrons in Si and explore the consequences of our results in terms of spin

decoherence and manipulation. I will also discuss our calculation of electron exchange in Si and compare it with results for GaAs quantum dots.

Recent experiments to probe individual spins of a few-electron silicon quantum dot

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Department of Physics and Astronomy, University of California at Los Angeles
Los Angeles, CA 90095

We have developed electrostatically-confined quantum dots on Si MOS based materials. An array of electrical characterization shows that the quantum dots have unprecedented device stability and controllability. In this talk, we present results of transport measurements in the few electron regime. Unusual spin filling configurations, along with non-linear transport features associated with high-spin states will be reported. An integrated charge sensing channel adjacent to the quantum dot has been used to study the individual electron tunneling and relaxation dynamics. Electron spin relaxation time T1 in the presence of an in-plane magnetic field is measured by the charge sensor with a pump-and-probe technique. We will discuss mechanisms leading to spin relaxation in this type of Si devices.

The work was sponsored by United States Department of Defense.

Pulsed electron spin resonance on silicon MOSFETs

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Dept. of Electrical Engineering, Princeton University

We present measurements of spin relaxation and coherence times, T_1 and T_2 for conned electrons in a Metal-Oxide-Silicon transistor (MOSFET) using pulsed electron spin resonance (ESR) at temperatures down to 350 mK. Upon biasing our MOSFET below threshold, we observe an ESR signal arising from two-dimensional (2D) electrons weakly confined by the disorder at the Si-SiO_2 interface. These confined electrons have a density of about 10^{10} cm^{-2}, a trap depth of a few meV and a Curie susceptibility characteristic of independent, isolated electrons. Using pulsed ESR, we measure a T_2 of 2 μs at 5 K, rising to around 10 μs at 1 K. T_2 saturates at 10 μs from 1 K down to 350 mK. In contrast, T_1 rises rapidly as the temperature is lowered, from 6 μs at 1 K to 1.1 ms at 350 mK. At 350 mK, biasing the MOSFET at threshold raises the electron density at the interface to about 10^{11} cm^{-2} and reduces T_1 to 15 μs. Our measured T_1's and T_2's are long for a 2D electron system; at 5 K when biasing our MOSFET above threshold, we find that mobile electrons have coherence times of only 0.3 μs. While the mechanism for spin relaxation and decoherence remain unknown, the long T_1 of 1.1 ms at 350 mK is promising for experiments on 2D electron spins conned in laterally gated quantum dots in silicon.

Modeling Si Double Quantum Dot Qubits

Rick Muller, Malcolm Carroll, Ralph Young, Harold Stalford, Erik Nielsen, Wayne Witzel, Rajib Rahman
Sandia National Laboratories

Abstract: We present the results of computational modeling of Si metal oxide semiconductor (MOS) double quantum dot (DQD) based qubits, and how a combination of modeling packages are coordinated to provide modeling guidance both to Si DQD experiment and architecture efforts. We have used semiclassical TCAD calculations to understand the quantum dot size and its dependence on gate voltage. The TCAD calculations are extended with capacitance calculations to produce a small signal model that can be used to understand the impact of the electronics control circuitry on the quantum dot. The TCAD calculations can also be extended with quantum mechanical calculations using atomistic or effective mass approximations to model the exchange energy and the impact of charge noise on qubit decoherence. Spin decoherence due to spin diffusion of MOS interface defects is also modeled to provide estimates of T2 when the qubit is idle and the exchange gate is not actuated. The combination of these models provides an interrelated design understanding of Si MOS DQD qubit that highlights a number of different influences spanning the realities of the experiment through to future anticipated architectural needs.

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The impact of classical electronics constrains on a solid-state logical qubit memory

A. J. Landahl, Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Probing charge state degeneracy in silicon isolated double quantum dots by a SET

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Although most solid state proposals for quantum computation rely on the original ideas of Kane[1], many variations were suggested for many years and the realisation of a viable quantum bit still remains at an early stage[2]. The approach we have developed uses charge states in an isolated double quantum dot (IDQD) in silicon as the basis element for quantum information as well as a nearby single electron transistor (SET) that is used for charge readout[3]. Here we report on the detection of charge motion in the double dot system by single electron tunnelling or cotunnelling event in the SET. We have probed the charge state degeneracy of the IDQD and showed that the electron displacement in the IDQD is associated with a substantial charge rearrangement in the SET island and the existence of two stable ground states of the SET. Also back-action from the SET is observed and gives an estimate of the maximum measurement duration.

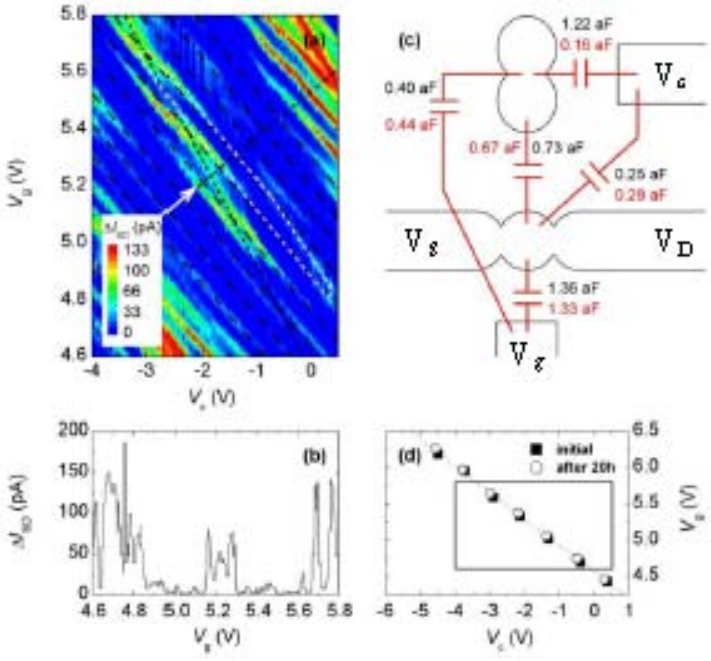

Fig. 1: a) Shifts in Coulomb peak b) Current profile c) Capacitance simulation d) Reproducibility.

The devices were fabricated from a silicon-on-insulator (SOI) substrate with a 45 nm-thick silicon layer, doped with phosphorous at a density of 2.9 10^{19} cm^{-3}. High resolution electron beam lithography and reactive ion etching were used to pattern a single dot for the SET and the isolated double dot. The SET and the IDQD are controlled by in-plane gates within the same SOI layer. A custom low temperature complementary metal-oxide-

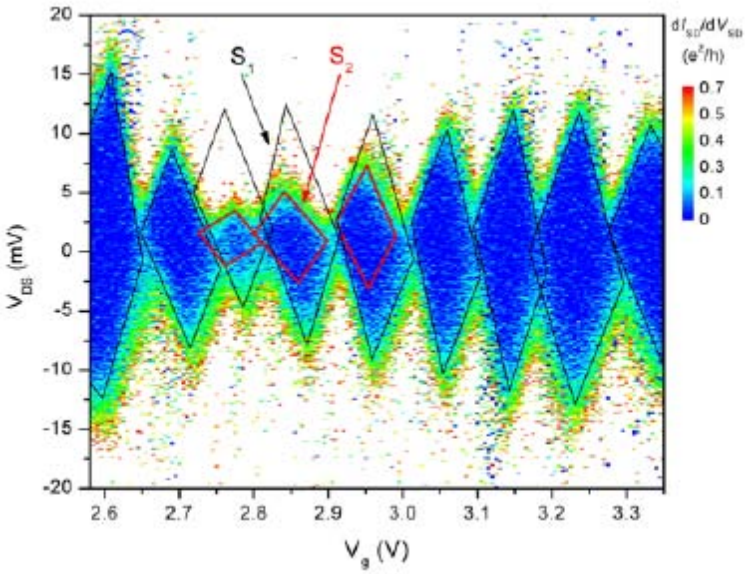

Fig. 2: Coulomb diamonds with state degeneracy (S_1 and S_2) associated with electron motion in the IDQD.

semiconductor circuit is used to provide the various voltages to the device and to measure the SET current through a charge integrator circuit[4]. Measurements were performed at 4.2 K.

SET current dependencies on SET and IDQD gates are complex but specific features associated with electron motion in the IDQD could be distinguished. These are characterised by an abrupt shift in gate voltage of a single Coulomb blockade peak (Fig. 1). The shift is about 1/3 of the Coulomb blockade period, a value much larger than the currently predicted ones by capacitance calculations[5] but explained by a modification of the occupancy of localised states around the SET island. Indeed these trap states control the coupling between the SET and the IDQD. Electron motion in the IDQD brings the SET into a degenerate state of different energy (Fig 2) and SET back-action on the IDQD is negligible for timescale shorter than 10 ms suggesting that charge qubit computation is possible in these structures.

This work was partly supported by Special Coordination Funds for Promoting Science and Technology in Japan.

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Coulomb Blockade and Charge Sensing in Double Top Gated Si MOS Nano-Structures

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We discuss measurements of a Si-MO S quantum dot with an open lateral non-collinear geometry. Periodic, single-period Coulomb blockade is observed. The measured gate-to-dot capacitances are consistent with 3D finite element calculations of the capacitance matrix for a lithographically defined quantum dot, indicating that the quantum dot confinement potential is dominated by the lithographically patterned gates and not by disorder. We present details of a fabrication process flow that led to demonstration of stable single period Coulomb blockade behavior will be presented, and we discuss characterization of the critical steps in that flow. Decreases in mobility and increases in charge defect densities (e.g., interface traps and fixed oxide charge) are reported for critical process steps, and we correlate low disorder behavior with a quantitative defect density. We also present charge-sensing measurements of the quantum dot using a nearby disordered constriction. The sensitivity of the charge sensing is as high as a 3% change in current due the change of one electron occupation in the sensed quantum dot. Drift of the Coulomb blockade was measured to be less than .4% of the Coulomb blockade period per day.

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Quantum Hall Charge Sensor for Single-Donor-Spin Detection in Silicon

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We propose a novel scheme for detecting a single donor spin of phosphorus in silicon in the integer quantum Hall effect (IQHE) regime. The IQHE exhibits the remarkable features of exact quantization of transverse resistance and zero longitudinal resistance. These features are robust to bulk scattering from most of the phosphorus donors in the sample, as well as other defects. It is known, however, that an additional constriction potential inside the electron channels significantly modifies these transverse and longitudinal resistances. Hence, we would anticipate identifying the charge state of an isolated donor near that constriction from the deviation of the IQHE conductance. We propose to alter the charge state of the donor via resonant optical pumping on the spin-dependent donor-bound-excition transitions, for which hyperfine selectivity has been demonstrated. The dominant decay channel of the donor-bound exciton in silicon is the Auger process; the resulting neutral-to-ionized donor transition modifies the IQHE conductance. We present numerical simulations of the conductance behavior for our proposed device, which combines a metal-oxide-semiconductor field effect transistor structure to form a two-dimensional electron gas system with a quantum point contact to isolate an individual donor.

Cryogenic CMOS circuits for single charge digital readout

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The readout of a solid state qubit often relies on single charge sensitive electrometry. However the combination of fast and accurate measurements is nontrivial due to large RC time constants due to the electrometers resistance and shunt capacitance from wires between the cold stage and room temperature. Currently fast sensitive measurements are accomplished through rf reflectrometry

techniques. In my talk, I will present an alternative single charge readout technique based on cryogenic CMOS circuits in hopes to improve speed, signal-to-noise, power consumption and simplicity in implementation. The CMOS readout circuit is based on a current comparator where changes in current from an electrometer will trigger a digital output. Initial measurements of stand-alone comparators at 4.2K have displayed current sensitivities of "4nA and switching speeds up to "6Ons. A cryogenic CMOS current pre-amplifier to boost the current sensitivity will also be presented. Cryogenic operation of these amplifiers have displayed gains ranging from 50 to 5000, bandwidths > 100kHz, and spectral noise following 1/f behavior. Both of the initial CMOS circuits were designed with 300K SPICE models and fabricated using Sandia's 0.35 um CMOS foundry process. The efforts to characterize and develop SPICE models for this foundry process at 4.2K will also be described along with progress towards the implementation of the combination of circuits and charge sensor.

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Compact modeling of cryogenic CMOS circuits using Verilog-A

A. Akturk, University of Maryland

Single -shot Electron Spin Readout of Individual Implanted Phosphorus Donors in Silicon

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The electron spin of a donor in silicon is an excellent candidate for a solid -state qubit It is known to have very long coherence [1] and relaxation [2] times in bulk, and several architectures have been proposed to integrate donor spin qubits with classical silicon microelectronics [3, 4, 5]. However, no demonstration of single -donor spin control and readout has been achieved so far.

Here we show the first experimental proof of single -shot readout of the electron spin of individual implanted P donors in silicon. This breakthrough has been obtained by coupling the implanted donors to a silicon Single-Electron Transistor (Si-SET) [6], where the SET island is used as a reservoir for spin-to-charge conversion [7]. The charge transfer signals are exceptionally large, and allow time-resolved measurement s of spin-dependent tunneling on a ~10 μs scale.

By measuring the occurrence of excited spin states as a function of wait time, w e find a spin lifetime ~50 ms. This is already much longer than in GaAs quantum dots, but still limited by spin diffusion due to dipolar interactions between nearby donors. Therefore, we consider the observed lifetime only as lower bound for the real spin-lattice relaxation time T_1.

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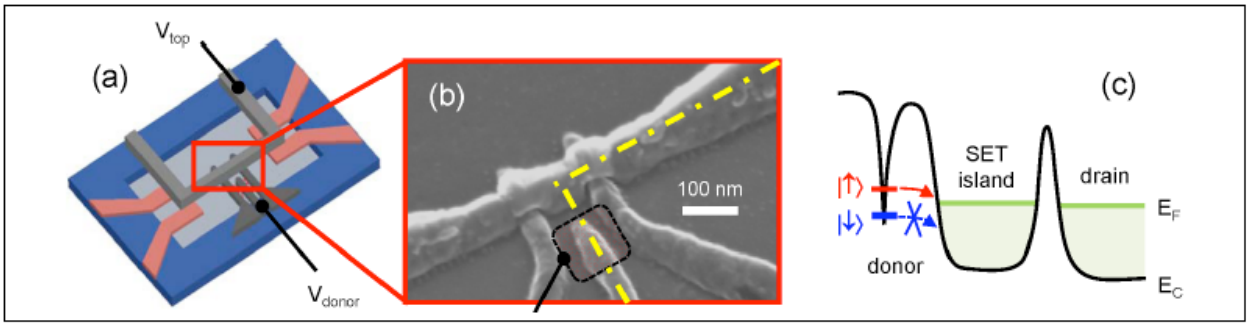

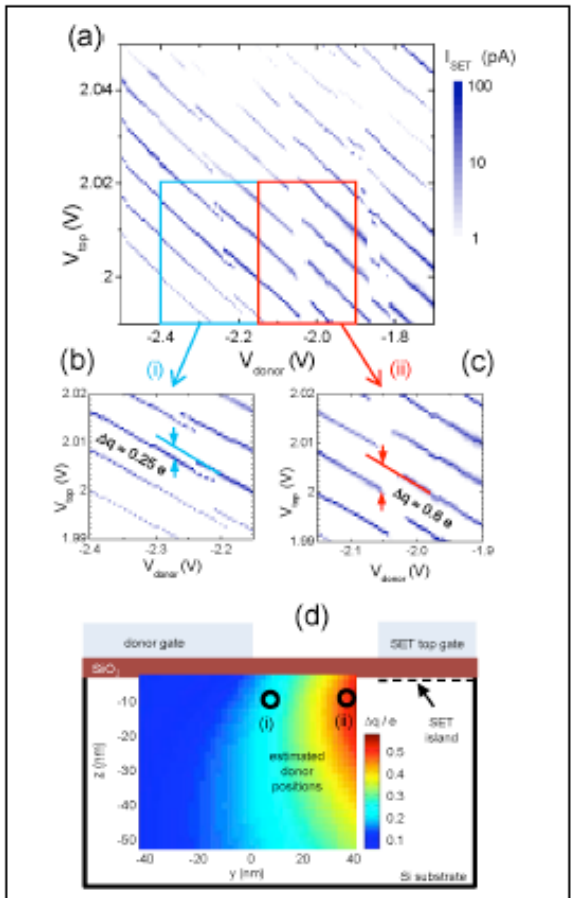

Fig.2. (a) Charge transitions between implanted donors and SET island, represented by the jumps in the series of SET current peaks. (b,c) Zoom-in of the transitions marked (i) and (ii), characterized by charge transfer signals $\Delta q = 0.25e$ and $\Delta q = 0.6e$, respectively. (d) Calculation of the charge transfer signals for a structure with a 50 nm gap between donor gate and top gate. The black dots indicate the estimated position of the donors corresponding to the transitions (i) and (ii), based on the observed values of Δq.

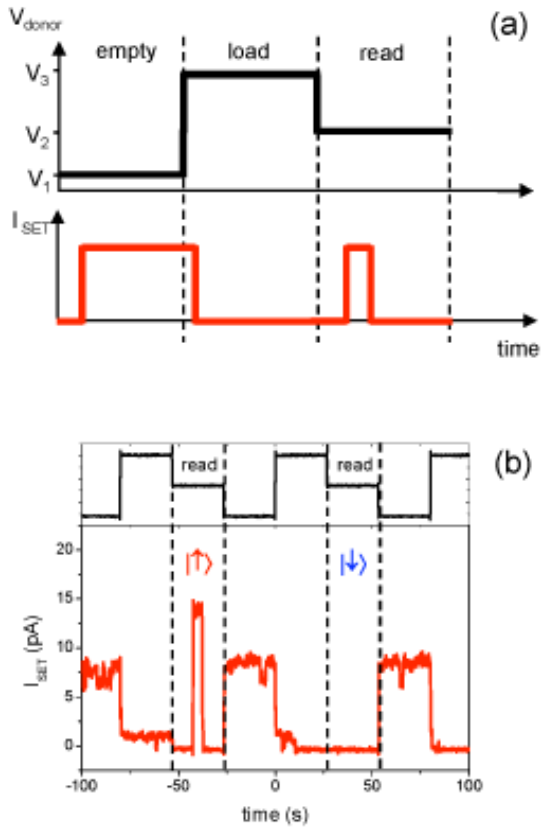

Fig.3. (a) Donor gate pulsing sequence, and corresponding values of I_{SET}, to achieve single-shot spin readout. The time evolution of I_{SET} is the one expected for an electron in the $|\uparrow\rangle$ state. (b) Single-shot time traces of V_{donor} (top panel) and corresponding I_{SET}. In the first "read" cycle, a blip in I_{SET} is observed, which can be interpreted as the readout of an $|\uparrow\rangle$ electron. In the second cycle, $I_{SET} = 0$, indicating a $|\downarrow\rangle$ state. This measurement was performed on the (i) transition in Fig. 2, with an applied field B = 5 T and a temperature T = 100 mK, much smaller than the Zeeman splitting $E_Z = 6.7$ K.

Excited Triplet state of a dopant and valley-orbit coupling in a nano MOSFET

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CMOS technology reached such a level that we can realize transport through a single dopant atom in a transistor. Such transport spectroscopy can probe the atomic orbitals and the interaction of the atom with the environment. This interaction in can consist of hybridization with other localized states and coupling to the leads. A dopant in a nano device has different properties than those known in the bulk such as the level spectrum and the charging energy. The system discussed is a gated donor where the donor-bound electron is partly pulled towards the interface by the gate electric field. Electronic control over the wavefunction of dopants is one of the key elements of Si quantum electronics. In this talk we focus on the role of the valley-orbit coupling and on the spin configuration of the two-electron state. The six valleys of the conduction band play an essential role for charge carriers in Si confined to the nanometer scale. For a dopant this effect is most dramatic and reaches a large fraction of the binding energy. We discuss the valley-orbit coupling for a CMOS quantum dot, a dopant, and their combination experimentally and compare it to tight-binding simulations. For the negatively charged donor we observe a reduced charging energy and bound singlet and triplet excited states. The existence of a bound triplet state is the basis for spin-to-charge conversion in donor-based quantum electronics. Lifetime enhanced transport makes it possible to identify the spin state and place a lower bound on the internal relaxation rates.

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Million-Atom Electronic Structure Simulations for Realistically Large Si-Based Quantum Devices

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Qubit device implementations proposed in Silicon based on quantum dots or single impurities may be "small" in the traditional sense of a traditional CMOS device and may be considered artificial atoms or molecules. The wavefunctions of these artificial atoms, however span spatially over possibly millions of real atoms and therefore experience the details of the local real atom arrangements. We have developed a Nanoelectronic Modeling (NEMO3D) tool suite which allows us to explore the qubit deign space consistent of millions of atoms in close collaboration with experimental groups. This presentation will overview the NEMO3D capabilities to study the electronic structure in very different spatial confinement concepts: 1) Si quantum wells confined

by SiGe strain inducers with non-ideal wafer slanting subject to a magnetic field, 2) [111] oriented Si quantum wells, 3) single impurities confined in a modern FinFET transistor, 4) arrays of single phosphorus impurities for qubits (CTAP), and 5) extremely highly Phosphorous doped Silicon nanowires and sheets. The key messages in these studies are that the tight binding method used in the work captures all the relevant physics without any additional fitting parameters, that local disorder and atom arrangements matter, and that indeed a multimillion atom representation of the extended device domain is critical.

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The importance of valley splitting in few-electron donor based quantum dots in silicon

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We report low temperature transport measurements of a few-electron P donor based quantum dot in silicon which shows a surprisingly dense spectrum of excited states with an average energy spacing of 100 μV. The energy spacing of these features is much too low to be accounted for by the nm-scale lateral confinement of either the dot or the leads. Instead we can explain these resonant features with lifting of valley degeneracy of the dot orbital states and present effective-mass calculations for this strongly confined Si:P system which are in good agreement with experimental findings.

Low temperature transport measurements of this STM-patterned planar, Si:P quantum dot reveal stable Coulomb oscillations in agreement with previous results [1] but with a rise in charging energy as the dot empties. Using in-plane gates, we are able to tune both the electron number in the dot and modulate the transparency of the tunnel barriers. This results in a gate-dependent device conductance as well as a gate-dependent asymmetry of the tunnel coupling to the source and drain leads which affects the visibility of excited state resonances. We discuss the role of valley splitting in P-donor based silicon dots and also present our latest results towards STM-patterned single donor devices wherein the charging energy and the excited state spectrum are consistent with charge transport through the orbital states of a single P-donor.

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Silicon donor devices and quantum computer architecture considerations

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In recent years there has been a growing convergence between experiment and theory in understanding and demonstrating controlled single donor systems. Generally, proposals for quantum processing applications (charge, nuclear or electron spin) often rely on the ability to modify the donor electron wave function in the presence of electric and magnetic fields. We will overview existing and recent theoretical work on the external field control of donor orbital and spin degrees of freedom. As new experimental results emerge a quantitative comparison with this theoretical description is already at a relatively precise level for the Stark shift of orbital levels and the hyperfine interaction, and for the case of microwave charge state control. With this base level of understanding we consider anew the challenges for scale-up.

Recent progress on transport through single phosphorus donors

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We report on first spectroscopic measurements of electronic states of individual phosphorus donors employing single-electron tunneling. For various samples, two transitions into the neutral and the negatively charged state are identified together with the corresponding charging energies and capacitances. All features in the transport window are identified, most of which correspond to non-uniform density of states in the leads as detailed studies have shown. We observe also the Zeeman splitting of the ground state degeneracy and map the electron g factor to be 2 within the error estimate.

Silicon single electron devices for quantum information processing

Dr. Marc Sanquer
CEA-Grenoble and coordinator of the AFSID project.

Very small SET can be produced from conventional CMOS FET by a special design of channel junctions to source and drain: tunnel barriers are formed by undoped silicon regions and a quantum dot is created by accumulation of carriers below the gate [1]. The barriers sit below nitride spacers which are used as a mask during source-drain implantation. Therefore a single gate gives a compact, controlled and stable quantum dot (MOS-SET).

In particular the SET is protected from external offset charge dynamics by the wrapping gate on three sides of the dot, the fourth side consisting of an excellent buried oxide.

Using this silicon SET as an electrometer permits the detection of single donors located in the

tunnel barriers. Their occupation number (both in DC and in real time measurements), location and spin could be sensed [2,3].

One of the work packages of the EU founded project AFSID (Atomic Functionalities on Silicon devices) [4] investigates coupled silicon quantum dots made on the MOS-SET techniques as well as a quantum dot with an antenna to serve as a sensitive electrometer for an external system on chip. The first results will be presented as well as the advantages of using a state-of-the-art CMOS platform for building dedicated SET devices in terms of compactness, stability and integration with CMOS electronics.

The research leading to these results has received funding from the European Community's seventh Framework (FP7 2007/2013) under the Grant Agreement nr:2 14989. The samples subject of this presentation have been designed and made by the AFSID Project Partners – www.afsid.eu

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Methods for the Electrical Readout of Nuclear Spin States

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In donor-based approaches to solid-state quantum computation both the electron spins and the nuclear spins of isolated donors can be used to store and process quantum information. For Phosphorus donors in Silicon we have recently demonstrated that the donor electron spin state can be electrically read out employing a spin-dependent recombination process using electrically detected magnetic resonance (EDMR). To manipulate and electrically read the nuclear spin states, we are currently investigating several methods which will be summarized in this contribution. At small external magnetic field strengths comparable to the P hyperfine coupling entangled states between the electron and the P nuclear spin are formed. Under resonant radio frequency irradiation in the MHz region, transitions between these entangled states are induced and can be detected via EDMR. To address 29Si nuclear spins we perform pulsed highfield EDMR measurements on

isotopically enriched 29SiP epilayers. We find a strong decrease of the electrically detected echo decay time in isotopically pure 29Si samples enabling us to electrically measure the spin coherence time of surface near donor electrons.

This work is funded by DFG through SFB 631, project C3, and partially by the JSTDFG Strategic Cooperative Program on Nanoelectronics and by the Grant-in-Aid for Scientific Research #18001002.

Electrically detecting electronic and nuclear spins in silicon

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Spins in silicon are prime candidates for both classical and quantum information processing. A significant challenge remains the ability to read them out, and, subsequently, a way to interface such readout with conventional classical electronics. Recently, numerous spin-to-charge conversion mechanisms have been utilized to undertake such measurements, utilizing standard materials and processing techniques.

In this talk, a number of such mechanisms, and the advantages and disadvantages associated with them, will be discussed. For example, we have recently shown that the spin coherence time of donors near interface defects used as probe spins is limited to ~1μs. Developments associated with the electrical readout of electronic spins will be discussed.

Finally, we will present initial work on the electronic readout of nuclear spin states using pulsed, electrically detected magnetic resonance combined with pulsed nuclear magnetic resonance (pEDENDOR). Briefly, we have successfully detected the signature of both ^{31}P and ^{29}Si nuclear spin ensembles in silicon using a novel pulse sequence. The ability of this technique to be extended to coherent readout, and the utility of this advance for quantum information and basic physics research, will be discussed.

Host silicon isotope effect on ^{31}P ENDOR frequencies

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Pulse EPR and ENDOR spectroscopy of an ensemble of phosphorus atoms in isotopically enriched silicon is reported.

Extremely long coherence times ~300 ms at 6K of electron spins bound to phosphorus and ~3 μs at 6K of ^{31}P nuclear spins have been obtained in an isotopically enriched ^{28}Si single crystal (99.992%). Such long coherence times allow for 10^7-10^8 quantum gate operations within T_2, comfortably satisfying the requirements of error correction algorithms. On the other hand, the ^{31}P nuclear spin coherence times in naturally available silicon containing 4.7% of ^{29}Si nuclear spins are much shorter (~0.5 μs), suggesting that the background ^{29}Si nuclear spins are the dominant decoherence source. According to theory, coherence time of nuclear spins should reach two times relaxation time of electrons ($T_{2n}=2T_{1e}$). Such relation has been confirmed with our isotopically enriched ^{28}Si single crystal with very dilute phosphorus doping ~1×10^{13} cm^{-3}. However, the relation $T_{2n}=2T_{1e}$ breaks down as the phosphorus concentrations is increased from 1×10^{13} cm^{-3} to 4×10^{15} cm^{-3}. Relaxation of electrons via hopping conduction between phosphorus impurities may be limiting the nuclear spin coherence in higher concentration samples.

Another surprising observation is the shift of ^{31}P nuclear transition energies (ENDOR peak positions) as we change the background silicon isotopic composition. Our analysis shows that the four nearest neighbor silicon isotopes of phosphorus affect strongly the nuclear transition energy of ^{31}P. Experimental results will be discussed in the context of isotope effect arising from differences in the nuclear mass and spins.

We thank fruitful discussion with Martin Brandt of Technical University of Munich. This work has been supported in part by Grant-in-Aid for Scientific Research #1 8001002, in part by Special Coordination Funds for Promoting Science and Technology, in part by JSTDFG Strategic Cooperative Program on Nanoelectronics, and in part by Grant-in-Aid for the Global Center of Excellence at Keio University.

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Spin-dependent scattering off Neutral Donors in Silicon Field-Effect Transistors

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Optimal experiment design for parameter estimation as applied to dipole- and exchange-coupled qubits

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Isotopically Engineered Silicon for Quantum Information Technology

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For a number of solid-state quantum computation (QC) schemes, the composition of stable isotopes must be carefully controlled. For example, natural silicon consists of ^{28}Si (92.23%), ^{29}Si (4.67%), and ^{30}Si (3.10%). The nuclear spin carrying isotope ^{29}Si can be regarded as an "impurity" which must be minimized, as in the use of a pure ^{28}Si matrix for 31P electron spin-based QC approaches [1], or precisely controlled, as in the proposal of an ordered array of ^{29}Si [2]. Simultaneous control of both chemical (e.g., dopants) and isotopic composition thus adds a new dimension to bulk and thin film Si technology.

The synthesis strategy to make isotopically enriched dislocation-free bulk single crystals and thin film structures will be described. For bulk crystal synthesis, a silane-based process compatible with the relatively small amounts of isotopically enriched precursors that are practically available was selected. In this approach, silane is decomposed to poly crystalline in a recirculating flow reactor with a silane to Si conversion efficiency exceeding 95%. Subsequent float zone processing produces single crystals of Si enriched in all three stable isotopes: ^{28}Si, 99.92%; ^{29}Si, 91.37%; and ^{30}Si, 89.8%. Thin films of the same isotopic composition can be grown by chemical vapor deposition. We will show that high chemical purity is maintained throughout the processing. The concentrations of shallow dopants P and B are as low as mid-10^{13} cm^{-3} and concentrations of C and O can be lower than 10^{16} and 10^{15} cm^{-3}, respectively.

It has been known since the invention of electron spin resonance spectroscopy that the $T2$ of the electron bound to 31P is increased in ^{28}Si enriched material due to depletion (derichment) of ^{29}Si with its spin carrying nucleus (1/2+). In this context, pulsed ESR measurements on a ^{28}Sienriched single crystal sample produced in this work holds the current "world record" with a $T2$ at 10 K of 5 ms [3]. We have recently lowered the P concentration in our ^{28}Si-enriched bulk crystals by a factor of ~10 by repeated zone-refining. This material has been used to demonstrate quantum memory storage with a $T2$ of over 1 second using coupling of the 31P electron and nuclear spins [4].

While these long coherence times are impressive, they are not yet at the limits suggested by the $T1$ timescale. In fact, the source(s) of decoherence which limits the electron (and, even more so, the 31P nuclear spin) are not well understood at this point. Isotopically controlled structures and experimental approaches to address this challenge will be described

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Solid State quantum memory using the nuclear spins in silicon

J. J. L. Morton, Oxford University

Optical Transitions of the ^{31}P Bound Exciton in ^{28}Si for Reading and Hyperpolarizing the Donor Electron and Nuclear Spins

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Enriched ^{28}Si is the material of choice for Si based quantum computing due to the absence of nuclear spin, but it has a number of other remarkable properties which may find applications in this field. We have found that many optical transitions are much sharper in ^{28}Si than in natural Si, due to the elimination of inhomogeneous isotope broadening. In particular we have found that the donor hyperfine splittings can be resolved in the donor bound exciton spectrum, allowing for the optical determination of the donor electron spin and nuclear spin.[1] More recently we have shown how the same transitions can be used to quickly hyperpolarize both the donor electron and nuclear spin.[2] I will discuss progress in using these transitions to perform NMR on dilute ^{31}P in ^{28}Si, and the possibility of using these same transitions to make measurements on a single ^{31}P.

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Stark effect for Si:Li spin qubits

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We study the effect of a static electric field on lithium donors in silicon. Friesen [1] demonstrated that there are two mechanisms which determine the behavior of electron levels in the *1s* manifold of a shallow donor in Si. These mechanisms are the quadratic Stark shift and manifold spectrum narrowing. For a lithium donor, the manifold spectrum narrowing is predicted to be less significant than the quadratic Stark shift. The anisotropy of the effective mass in a single valley leads to an anisotropy of the quadratic Stark susceptibility. We demonstrate this anisotropy using large-basis variational method calculations similar to those used by Faulkner [2], and we consider the valley-orbit effects using a perturbational method. The anisotropy of the Stark susceptibility causes a nontrivial interplay of the Stark and Zeeman effects which could be used to manipulate

and control Si:Li spin qubits.

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Single ion doping of spin readout transistors

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Quantum computation has the potential to revolutionize science and technology since it could solve problems that any classical computer fails to handle. Novel device concepts can be implemented if a single dopant is used as the functional part of the device itself instead of just providing charges as with classical devices. There exist several proposals to achieve this goal. Among them is Kane's proposal of a quantum computer based on donor spin qubits in silicon devices integrated with control gates and readout structures [1]. Another approach uses electron spins of nitrogen vacancy (NV) centers in diamond [2]. Control of precise ion implantation is needed to realize and validate basic ideas and development of both architectures. We try to achieve this goal with our ion implanter, which features a surface probe microscope with an aligned ion beam [3]. Our work focuses on the implantation of field effect transistors which are also used for the development of a single spin read out mechanism [4]. Changes in device currents are used to detect single ion impacts [5] and to test and improve our implant precision [6]. Further, ways to improve the low nitrogen vacancy formation (few per cent) is studied by implantation of nitrogen into diamond [7].

Acknowledgments:
This work is supported by NSA under Contract Number MOD 7131 06A, the National Science Foundation through NIRT Grant No. CCF-0404208 and by the Director, Office of Science, of the Department of Energy under Contract No. DE-AC02-05CH1 1231.

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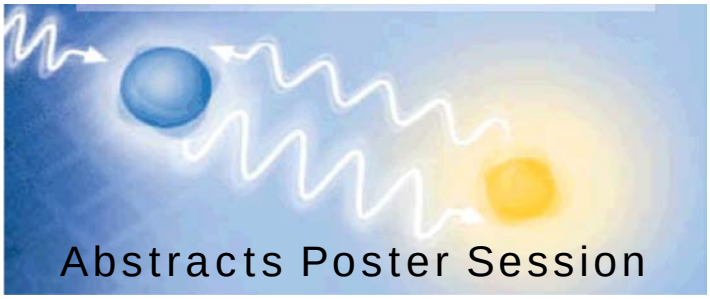

Development of Self-Aligned Single Donor Implanted Lateral Double Quantum Dots

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Fabrication of single donor devices for quantum bits (qubits) has been an elusive goal to date. A contributing factor is that many proposed geometries require highly accurate control of the donor position. In this work, we present progress on the development of single donor implanted double-quantum-dots. This device geometry is intended to relax the donor placement requirements through mediating many qubit operations with the quantum dots (e.g., spin read-out and exchange).

The proposed single donor implanted double-quantum-dot requires the development of several critical elements: (a) quantum dots and charge sensors; (b) single ion detectors; (c) single ion detector integration with the quantum dot fabrication process; and (d) a focused ion beam to implant multiple locations with only one e-beam lithography step. Ion beam development has focused on a new micro-beam at Sandia with ultimate resolution of <l00 nm. Single ion detection has concentrated on the development of a single ion Geiger mode avalanche (SIGMA) diode detector to allow for lower energy (less straggle) ion implantations while assuring single ion arrival. We have demonstrated 100% detector efficiency to single ion strikes at 77K for both direct and diffused carriers. Finally, we have also done timed implants into tunnel barrier regions of silicon quantum dots in order to examine the viability of this combined process flow for future donor spectroscopy measurements.

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Density Functional Theory modeling of delta-doped phosphorus in silicon

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Density Functional Theory models of 0.25 monolayer phosphorus in silicon using various functionals were constructed and contrasted. Measures of efficacy included the amount of surrounding silicon ”cladding” required to converge several properties to stable values, and direct comparison of these values to experimental data.

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Towards a single P donor in silicon

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Towards the goal of realizing single dopant based qubits in silicon, we demonstrate the fabrication of STM-patterned planar quantum dots, consisting of ≤7 phosphorus donors. Low temperature transport through such devices shows stable Coulomb oscillations with typical charging energies exceeding tens of meV. Bias spectroscopy of a dot with ~7 donors shows a dense spectrum of excited state resonances. Based on effective mass calculations, these resonances are attributed primarily to valley splitting of the orbital states within the quantum dot. Transport through an even smaller dot reveals excited state resonances consistent with a single phosphorus donor in silicon. Additionally, we investigate the possibility of integrating schemes for non-invasive detection of single donor charge/spin states, in our planar fully-epitaxial, STM-patterned device architecture. We also present statistical analysis of phosphorus incorporation in silicon at the extreme limit of sub-nanoscale STM lithography. Such studies were performed with the aim of atomically precise positioning of phosphorus in silicon, for future donor-based devices.

Protecting Quantum Information with Optimal Control

Matthew Grace, Sandia National Laboratories

Methods of optimal control are applied to elements of a quantum information processor (QIP), providing solutions for the generation of logical operations and the suppression of undesired environmental effects. The results illustrate how practical quantum computing can be greatly facilitated by optimal control theory and reveal interesting physical insights through the discovery of effective control mechanisms. Optimization algorithms are developed which generate controls that protect the QIP from the effects of the environment, and simultaneously achieve a target objective, e.g., a state-to-state transition or unitary quantum operation. We considered different types of environments producing either reversible or irreversible dynamics. The resulting optimal controls cleverly identify and use various properties of the composite system to effectively attain the desired objectives. Controls obtained for systems with reversible dynamics utilize induced coherence revivals and are robust to random variations in system-environment coupling strengths. For irreversible dynamics, the controls employ decoherence-free states and are practically insensitive to the structure of random environments. Potential applications of optimal control theory to silicon-based quantum computation for designing logical operations and minimizing decoherence will also be presented.

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Electron Spin Resonance in Modulation Doped Si/SiGe Heterostructures with Large Area Gates

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A large area electrostatic gate was fabricated on modulation doped SiGe/Si/SiGe heterostructures in order to manipulate electron density in a controlled way. The gate structure consists of 100 nm of Al_2O_3 deposited by atomic layer deposition (ALD) and electron-beam evaporated aluminum. The gate exhibits low leakage even over an area of several square millimetres. The intensity of the electron spin resonance (ESR) signal originating from the Si quantum well was measured in a conventional X-band ESR spectrometer. This signal depends strongly on the gate voltage. Its amplitude remains constant at large positive gate voltages, and drops almost linearly when the voltage is lowered below 0 V. At -2 V the signal vanishes completely, which indicates a complete depletion of electrons in the quantum well. The temperature dependence of the spin resonance was investigated at several gate voltages and indicates that electrons may undergo a transition from a mobile 2D system under positive gate voltage to states confined by intrinsic disorder in the quantum well under negative gate voltage.

Optimal coupling between an LC resonator and an electric or magnetic dipole qubit

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In the present work we attempt to optimize the coupling strength between a superconducting LC resonator and a qubit with an arbitrarily-sized electric or magnetic dipole moment. The coupling strength is a direct measure of the rate of conversion of quantum information between the state of a qubit and the state of a photon, which is used to communicate this information to another qubit. The current state of the art superconducting resonator for coupling to qubits is the transmission line resonator. It is typically used with superconducting qubits, which couple well to the resonator only because they have large dipole moments. However, superconducting qubits are exceedingly large and their fidelity is not as high as desired. Thus we seek to design an optimal resonator that will couple well to a qubit with any dipole strength.

We define a figure of merit to show that, at a given frequency, the resonator with the highest impedance (defined as the square root of the ratio of lumped inductance to lumped capacitance) couples best to electric dipoles, while the resonator with the lowest impedance couples best to magnetic dipoles. We postulate that a single-layer solenoid is an optimal resonator for coupling to electric dipoles. Even with a planar structure that is designed for ease of fabrication, we achieve a figure of merit ~150x larger than for a standard 50Ω transmission line resonator coupling to an electric dipole at 10 GHz. For coupling to a magnetic dipole, a parallel-plate resonator is optimal, and at 10 GHz we achieve a figure of merit ~l00x bigger than for a 50Ω transmission line resonator.

Quantum search with Decoherence

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Decoherence is often considered to be the bane of quantum information tasks. It typically devolves coherent quantum states into mixtures which do not provide any computational benefit over classical computation. In this talk we consider whether decoherence can ever be useful for quantum information processing tasks. In particular we show how a contrived dephasing process could be used to drive a quantum mechanical search.

Metal-oxide-semiconductor single-electron transistor in pure silicon

B. Hu, University of Maryland

SiGe Quantum Dot Structures: Effects of Inter-Valley Mixing on Qubit Operation

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We have analyzed the effects of valley degeneracy and valley mixing on single- and few-electron states in (001) electrostatically defined Si/SiGe quantum dots (QDs), relevant to our efforts on SiGe-based accumulation-mode QD structures. Specifically, we focus here on configuration interaction (CI) calculations of addition energies, multi-electron excitation spectra (both with and without substantial inter-valley mixing), and estimates of inter-valley relaxation times. We have successfully validated our models by comparison with recent experimental data from our group on SiGe QDs, in which good correspondence is generally found. The shell structure observed in the spacing of consecutive charging events in SiGe QDs exhibits a striking contrast to what we typically calculate or obtain experimentally in III-V QDs. It provides clear evidence of a higher-level degeneracy that allows for an increased occupancy for each QD orbital.

Qualitative analysis suggests that interface steps and variations in interface quality can dramatically modify valley-induced effects; hence in our numerical simulations, we explicitly allow for an arbitrary and spatially inhomogeneous stacking of heterolayers in the active area of the device. In particular, we report here on the structure of few-electron states in both single and double SiGe QD structures taking into account the oscillatory behavior of exchange coupling in the presence of nonplanar heterointerfaces.

We have also considered various mechanisms of inter-valley relaxation in (001) electrostatically-defined SiGe QDs and evaluated their characteristic times.

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SOS Current Mirror Matching at 4K: a brief study

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Current architectures for the control and readout of silicon qubits often involve the use of classical CMOS electronics used at temperatures below 4K. Fully depleted silicon on insulator CMOS is a

primary candidate for such electronics as they are less affected by low temperature bulk induced hysteresis and kink effects and have lower parasitic capacitances than their bulk counterparts. While MOS transistors are known to work at low temperatures, a hitherto unexplored maxim of integrated circuit design is the use of matched components at low temperatures. In this study, we investigate the effect of low temperature operation on the matching in CMOS current mirrors: we compare measurements of the low frequency accuracy in a silicon on sapphire mirror at 300K and 4K. We find that mirror mismatch increase by roughly a factor 2–3 from 300K to 4K; thus while matching is reduced at low temperatures, circuit structures relying on matching components can still be employed at low temperatures albeit at reduced performance.

The impact of classical electronics constraints on a solid-state logical qubit memory

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Thomas M. Gurrieri, Robert D. Carr, Malcolm S. Carroll
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We describe a fault-tolerant memory for an error-corrected logical qubit based on silicon double quantum dot physical qubits. Our design accounts for constraints imposed by supporting classical electronics. A significant consequence of the constraints is to add error-prone idle steps for the physical qubits. Even using a schedule with provably minimum idle time, for our noise model and choice of error-correction code, we find that these additional idles negate any benefits of error correction. Using additional qubit operations, we can greatly suppress idle-induced errors, making error correction beneficial, provided the qubit operations achieve an error rate less than 2 x iO. We discuss other consequences of these constraints such as error-correction code choice and physical qubit operation speed. While our analysis is specific to this memory architecture, the methods we develop are general enough to apply to other architectures as well.

Online version of paper at http:Ilarxiv.orgIabsIO9O4.0003.

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Classical Electronics Constraints on Solid-State Qubits

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While designing and fabricating quantum hardware (qubits) is a herculean effort in itself, it is only one part of the puzzle to creating robust, high accuracy quantum circuits. Another piece of that puzzle is the classical electronics used to bias, control, and measure the qubits. The classical

circuits that perform these operations, such as pulse generation and a variety of read-out techniques, require precise timing, voltage and current control and carry with them their own set of constraints and limitations that will affect qubit operation. We examine the impact of the electronics on the error probability of a logical qubit memory for a particular solid-state architecture. The qubit used in this work is a double quantum dot (DQD) enhancement mode silicon structure, which is being pursued in order to migrate the GaAs DQD qubit, demonstrated by Petta et. al. [1], to silicon. Complementing the experimental work by Petta et al., Taylor et al. [2] proposed an architecture based on singlet-triplet encoding of two spins. The Taylor architecture was modified, in this work, for the proposed silicon enhancement mode DQD approach [3] and we extend the analysis to consider routing density, qubit density, cryogenic-staging, bandwidth, cross-talk, charge injection, voltage, current and timing precision, and how these manifest themselves as constraints on scheduling a logical qubit as well as guidance about the choice of read-out circuitry and transport for a particular algorithm and lay-out. In support of this analysis, theoretical estimates of Si DQD qubit gate operation and noise models were also developed and are discussed elsewhere [4]. The results show that for a Bacon-Shor error correction code utilizing 9 data and 12 ancilla qubits the addition of classical electronics constraints decreases the threshold due to additional idle times required to meet the electronics constraints.

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Development and Characterization of FinFets for Donor Spin Qubit Readout

C. C. Lo, Lawrence Berkeley National Laboratory and UC Berkeley

Electrical characterisation of MOS structures for silicon-based quantum computer device fabrication

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Solid-state quantum computers require spin readout and control in order to transfer information to and from spin-encoded electrons or nuclei. They also require enormous care to be used in the choice of device processing parameters in order to minimise defects both within the bulk and at the dielectric-semiconductor interface. This presentation outlines some of our electrical characterisation studies of defects in MOS test capacitors. These measurements have been used to optimize the fabrication strategies for some of our devices. As an example, we will present results for arsenic implanted MOS capacitors. These are being used to find optimum processing conditions to fabricate MOS Field-Effect Transistors for Electrically Detected Magnetic Resonance studies of the hyperfine states of implanted arsenic donors.

Probe and control of the reservoir density of states in single-electron transistors

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We present a systematic study of quasi-one-dimensional density of states (DOS) in electron in accumulation layers near a $Si/Si0_2$ interface. In the experiments, we have employed two conceptually different objects to probe DOS, namely, a phosphorus donor and a quantum dot, both working as single-electron transistors. We not only present results consistent with the theory, but also show how the peaks in DOS can be moved in the transport window independent of the other device properties. This method provides a fast and convenient way of characterizing excited states in these emerging nanostructures.

Charge detection in intrinsic silicon quantum dots

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We describe charge sensing measurements on a gate defined silicon quantum dot with a nearby single electron transistor (SET) acting as an electrometer. Silicon quantum dots are an excellent candidate system for the implementation of a quantum computer, due in large part to the expected long electron spin coherence time. For the purpose of quantum information processing the few-electron regime is of particular interest. However in this regime the electrical currents that pass through the device can be very small, and as such are difficult to measure with conventional techniques. In this case, a nearby charge sensor becomes an invaluable tool, offering a method to detect the charge occupancy of the quantum dot.

In our device both the quantum dot and SET are electrostatically formed in bulk intrinsic silicon using two layers of surface gates [1]. A two-dimensional electron gas (2DEG) is formed by applying a positive top gate potential, whilst two lower gates (barrier gates) are used to deplete the 2DEG, creating the tunnel junctions. For ease of fabrication, in this device the barrier gates are shared by both the SET and the quantum dot. The device dimensions are largely determined by the geometry of the top gates and barrier gates, resulting in dot sizes of approximately 50 x 85 nm, with an SET to quantum dot separation of 125 nm.

Electrical measurements are performed at <50 mK. The barrier potentials are tuned so that both devices exhibit Coulomb oscillations with respective top gate voltage. The charge sensing experiment consists of simultaneous transport measurements of both the SET and quantum dot. We show that as an additional electron is added onto the quantum dot, seen as a peak in the quantum dot transport current, this electron is detected in the SET as a shift in the Coulomb blockade oscillation of approximately 0.2 e. The constraints imposed by the common barrier gates mean that these measurements are performed in the many electron regime, where we can count in excess of 20 charge additions onto the quantum dot. Having demonstrated this proof of principle device, we plan to modify the device design to enable the single electron regime to be accessed.

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Precision control of tunneling in STM-patterned Si:P devices

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Controlling the tunneling resistance in STM-patterned Si:P devices is a key requirement towards the goal of fabricating Si:P qubits with atomically precise architectures. We have exploited the unique advantage of STM lithography, where we know the precise location of the dopants, to investigate systematically the effects of device geometry on the resistance Si:P tunnel barrier devices. We have characterized the electronic transport of Si:P tunnel gap devices with gap-size *d* and leads/width *w* in the 10-90 nm and 5-30 nm range respectively. For devices with wide leads ($w > 16$ nm), increasing the gap size from 10 to 90 nm, the tunnel resistance increases eight orders of magnitude from 10^4 Ω to 10^{12} Ω, changing the tunnel barrier from transparent to opaque. This dependence is enhanced for devices with narrow leads ($w < 16$ nm), which show the same variation resistance over a smaller tunnel gap width range (10-20nm).

We subsequently control the tunnel gap resistance using three different gating architectures: in-plane gating with STM patterned phosphorus-doped leads; surface gating with a native SiO_2 dielectric and surface gating with a low temperature, SiO_2 dielectric deposited in UHV. The latter architecture allows maximal control over tunnel resistance due to the large electric field (2 MV/cm) sustained by the surface dielectric before leakage. By increasing the top gate from 0 to +10 V we demonstrate tuning of the Si:P tunnel gap resistance by three orders of magnitude.

Following these results, we investigated the combination of in-plane and surface gates on a low temperature dielectric to tune tunneling in STM-patterned Si:P quantum dots. We fabricated a planar Si:P quantum dot containing ~750 electrons. Electrical characterization at 4K shows that applying a negative top gate voltage to the device we can tune the tunnel barriers from transparent to opaque and control the resistance through the quantum dot by an order of magnitude. Finally we discuss the benefits of a combined in-plane/top-gate approach to the control of transport in STM-patterned Si:P devices.

Coherent electron transport by adiabatic passage in a triple donor system with imperfect donor placement

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A solid-state analog of stimulated Raman adiabatic passage can be implemented in a triple-well solid-state system to coherently transport an electron across the wells with exponentially suppressed occupation in the central well at any point in time. Termed coherent tunneling adiabatic passage (CTAP), this method provides a robust way to transfer quantum information encoded in the electronic spin across a chain of quantum dots or donors. Using large-scale atomistic simulations involving over 3.5 million atoms, we verify the existence of a CTAP pathway in a realistic solid-state system: gated triple donors in silicon. Realistic gate profiles from a commercial Poisson solver were combined with the tight-binding method to simulate gate control of tunnel barriers in the presence of crosstalk. Our results show that a three-donor CTAP transfer, with inter-donor spacing of 15 nm can occur on timescales greater than 23 ps, well within experimentally accessible regimes. We also investigate the effect of straggle on the adiabatic path, and present control schemes to correct for such imperfect donor placements.

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Raman Spectroscopy of Si:P System

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Raman spectroscopy is well known for its ability to study lattice vibrations in semiconductors (i.e. phonons) however, it can also be used to probe dopant states. The one photon forbidden absorption of phosphorus donors from the lowest energy singlet $1s_{(A1)}$ to the doublet $1s_{(E)}$ state can be probed using the electronic Raman scattering technique. Changes to the line-width and peak position of this transition in moderately phosphorus doped ($2x10^{16}$ P $cm^{-3}$and $1x10^{17}$ P cm^{-3}) silicon have been observed as a function of both donor concentration and temperature (>100K) where thermal ionisation of donors is known to occur. We attribute these changes to Stark broadening (with possible shifting) of the neutral donor levels caused by inhomogenous (intrinsic) electric fields arising from neighbouring ionised donor atoms in the silicon lattice. In addition, photo-excitation of the donor ground state is accompanied by the simultaneous emission of an intervalley phonon. The electron-phonon interaction is evidenced by a Fano resonance giving rise to an asymmetric lineshape to the donor transition.

Tunnelling Spectroscopy of Individual Implanted Phosphorus Donors in Silicon

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Introduction: The ability to confine, manipulate and measure electrons localized on phosphorus (P) donors is a key ingredient for realizing a Si:P quantum computer [1]. Recent developments in metal-oxide-semiconductor (MOS)-compatible nanostructures in silicon[3] integrated with single-ion detection capabilities [4] hold promise for the realization of dopant-based spin qubits in silicon. Expected long spin coherence times [5] render this scheme very attractive. Studies of dopant spectroscopy have been carried out on a variety of different nanostructures [6-8] but the presence and position of the donors were always random. Hence, as a crucial intermediate step towards the realization of Si:P spin qubits, a double-gated nano-field-effect-transistor (nanoFET) with a few P donors deterministically placed into silicon was utilized to study the charge and spin states of individual P atoms.

Methods: The tuneable nanoFET [Fig.1(a)] described in this paper consists of two independent aluminium gates: (i) A top gate that is used to induce a two dimensional electron gas (2DEG) for transport from source to drain; (ii) A barrier gate that depletes electrons in the active area of the 2DEG, hence creating tunnel barriers [Fig. 1(c)]. This allows the electrical manipulation of the neutral state (D^0) and the first charged state (D^-) of individual phosphorus donors under the barrier gate. In particular, the barrier gate can be used to tune the donor states in resonance with the source and drain 2DEG, enabling electron transport to occur.

Results: Two samples (referred to as sample A and B) with implanted donors have been measured. Figure 2(b) show the source-drain differential conductance of Sample A as a function of the dc source-drain voltage and the barrier gate voltage, with a top gate voltage fixed to 3.5 V. Sharp conductance peaks are clearly observed before the barrier turn-on of the channel. These features are signatures of resonant tunnelling through discrete energy levels of the donors. Figure 2(a) shows the stability diagram of a control device with no implants. It is significantly different from the data obtained with donors in the active region in the sense that there are no conductance features that can be attributed to discrete energy states, reinforcing the interpretation that the observed peaks are evidence of resonant tunnelling through implanted P donors.

The stability diagram of Sample B is presented in Figure 3(a). Here, a pair of $D^0$and D^- (neutral and charged) states, denoted by d1 and d2 is highlighted. Figures 3(b)-(e) consist of a set of stability diagrams of peak d1 at 0, 2, 4, and 6 T magnetic fields. The energy splitting is indicated by red (green) arrows which correspond to resonant tunnelling through the spin-down (-up) state of the D0. We obtain a g-factor of 1.811 ± 0.465 from the spin-splitting in Figure 3 (b)-(e), consistent with the g-factor of 2 for electrons in silicon. Also, the D^0 to D^- charging energy of 34 meV deduced from measurement is in agreement with simulated results.

Conclusion: Resonant tunnelling of electrons through D^0 and D^- states of individual phosphorus donors in silicon has been observed via transport spectroscopy. The charging energies of the donors and their magnetic field dependence are consistent with the values expected for P donors in a gated nanoFET structure. Furthermore, control devices without phosphorus donors showed none of the resonant tunnelling features that could be seen in identical donor-implanted nanoFET structures.

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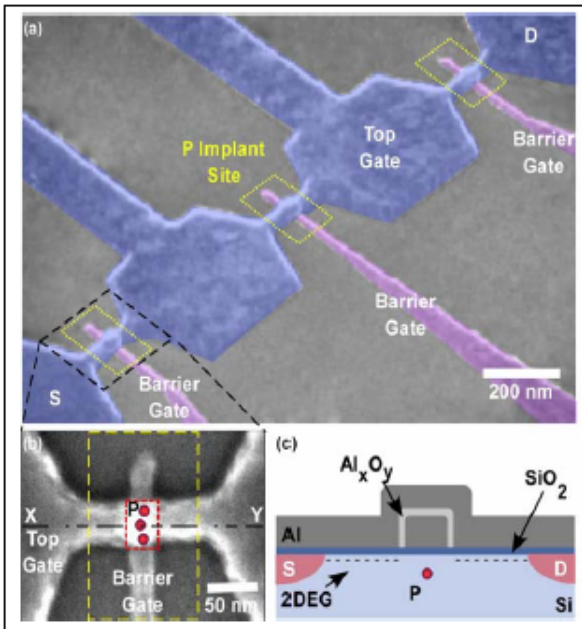

Fig.1. (a) Coloured SEM image of tri-barrier transport device. Suitably applied voltage on the top gate induces a two dimensional electron gas (2DEG) reservoir that extends to diffused source-drain ohmic contacts. Barrier gates that are overlapped by the common top gate allow electrical control of donor energy levels and, depending on the applied voltage on these barriers, the chemical potential can be brought into resonance with Fermi levels of adjacent reservoirs. (b) Zoomed-in SEM image of a transport device. Yellow dashed line indicates the P implant window and red dotted line indicates the active region where expected number of donors is three. (c) (Not to scale) Schematic cross section of a transport device along line XY in panel (b).

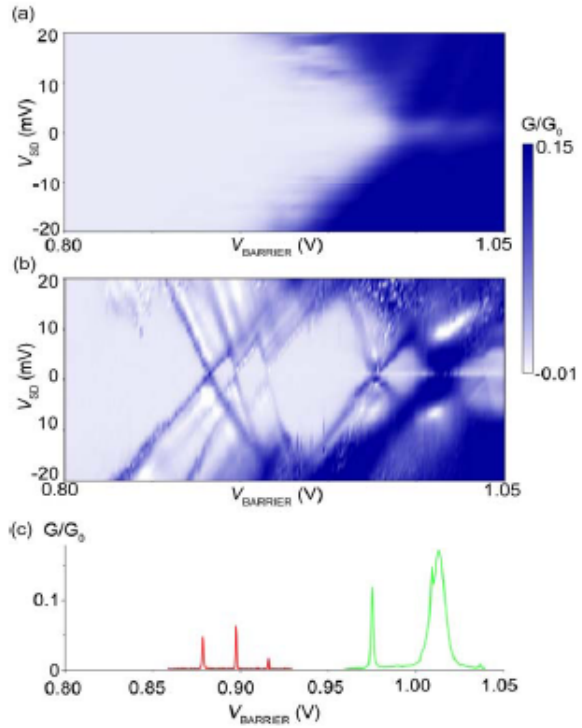

Fig.2. (a) Stability diagram showing differential conductance as a function of barrier gate and dc source-drain (SD) bias of a control device with no implanted phosphorus (P) donors. (b) Stability diagram of Sample A containing approximately 3 P donors in the active region. Here, G_0 is the conductance quantum. (c) A cut of the stability diagram in panel (b) at V_{SD} = 0 V highlighting the resonant tunnelling peaks associated with P donors.

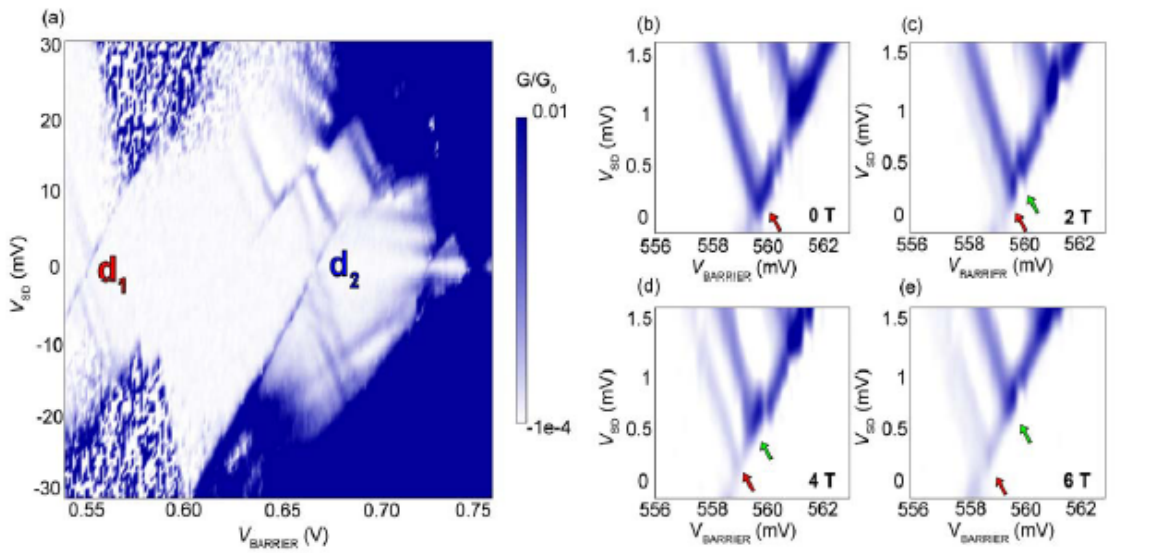

Fig.3. (a) Stability diagram showing differential conductance as a function of barrier gate and dc SD-bias of Sample B. (b)-(e) Detailed stability diagram of peak d_1 at B=0, 2, 4, and 6 T. Red (green) arrows indicate spin-down(-up) states.

Back End Processing and CV Characterization for Qubit Devices

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Silicon Quantum Dot fabrication for qubits requires a minimum of defects to produce clean quantum dots and barriers. Identifying sources of defects in the process flow is critical for this goal. Characterization of oxide quality with C-V and mobility measurements therefore assists in optimization of the device fabrication processes as well as providing quantitative estimates of the defects, which provides guidance to design and modeling efforts. Correlating these measurement results with specific fabrication steps enables iterative process improvements and the creation of a stable process flow. In this presentation, we report on the impact of several critical process steps, including poly-Si etch, top gate metallization, atomic layer deposition of dielectrics, and various anneals.

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Coulomb Blockade Transport though Unintentional Defects in a Silicon FinFET

Ted Thorbeck, JQI – NIST and University of Maryland
Neil Zimmerman, NIST
Akira Fujiwara, Yukinori Ono, Yasuo Takahashi & Hiroshi Inokawa, NTT

Silicon finFETs have received a lot of attention recently as a useful structure for silicon quantum computation. Our devices consist of a mesa-etched silicon nanowire with two layers of polysilicon gates: an upper gate to invert the device and a set of finFET-like lower gates used to create tunnel barriers. While most of our devices create defect-free tunnel barriers, we will focus on a device that shows a very interesting set of unintentional Coulomb blockade peaks. Despite creating only a single intentional tunnel barrier, the pattern of current through the device appears to be caused by multiple unintentional coupled islands. Unlike most defect-dominated devices, the pattern of current peaks is regularly spaced over more than fifty periods. Given that we rarely observe defect dominated tunnel barriers, combined with this observation of multiple islands suggests the islands have a common cause. In addition the islands have very different charging behaviors leading to very different numbers of electrons on the islands, ranging from a few electrons to more than fifty. Details of the transport and our thoughts on a model for the data will be presented.

Two dimensional electron transport and RF measurements for Si quantum computing

L. A. Tracy, Sandia National Laboratories

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Progress in deterministic doping of single atoms in Si

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Deterministic doping via ion implantation requires confinement of the ion beam, the ability to register the position of the ion beam on the substrate surface and the ability to detect a single ion entering the Si substrate. We routinely detect single 14keV P^+ ions entering a p-i-n doped Si substrate, recently with the addition of a p-doped guard ring for the reduction of surface leakage in subsequently fabricated devices. Sub-100nm confinement of the beam is achieved with a specifically fabricated nano-aperture. The scattering of 0.5 MeV He^+ from such apertures has been investigated. Confinement of keV ions has been shown through the irradiation of PMMA with 14keV Ar^+ and the implantation of 14 kev P^+ into Si. The registration of position has been demonstrated to 100nm using the same mechanism as single ion detection.

Error threshold simulations of surface and colour codes

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Quantum error correcting codes based on topological quantum computation has been shown to be able to tolerate high physical error rates. We will consider two such codes that may be implemented on two dimensional arrays of qubits with only local interactions. First, the surface code for its remarkable simplicity, and second, the colour code which is able to implement all Clifford group gates without the need for state distillation. The surface code has a threshold error rate of approximately 1%, while the colour code has threshold of approximately 0.1%.

Decoherence Induced by Dangling Bond Spins at a $Si/Si0_2$ Interface

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Even at relatively low densities (10^{11} - 10^{12} / cm^2), dangling bond spins at defects on a $Si/Si0_2$ interface can be a significant source of decoherence. Experiments [T. Schenkel *et al*, Appl. Phys. Left. **88,** 112101 (2006)] on Sb donor electron spins demonstrate sub-millisecond T2 decoherence times that may be prolonged by increasing donor depth or passivating the Si surface with hydrogen. A previous theory [R. de Sousa, Phys. Rev. B 76, *245306* (2007)] based upon 1/f noise fails to explain these decoherence times at physically realistic dangling bond spin densities. Here we demonstrate a stronger decoherence mechanism based solely upon dipolar interactions among electron spins (dangling bonds and the qubit). Although our mechanism is simply defined, it requires the use of recently developed [W. M. Witzel, R. de Sousa, and S. Das Sarma, Phys. Rev. B 87, 052106 *(2005)*, W. Yang and R.-B. Liu, Phys. Rev. B 78, 085315 (2008)] cluster expansion techniques and new variants/strategies to compute the resulting decoherence dynamics.

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

A single-electron Si metal-oxide-semiconductor quantum dot

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We report low-temperature electronic transport measurements of quantum dots in Si metal-oxide-semiconductor (MOS) nanostructures, revealing the observation of the last electron leaving the dot. Based upon recently developed double-gated silicon quantum dots we have made a novel design, where the gates that define the quantum dot are made of three Al layers. This layout allows independent control of the potential of the island, without affecting the electron density in the source and drain reservoirs. Bias spectroscopy measurements show single quantum dot behaviour as evidenced by regular closed Coulomb diamonds. By driving the gate voltage towards less positive values we are able to deplete the dot before the tunnel barriers become too opaque to block ground state transport. Magnetospectroscopy of the spin ground states reveals that first two charges entering the dot are spin-down electrons. The experimental realisation of a single-electron quantum dot which is compatible with current day MOSFET standards is an important step towards scalable spin-based quantum bits.