Abstracts DAY ONE

Single-shot readout and microwave control of an electron spin 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 and relaxation times in bulk [1], and several architectures have been proposed to integrate donor spin qubits with classical silicon microelectronics [2]. Here we show the first experimental proof of single-shot readout of an electron spin in silicon. This breakthrough has been obtained with a device consisting of implanted phosphorus donors, tunnel-coupled to a silicon Single-Electron Transistor (Si-SET), where the SET island is used as a reservoir for spin-to-charge conversion [3]. The charge transfer signals are exceptionally large, and allow time-resolved measurements of spin-dependent tunneling on a < 10 microseconds scale, with readout fidelity better than 90%. By measuring the occurrence of excited spin states as a function of wait time, we find spin lifetimes (T_1) up to ~ 6 s at B = 1.5 T, and a magnetic-field dependence $T_1^{-1} \propto B^5$ consistent with that of phosphorus donors in silicon [4].

In a subsequent experiment we have integrated the single-shot spin readout device with an on-chip microwave transmission line for coherent control of the electron spin. We have detected the spin resonance of a single electron, and observed two hyperfine-split resonance lines. Further experiments are underway to demonstrate coherent spin control and observe Rabi oscillations. This constitutes the first demonstration of microwave control of a single spin, detected electrically with single-shot spin readout.

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Transport and electrically detected magnetic resonance measurements of few donor semiconductor nanostructures

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We report on our progress in developing few donor semiconductor nanostructures and measurement techniques for single donor electron spin detection and control. We have developed triple-gate FinFET devices with a few implanted donors, and low temperature transport measurements have been carried out to identify signatures of donor mediated transport [1]. We have also performed electrically detected magnetic resonance in a W-band (100GHz) microwave resonator, and show that the donor resonance line intensities are much enhanced compared to X-band (10GHz) measurements [2]. Selected devices are designed for compatibility with single donor implantation sensing via the detection of changes in the device current [3, 4].

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Excited states and valley effects in a negatively charged impurity in a silicon FinFET

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The observation and characterization of a single atom system in silicon [1,2,3] is a significant landmark in half a century of device miniaturization, and presents an important new laboratory for fundamental quantum and atomic physics. We compare with multi-million atom tight binding (TB) calculations the measurements of the spectrum of a single two-electron (2e) atom system in silicon – a negatively charged (D-) gated Arsenic donor in a FinFET. The TB method captures accurate single electron eigenstates of the device taking into account device geometry, donor potentials, applied fields, interfaces, and the full host bandstructure. In a previous work [1], the depths and fields of As donors in six device samples were established through excited state spectroscopy of the D0 electron and comparison with TB calculations. Using self-consistent field (SCF) TB, we computed the charging energies of the D- electron for the same six device samples, and found good agreement with the measurements. Although a bulk donor has only a bound singlet ground state and a charging energy of about 40 meV, calculations show that a gated donor near an interface can have a reduced charging energy and bound excited states in the D- spectrum. Measurements indeed reveal reduced charging energies and bound 2e excited

states, at least one of which is a triplet. The calculations also show the influence of the host valley physics in the two-electron spectrum of the donor.

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Quantum interference and many-body effects in a double donor system

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In recent years, an increasing number of experiments presenting donor transport in different architectures appeared. These systems are stepping-stones towards donor based quantum computing. Understanding the charge transport is crucial to infer the intrinsic electronic properties of these systems. Not only is it important to understand sequential electron transport, but also higher order tunneling processes and correlation effects. We present a detailed analysis of the charge transport in a double donor system embedded in a nanowire transistor. Low temperature electronic transport data yields information about the way the donors are coupled and the role of coherence and many-body effects in this system. For example, we observe a Fano resonance, which originates from the presence of phase coherent electron transport between two donors. This Fano resonance is tunable, i.e. the symmetry of the resonance in gate voltage alternates with magnetic field. This is explained as follows, a net magnetic flux pierces trough a loop enclosed by two current paths connecting the donors to the lead and effectively tunes the accumulated phase for electrons going different ways around. Away from the Fano resonance a Kondo effect produces the well known zero bias feature. Surprisingly, this feature is first monotonously suppressed and then enhanced again magnetic field. This upturn of the Kondo conductance corresponds to a symmetry flip of the Fano resonance, suggesting a common origin. We speculate that the Kondo effect is, at least partly, due to an orbital Kondo effect, in a similar way in which it can occur in double parallel quantum dots, involving both donors and the leads. These experiments illustrate the importance of higher order contributions to the tunneling current

in a coupled donor system. A thorough understanding of these coherent virtual processes may lead to novel, robust electrons manipulation schemes.

Transport and charge sensing in donor-based qubit architectures realized by STM lithography

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The spin states of a single electron bound to a shallow donor in silicon (Si) represent a promising two-level-system for realizing semiconductor quantum bits (qubits) [1-3]. Due to a weak spin-orbit coupling and zero nuclear spin of the more abundant ^{28}Si isotope, electron spins in silicon have extremely long coherence and relaxation times. These favorable features have motivated immense research efforts to realize donor-based scalable quantum information processing schemes in silicon. Implementing such qubit-architectures for the design of a scalable quantum computer needs a thorough understanding of the electronic states associated with donors in silicon and their behavior in applied electric and magnetic fields. The technological complexity in positioning individual donors at precisely defined locations and fabricating nanometer-scale gates for locally applying external fields make such studies challenging. Fortunately however, recent progress made in STM-lithography has made it possible to deterministically place single P donors at defined locations on a Si(001) surface [4]. By the same technique an all-epitaxial, strictly-planar device architecture has also been developed [5] and the electronic states of a P-donor-based small quantum dot has been probed [6].

Here we report the STM-lithography fabrication and low temperature transport spectroscopy of the first deterministically positioned single P donor in silicon. In STM-lithography, the surface of a hydrogen (H)-terminated, 2x1 reconstructed Si(001) surface is denuded in a defined pattern by STM-tip induced desorption of the H-resist monolayer. Subsequently, the surface is exposed to PH_3 gas at room temperature and subjected to a short anneal (60 s) at 350°C, whereby P is incorporated selectively in the surface layer of the patterned regions. The key to deterministic positioning of a single P donor lies in the particular kinetic pathway in which PH_3 dissociates, when the size of the de-passivated area consists of just 3 consecutive Si dimers and the PH_3 dosing conditions are appropriately chosen. In transport spectroscopy, stable Coulomb blockade oscillations have been observed at temperatures up to 4 K. As expected for a bulk single P donor, the diamond corresponding to the 0-electron D^+ state does not close for a source-drain bias voltage as high as 400mV. The charging energy corresponding to the transition from the charge neutral D^0 to the singly negatively charged D^- state is measured to be 46±3 meV. The value compares extremely well to the difference in the binding energies of the corresponding charge states of a bulk P donor in Si. Zeeman shift of the D^0 ground state has been observed in magnetic fields up to 8 T. The extracted g-factor is 2.2±3.

While transport spectroscopy allows probing the electronic states of an isolated donor, manipulation and read-out of spin states of the donor-bound electron requires schemes for spin to charge conversion and charge-sensing by a sensitive electrometer. Towards this end, we have developed a completely in-plane device pattern wherein a dopant-defined single electron transistor is (tunnel and capacitively) coupled to a very small cluster of P donors acting as the qubit. Charge stability diagrams have been recorded in low temperature transport spectroscopy which allowed us to determine the charge transfer signal and the tunnel rates between the qubit and the SET dot. We discuss the advantages and challenges of scaling the qubit down to the single donor limit in this strictly in-plane device architecture.

Finally, we report on the fabrication and transport spectroscopy of a tunnel-coupled pair of ultra-small QDs in series. The ultimate goal of this architecture is to demonstrate driven coherent oscillations of a single spin and thereby determine the spin coherence time [7].

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Quantum Transport in Ultra-scaled Phosphorous δ-doped Silicon Nanowires

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Highly phosphorous δ-doped nanowires in silicon (Si:P NW) represent the ultimate nanowire scaling limit of one atom thickness and a few atoms width. Experimental data are compared to an atomistic full-band model. Charge-potential self-consistency is computed by solving the exchange-correlation LDA corrected Schrodinger-Poisson equation. Transport through donor bands is observed in ⟨110⟩ Si:P NW at low temperature. The semi-metallic conductance computed in the ballistic regime agrees well with the experiment. Sensitivity of the NW

properties on doping constant and placement disorder on the channel is addressed. The modeling confirms that the nanowires are semi-metallic and transport can be gate-modulated.

Spectroscopy and capacitance measurements of tunneling resonances in an Sb-implanted point contact

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We fabricated a split-gate defined point contact in a double gate enhancement mode Si-MOS device, and implanted Sb donor atoms using a self-aligned process. E-beam lithography in combination with a timed implant gives us excellent control over the placement of dopant atoms, and acts as a stepping stone to focused ion beam implantation of single donors. Our approach allows us considerable latitude in experimental design *in-situ*.

We have identified two resonance conditions in the point contact conductance as a function of split gate voltage. Using tunneling spectroscopy, we probed their electronic structure as a function of temperature and magnetic field. We also determine the capacitive coupling between the resonant feature and several gates. Comparison between experimental values and extensive quasi-classical simulations constrain the location and energy of the resonant level. We discuss our results and how they may apply to resonant tunneling through a single donor.

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Heterointerface effects on the charging energy of negatively charged shallow donors in silicon: the role of dielectric mismatch

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A shallow donor, as P or As in Si, can bind one electron in the neutral state, denoted by D^0, or two electrons in the negatively charged state, denoted by D^-. Donor states in Si nanodevices can be strongly modified by nearby insulating barriers and metallic gates. From transport spectroscopy measurements in non-planar field effect transistors (FinFETs) with a single donor in the conduction channel [1], a charging energy smaller than the known value in bulk is found [2].

Within a single valley effective mass formalism [3] we estimate how the charging energy of D^- in Si changes due to the modification of the screening produced by a nearby barrier material. Specifically we study the problem of two electrons bound to a shallow donor, and we find that the measured reduction in the charging energy may be due to a combined effect of the insulator screening and the proximity of metallic gates. Our work confirms the relevance of the barrier and gates dielectric contributions to nearby donor states and proposes a physical way to incorporate the effective metallicity of both components by a single phenomenological parameter [2].

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Electron Spin Coherence of Phosphorus Donors in High-Purity ^{28}Si Silicon

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We report on electron spin coherence measurements for phosphorus donors in high purity, highly-enriched ^{28}Si, with residual ^{29}Si of less than 50 ppm. At this low ^{29}Si density, spectral diffusion processes by nuclear spin flip-flops are suppressed, and therefore other relaxation processes become prominent. By examining a series of ^{28}Si crystals with a donor concentration ranging from 1×10^{14} to 3×10^{15}/cm^3, we confirmed that the predominant decoherence mechanisms are donor concentration dependent, thus suggesting a role for donor-donor interactions.

We identified three decoherence mechanisms. One is known as instantaneous diffusion, caused by flips of donor spins induced by the applied microwave pulses and it can be suppressed by using small rotating angle pulses during a Hahn echo experiment. The second mechanism is associated with a spectral diffusion caused by T_1-induced flips of neighboring donors; this mechanism shows a prominent temperature dependence and is largely suppressed below 4K when the T_1 of donors becomes very long. The third mechanism is temperature independent and is caused by spectral diffusion due to donor spin flip-flops. It is this third mechanism that limits the decoherence time to T_2~1 sec in our lowest doped sample (1×10^{14}/cm^3) when measured at 2K. By applying an external magnetic field gradient and increasing the ESR linewidth from 30mG to 0.3G we are able to suppress this flip-flop mechanism, leading to measured coherence times which extrapolate to T_2~10 sec.

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Decoherence of Donor Electron Spins in Isotopically Enriched Silicon

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Silicon is promising for spin-based quantum computation because nuclear spins, a source of magnetic noise, may be eliminated through isotopic enrichment. Long spin decoherence times T_2 have been measured in isotope-enriched silicon but come far short of the T_2=2T_1 limit. The effect of nuclear spins on T_2 is well established. However, the effect of background electron spins from ever present residual phosphorus impurities in silicon can also produce significant decoherence. We study spin decoherence decay as a function of donor concentration, ^{29}Si concentration, and temperature using cluster expansion techniques specifically adapted to the problem of a sparse dipolarly coupled electron spin bath. Our results agree with the existing experimental spin echo data in Si:P and establish the importance of background dopants as the ultimate decoherence mechanism in isotope-enriched silicon.

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Electron spin coherence and electron nuclear double resonance of Bi donors in natural Si

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Donors in silicon hold considerable promise for emerging quantum technologies, due to their uniquely long electron spin coherence times. Bi donors in silicon differ from P and other Group V donors in several significant respects: they have the strongest binding energy (70.98 meV), a large nuclear spin (I = 9/2) and strong hyperfine coupling constant (A = 1475.4 MHz). These larger energy scales allow us to perform a detailed test of theoretical models describing the spectral diffusion mechanism that is known to govern the electron spin coherence time (T2e) of

P-donors in natural silicon. We report the electron nuclear double resonance spectra of the Bi donor, across the range 200 MHz to 1.4 GHz, and confirm that coherence transfer is possible between electron and nuclear spin degrees of freedom at these higher frequencies.

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Hyperfine structure and nuclear hyperpolarization observed in the bound exciton luminescence of Bi donors in natural Si

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As the deepest Group V donor in Si, Bi has by far the largest hyperfine interaction, and also has a large $I = 9/2$ nuclear spin. At zero applied magnetic field this splits the donor ground state into states having total spin 5 and 4, which are fully resolved in the luminescence spectrum of Bi donor bound excitons, even in natural Si. Under an applied magnetic field, the 60 expected allowed donor bound exciton transitions cannot be individually resolved in natural Si, but the effects of the nuclear spin distribution, $-9/2 \leq I_z \leq 9/2$, can be clearly observed. Under conditions leading to a significant equilibrium polarization of the neutral donor and free exciton electron spins, a strong hyperpolarization of the nuclear spin, with sign opposite to the expected equilibrium polarization, is observed to result from the nonresonant optical excitation used to produce the luminescence.[1]

This is very similar to the recently reported [2] optical hyperpolarization of P donors observed by EPR at higher magnetic fields. We propose a new model, inherent in the capture of spin polarized free excitons on spin polarized donors to form donor bound excitons, to explain this effect. This process should apply to all substitutional donors in Si, and may also play a role in donor bound exciton systems in other materials. We have not yet been able to measure a time constant for this nuclear polarization process, but suggest that under the conditions used in these experiments it may be very fast.

Future work on the Bi donor bound exciton system will focus on observing the same transitions in absorption or photoluminescence excitation spectroscopy,[3] which will give more direct information on the populations in the Bi hyperfine states than does luminescence spectroscopy. Eventually, samples of enriched ^{28}Si:Bi should show 60 fully resolved hyperfine components in

the donor bound exciton spectrum, enabling more detailed experiments on the optical measurement and control of the Bi donor nuclear polarizations.

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On-Chip Avalanche Detectors for Deterministic Doping of Silicon Nano-Devices with sub-10 keV single ion implantation

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Abstract Summary

We investigated silicon diode avalanche multiplication operation both linear and Geiger modes for deterministic doping nano-devices by single ion implantation at a very shallow depth. We apply this technique for the nanofabrication of single donor nano electronic devices.

Keywords- avalanche multiplication; deterministic doping; single ion implantation; nanofabrication; nano electronic devices

I. INTRODUCTION

Recent progress in avalanche photo-diode (APD) technology development has been driven by potential applications, including telecommunications with high-bit-rate and high sensitivity optical fibre communications [1], especially including the promising applications in quantum information technology with reliable single photon detection capability [2, 3, 4]. The APD also finds novel applications for the detection of electrons [5], x-rays [6] and ions [7].

We intend to adapt the APD technology to improve our current PIN detector operation currently using 14 keV P+ ions in the single ions implantation fabrication process. Reducing the phosphorus ion implantation energy from 14 keV to 7 keV will improve ion stopping straggling uncertainty from 11 nm to 5 nm, but it will also greatly increase the difficulty to detect the lower energy ion impact in the implantation site due to the drastically reduced numbers of initial charge carriers generated by the single ion impact in the silicon substrate.

APDs can be operated in linear mode with a low gain (less than 100) [3, 8] or Geiger mode with a high gain (above 100) [7, 9]. The advantage of low gain linear mode is the potential ability to

detect and discriminate single event (photons or ions) against a pile-up of multiple events. A single-event-resolving APD operation that can count the number of photons or ions on-line is highly desirable in future applications. Also if the ion-number-counting capability can be attained for low energy single ion implantation, construction of single donor devices and single atomic qubits [10-13] is possible through single ion implantation process. We investigate the potential of APD devices to be used for sub-10 keV single ion detection with both linear operation and Geiger modes.

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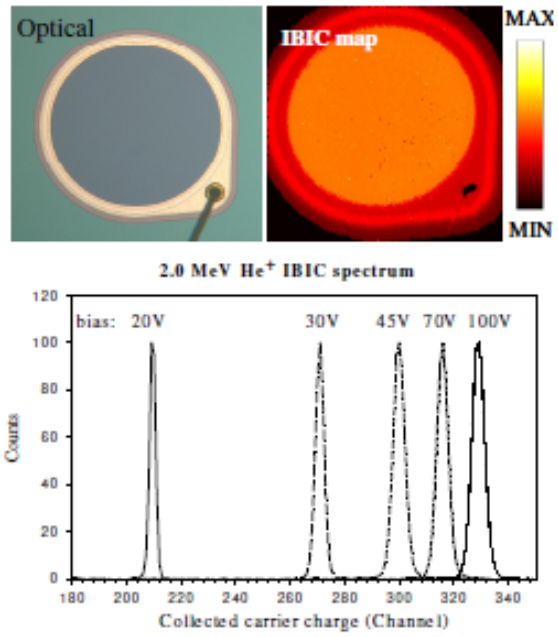

Figure 1. IBIC measurement of relative charge collection efficiency in a APD device. The device reaches about 100% charge collection efficiency (at 210 channels) with 20 V bias, and it increases the collected charge above 100% along the bias voltage increasing due to the internal charge carriers' multiplication effect.

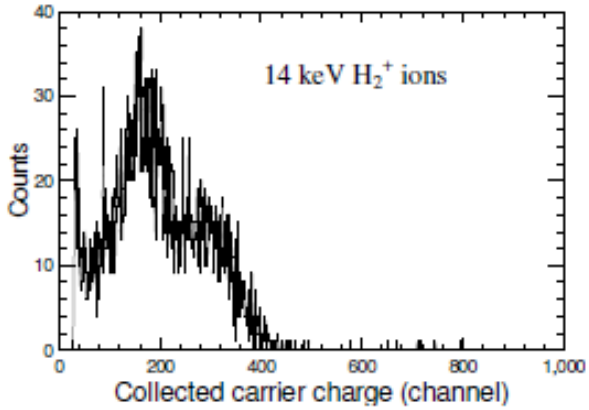

Figure 2. Energy spectrum of low energy H_2^+ ions into an APD detector operated with linear avalanche mode. The 14 keV H_2^+ ions passed through 300 nm SiO_2 dead-layer and lost a large amount of kinetic energy before they reached a depth of an active detector area. The internal charge gain was tuned to about 100.

Using Pulse Sequences to Characterize and Robustly Mitigate Qubit Noise

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The feasibility of nearly every investigated technology for quantum information processing is limited by the noise caused by the coupling the quantum system with its environment. Knowledge of the noise spectrum is an essential prerequisite for mitigating the effects of noise on quantum manipulations and may provide quantitative bounds on theories hoping to describe the source of this noise. In the first part of this presentation we demonstrate a novel approach to characterize the noise acting on a qubit by making measurements of coherence decay under the influence of a carefully designed train of applied control pulses. The second part of the presentation shows how a broad range of qubit noise spectra may be efficiently represented in stochastic simulations using multi-state Markovian fluctuators combined with convex optimization techniques. We then show that this allows the generation of numerically optimized control pulse sequences to provide robust mitigation of the effects of qubit dephasing and coupling noise, with application to electron spin qubits in silicon.

Channel-Optimized Quantum Error Correction & Control

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Quantum Error Correction (QEC) that is optimized with respect to the *specific* system at hand can significantly reduce ancilla overhead while raising error thresholds for fault-tolerant operation [1–4]. In this approach, QEC design is cast as a bi-convex optimization problem, iterating between encoding and recovery, each being a semidefinite program [5]. While in the standard case only the class of errors need be known, for this channel-optimized method a more precise knowledge of the noise map is required. Thus to gain the promised benefit of reduced resources from optimized QEC will require obtaining the specific error model. This is a task that most likely would start with an existing nominal model to be refined by some form of quantum estimation, *e.g.*, Hamiltonian parameter estimation (HPE) or quantum process tomography (QPT). This leads to an intriguing prospect: to implement a complete "online" error correction scheme, that takes the results of quantum estimation as input, and iterates until it finds an optimal error correcting encoding and recovery (Fig.1).

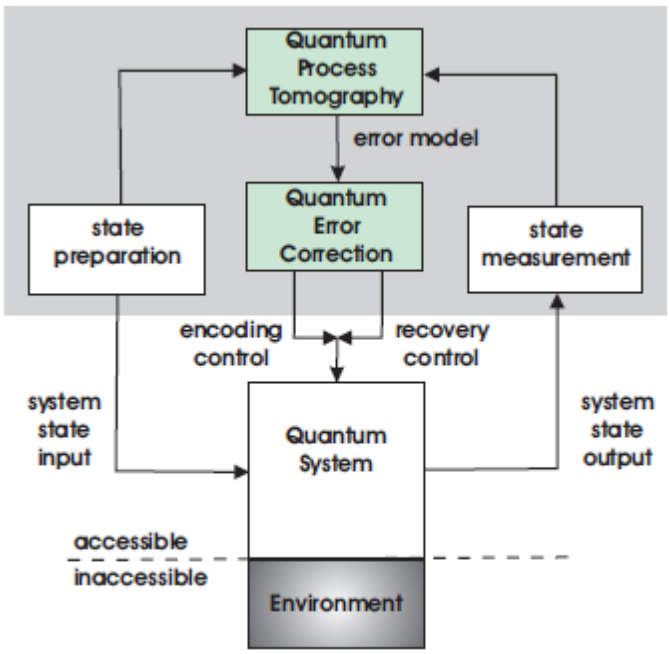

FIG. 1: On-line adaptation via QEC and QPT

Whether such a procedure is necessary for quantum information systems is an open question. And if it is, can it be efficiently implemented? In this talk I will describe two recent results which hold the potential for making such an adaptive scheme feasible:

1. For channel-optimized QEC we showed in [3] how to modify the objective functions to account for robustness, and in [6] we posed the problem in an *indirect* form which can be solved via a sequence of *constrained leastsquares* problems. Both of these modifications

open the way for solving higher dimensional problems with model uncertainty in a reasonable (off-line) time period, either from models or on-line from measured data.

2. HPE is a non-convex optimization in the Hamiltonian parameters [7, 8], whereas QPT, although convex in the process matrix, scales exponentially with the number of qubits [9]. Recent results utilizing methods of *compressed sensing* from signal processing [10, 11], when applied to QPT herald a *linear* scaling in the number of qubits [12, 13]. We refer to this approach as *compressed qantum process tomography* (CQPT). Similar results accrue for quantum state tomography of low-rank density matrices via a related approach referred to as *matrix completion* [14] as applied in [15].

In the case of using CQPT and channel-optimized QEC, both steps involve solving convex optimization problems. In principle this makes the optimization efficient, although there are still scaling issues for off-line computation.

Control is ubiquitous in quantum information systems, *i.e.*, every required unitary logic gate is generated by control. In particular, any form of QEC has to be implemented by control. I will also discuss control design for CQPT/QEC and in the more general framework where the quantum estimation step can be any quantum estimation procedure which is useful for the intended purpose, *e.g.*, Hamiltonian parameter estimation, quantum state tomography, or quantum process tomography. Likewise the control can be *any* feedforward scheme such as the one required to implement the aforementioned channel-optimized QEC encoding and recovery, or to implement a *dynamic decoupling* sequence, or to adjust a real-time classical or coherent feedback protocol.

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Robustness of optimally controlled unitary quantum gates

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External controls are necessary to enact quantum logic operations, and the inevitable control noise will result in gate errors in a realistic quantum computer. An important issue is the scaling of these errors with respect to the size of a quantum circuit (i.e., the number of physical qubits) in the presence of inter-qubit interactions. Such interactions can be a part of the system design in a situation where multi-qubit gates are implemented on purpose or, more realistically, arise due to unwanted couplings between separated one- and two-qubit subsystems. We investigate the robustness of unitary quantum gates to the control noise in the vicinity of an optimal solution, by utilizing properties of the quantum control landscape that relates the physical objective (in the present case, the quantum gate fidelity) to the applied controls. We also explore possibilities of identifying controls with improved robustness by using (1) the analysis of landscape characteristics in the vicinity of the optimal control manifold, and (2) multi-objective optimization that will explicitly incorporate the requirement of high robustness.

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DAY TWO

Spin Coherence and Relaxation of Disorder-Confined Electrons at Interfaces in Silicon

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Electrons confined in Si quantum dots are prospective candidates for the implementation of devices for spintronics and quantum computation due to their long anticipated spin coherence times and their potential scalability using the advanced Si processing technology. However, many of their spin properties still remain unclear.
In this work we present our recent electron spin resonance (ESR) results on disorder-confined electrons (i) at the Si/SiO_2 interface in a Si MOSFET [1] and (ii) at the Si/SiGe interface of a gated modulation-doped SiGe/Si/SiGe heterostructure. In both cases, an ESR signal with a g-factor close to 2 ($g = 1.9999$ for the Si MOSFET and $g = 2.0003$ for the SiGe/Si/SiGe heterostructure) appears when the gate voltage is above the conductance threshold. The ESR signal amplitude decreases significantly but does not fully disappear as the gate voltage is lowered below threshold. The integrated signal amplitude measured above threshold as a function of temperature, shows Pauli behavior characteristic of mobile, two-dimensional electrons. On the other hand a Curie susceptibility is observed below threshold, indicating that a repulsive gate voltage leads to the depletion of the two-dimensional electron system, confining electrons into isolated, natural quantum dots formed by the intrinsic disorder at the respective interfaces.

The spin relaxation and coherence times (T_1 and T_2, respectively) of these natural quantum dots were measured using pulsed ESR at 350 mK. In both systems T_1 and T_2 of the confined electrons are substantially longer than those of the mobile electrons. In the case of isolated spins at the MOSFET interface, values of $T_1 \sim 0.8$ ms and $T_2 \sim 30$ μs were obtained at 350 mK, compared to approximately 0.3 μs T_1 and T_2 values for mobile electrons at 5 K. Similarly, in the case of the SiGe/Si/SiGe heterostructure, the confined electrons exhibit $T_1 \sim 0.5$ ms and $T_2 \sim 20$ μs, in contrast to $T_1 \sim T_2 \sim 3$ μs [2] for mobile electrons at 5 K.

The fact that T_1 and T_2 of confined electrons in both systems are similar suggests that the spin decoherence mechanism is independent of the details of the heterostructure composition. T_1 is substantially longer than T_2 in both systems, a clear indication that spin relaxation is not governed by spin-orbit coupling mechanisms such as Dyakonov-Perel or Elliot-Yafet that are present in two-dimensional systems. Instead, the conduction electrons in these Si structures can be confined into natural quantum dots, resulting in the increase in T_1. An increased T_2 at a lower electron density in the MOS heterostructures suggests that interactions between the confined electrons may be limiting T_2.

This work was supported by the NSF through Princeton MRSEC (DMR-0213706), by NSA/LPS and ARO through the University of Wisconsin (W911NF-08-1-0483), and by the FWF (Vienna, Austria, J2903-N20).

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Spin Filling and Valley Splitting in a Few-electron Silicon Quantum Dot

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Scalability and long coherence times are two essential criteria for the implementation of quantum computers. Silicon quantum dot is an excellent qubit candidate because it holds promise for long spin coherence times and is also a scalable technology. Previous work by our group has demonstrated the ability to confine a single electron in a highly tunable silicon metal-oxide-semiconductor (MOS) quantum dot, which has independent gate control over the electron density in the quantum dot island and the leads [1]. Based upon the developed architecture, here we report the demonstration of a silicon MOS quantum dot with very low disorder, containing a tunable number of electrons starting from zero. The low disorder together with the absence of charge fluctuations and drift enable the observation of a large number of electron occupancy in the dot. By applying a parallel magnetic field, we observe the spin filling of electrons in the quantum dot up to N=25. A careful investigation of the evolution of the first two Coulomb peaks as a function of magnetic field allows us to experimentally extract a valley splitting of ~100 μeV in the few-electron silicon quantum dot.

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Measurements of Valley Splitting in Few-Electron Si/SiGe Quantum Dots

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We report on measurements of the valley splitting of accumulation-mode Si/SiGe quantum dots that provide full control of electron numbers starting from N=0 up to N=15 indicating addition energies as high as 4.5 meV. The devices are based on a double-well heterostructure in which electrons are localized in the top, nominally empty well by forward biasing a single circular gate. The high symmetry of these dots has enabled the observation of a clearly identifiable shell structure. Comparison to similarly fabricated and tested InAlAs/InGaAs dots highlights a strikingly different addition spectra and shell filling that is consistent with the presence of valley splitting smaller than the orbital and charging energies. These devices have been modeled using a real-space Poisson-Schrodinger code coupled to a full configuration interaction (FCI) method in which both spin and valley degrees of freedom are explicitly included. Good agreement is found with measured ground state addition spectra allowing us to conclude that valleys play an essential role in Si QDs and that we have conclusively demonstrated single-electron quantum dots in Si/SiGe. We will present calculations of the multi-electron excited-state spectra for both III-V and Si/SiGe accumulation-mode quantum dots. These show how valley splitting can be straightforwardly determined from magnetospectroscopy measurements in dots with large orbital energies. Utilizing this approach, magnetospectroscopy measurements of the ground state shifts with magnetic field have allowed us to infer valley splittings in different Si dots ranging from 50 to 270 μeV and are consistent with excited-state spectroscopy measurements on the same devices.

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Charge sensing spectroscopy in Si/SiGe quantum dots

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Charge sensing with integrated point contacts is an essential component to the development of Si-based quantum dot spin qubits. We discuss spectroscopic measurements made using charge sensing in two complementary ways. In the first approach, pulsed gate voltages of increasing

amplitude are applied to a gate. In the second approach, a non-zero dc source-drain bias is applied across the quantum dot. In neither case does measurable current flow through the dot. Instead, in both approaches excited states appear as sharp changes in time-averaged charge-sensing measurements performed with the integrated quantum point contact. The advantage of this approach is that it enables spectroscopy of quantum states when no transport is possible through the dot, which is a common situation for quantum dots in the one-electron limit. I will also present data demonstrating a Si/SiGe double quantum dot with exactly one-electron in each dot.

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Valley polarization and interface quality in SiO_2/(100)Si/SiO_2 quantum well

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The valley splitting, that is the energy splitting of valley degeneracy in Si two-dimensional (2D) electron systems, has attracted a recent renewal of interest because the valley degeneracy is considered to cause complications and decoherence in electron-spin-based Si quantum computer [1, 2]. While typical values of the valley splitting are less than around 1 meV, recent transport experiments in Si/SiO_2 quantum well (QW) fabricated on SIMOX (Separation by IMplanted OXygen) substrates show the interface between Si and buried oxide (BOX) leads to vastly enhanced valley splitting of tens of meV, which can be tuned flexibly by electric gates [3].

It remains unclear why these devices show such giant valley splitting. Recent calculations have pointed to the abruptness of the interface as the cause, suggesting that the Si/BOX interface is extremely abrupt. However, in IMOX based QW, it is known that the low temperature electron mobility at the Si/BOX interface (especially, under fully valley polarization) is much reduced compared to the Si/Thermal-SiO_2 (T-SiO_2) interface. It is unclear to what extent this difference in mobility is caused by possible additional sources of scattering, or the valley splitting itself.

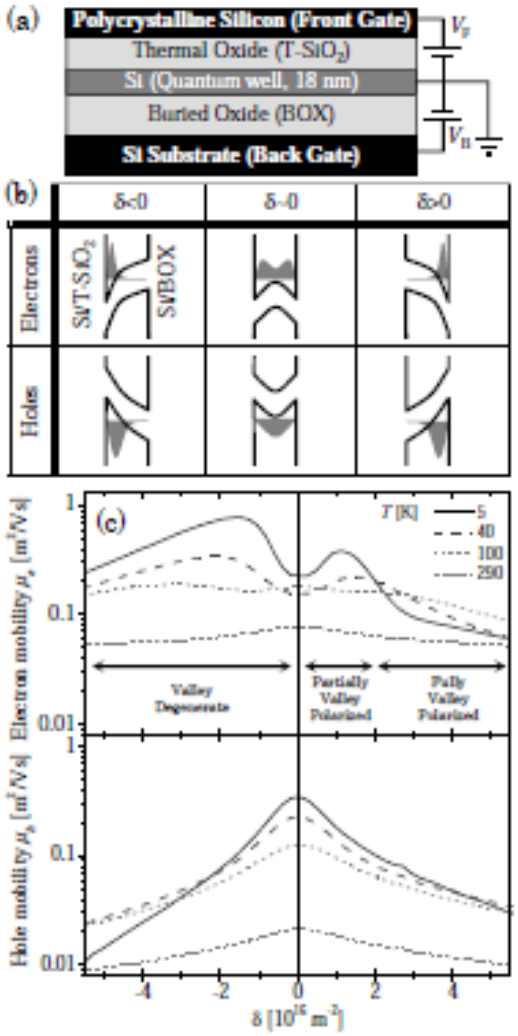

Figure (a) Schematic cross section of the double-gate SIMOX MOSFETs. V_B and V_F are back- and front-gate voltages, respectively. (b) Schematic band diagrams and carrier distributions: δ (= n_B - n_F) > 0 and δ < 0 correspond to the carriers residing at the Si/BOX and Si/T-SiO_2 interface, respectively. δ indicates the degree of asymmetry of the QW. n_B and n_F are the carrier densities contributed from V_B and V_F, respectively. (c) δ dependence of the electron and hole mobility at $n_{tot} = 1 \times 10^{16}$ m^{-2}.

Here, by using devices with *p*-type as well as *n*-type contacts and front- and back-gate electrodes (Fig. (a)), we compare the Si/TSiO_2 and Si/BOX interfaces through transport of two different types of carriers with and without the valley degree of freedom. Transport characteristics were measured for 2D electrons and holes in the same device from 5 K to 290 K.

Figure (c) shows the mobility of the electrons and holes as a function of the potential asymmetry δ in the QW (see Fig. (b) and its caption), where the total carrier density in the QW is kept at 1×10^{16} m^{-2}. At higher temperatures, as $|\delta|$ increases and the confinement of the QW becomes strong, the effect of surface roughness dominantly affects transport behavior and the mobility decreases. Both electrons and holes show symmetric behavior, unaffected by the polarity of δ. At lower temperatures, there are two major changes to the electron mobility. One is mobility supersession at $\delta \sim 0$, which is understood as the effect of the first excited subband, which resides over the ground state. As $|\delta|$ increases and confinement of the QW becomes strong, this structure disappears. The other is that the mobility at the Si/BOX interface is suppressed compared with the Si/T-SiO_2 interface as found in previous studies. Contrary to common expectations, however, holes exhibit only slightly asymmetric mobility where the values are greater at the Si/BOX interface. This indicates smaller effects of interface roughness and disorder at the Si/BOX interface. Our results strongly suggest that suppressed electron mobility at the Si/BOX interface originates from not only the interface roughness scattering but also valley polarization.

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Absence of Valley Degeneracy in Si/SiO2 Interfaces

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The excitation energy between the two lowest orbital levels of electrons in Si/SiO2 quantum wells is investigated theoretically. The valley degeneracy is shown to be lifted well beyond the interface induced valley splitting in certain regimes. We identify these regimes as being those where strong hybridization between the well states and intrinsic interface states happen. It is demonstrated that the ubiquitous disorder in Si/SiO2 interfaces enhances the excitation energy through this mechanism. We also show indications that these hybrid states are not laterally confined by Anderson localization, and therefore they contribute to electronic transport.

Valley-related challenges for SiGe quantum dot structures

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We discuss potential challenges introduced by valley degeneracy, valley mixing, and valley relaxation to the development of Si qubits based on (001) electrostatically defined SiGe quantum dots (QDs). We focus on the effects on single- and few-electron states most sensitive to macro- and microscopic characteristics of Si/SiGe interfaces. Theoretical analysis demonstrates that interface steps, variations in interface quality, and especially intentional *interface engineering* can dramatically modify valley-induced effects. This notion is further supported by numerical simulations, where we explicitly allow for an arbitrary and spatially inhomogeneous stacking of heterolayers in the active area of the device. The current state of valley-related physics in SiGe QDs is critically examined in view of recent experimental data.

We further discuss the resilience of the valley degree of freedom to environmental interactions in (001) SiGe QDs. We identify an “admixture” mechanism, based on valley-orbit mixing, as a likely leading candidate for intervalley relaxation and evaluate its characteristic times for a number of relevant scenarios. This admixture mechanism is strongly suppressed in a truly planar geometry, whereas it can provide a fast relaxation channel for structures with macroscopically inhomogeneous interfaces.

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Aspects of Si quantum computation

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Unintentional Dots in Silicon Nanowires

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Charged defects, such as dangling bonds or dopants, create local potential wells that can create unintentional quantum dots. Our devices consist of a mesa-etched silicon nanowire, with local gates to create intentional dots. In multiple devices we have observed very similar defect induced double quantum dots. We will present a model of the unintentional dots that explains the unusual transport we measure, as well as simulations that reproduce our measurements. It is remarkable that in defect induced double quantum dots we see very similar dot configuration, junction parameters and gate capacitances. There is still basic physics of the interaction of these dots that we do not understand. If time permits I will also discuss homogeneity in our devices. We have measured 20 similar devices and can report on the homogeneity of the gate capacitances to intentional dots and compare it to simulations from lithographic parameters.

Double Quantum Dot with Tunable Coupling in an Enhancement-Mode Silicon Metal-Oxide-Semiconductor Device with Lateral Geometry

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We report low-temperature transport measurements of a silicon metal-oxide-semiconductor (MOS) double quantum dot (DQD). In contrast to previously reported measurements of DQD's in Si MOS structures, our device has a lateral gate geometry very similar to that used by Petta *et al*. [1] to demonstrate coherent manipulation of single electron spins. This gate design [2] provides a high degree of tunability, allowing for independent control over individual dot

occupation and tunnel barriers, as well as the ability to use nearby constrictions to sense dot charge occupation. Comparison of experimentally extracted capacitances between the dot and nearby gates with electrostatic modeling demonstrates the presence of disorder and the ability to partially compensate for this disorder by adjustment of gate voltages. We experimentally show gate-controlled tuning of the interdot coupling over a wide range of energies, an important step towards potential quantum computing applications.

This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences user facility, and was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories.

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A Novel Spin-Flip Co-Tunneling Process in the Effective Three-Electron Regime of a Si/SiGe Double Dot

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We study the transport current of a Si/SiGe double quantum dot in the effective three-electron regime, commonly referred to as hole transport in the literature. Experimental data is modeled with a Hartree-Fock Hamiltonian. We show that the conventional hole transport picture cannot account for all of the features of the data. We also show that understanding the experimental data requires a novel co-tunneling process involving spin flips. This process is possible partly due to the effect of lifetime-enhanced transport [1].

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Highly-Tunable Few-Electron Silicon MOS Double Quantum Dot

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Semiconductor quantum dots (QDs) are highly tunable structures for trapping and manipulating individual electrons. Silicon QDs are also promising candidates as qubits for spin-based quantum computation as they are expected to have long lifetimes and slow dephasing, due to the weak spin–orbit interaction and low nuclear spin density in silicon. Previous work on silicon single QDs has demonstrated the ability of a metal-oxide-semiconductor (MOS) compatible architecture to confine a single electron in the QD [1]. Using the same approach, a triple-gated double quantum dot (DQD) has been fabricated and measured at low temperature to study the energy spectrum of the device. The DQD structure can be electrically tuned to control the inter-dot coupling over a wide range, enabling measurements in both the weakly coupled and strongly coupled regime. The device exhibits robust charge stability over wide range of electron occupancy of the lithographically-defined dots. We will report bias spectroscopy measurements and attempts to observe spin-dependent tunneling effects in this device.

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Coupling an electron spin to a cavity

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We investigate how to couple an electron spin in a semiconductor quantum dot to a microwave cavity via the electrically driven spin resonance technique. Spin degree of freedom is accessed here through either spin-orbit interaction or inhomogeneous magnetic field. We derive the spin-photon coupling Hamiltonian, and assess the coupling strength from cavity and quantum dot parameters. Based on these considerations, we identify parameter regimes that are best suited for reaching the strong-coupling regime for the spin-cavity system, and identify Si as a good candidate material for this purpose.

We acknowledge support by NSA/LPS via ARO.

A circuit QED structure comprised of a silicon quantum dot charge qubit and a lumped-element microwave resonator

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Circuit quantum electrodynamics (circuit QED) principles have successfully been applied in experiments with superconducting qubits [1], demonstrating the potential of this architecture for on-chip quantum communication. It is necessary to extend these concepts to other kinds of qubits, such as silicon quantum dots, because of their potentially superior coherence properties. However, most qubits have smaller transition electric dipole moments than superconducting qubits [1], making it difficult to strongly couple them to resonant circuits.

By applying classical circuit theory we have found guidelines for developing the optimal microwave resonator for circuit QED [2]. Our figure of merit in these calculations, which needs to be much larger than one to achieve high fidelity quantum communication, is the ratio of the circuit-qubit coupling rate to the quantum information loss rate, also known as the cooperativity. The most important factors to maximize the cooperativity are (i) the resonator's Q-factor, (ii) the fraction of the resonator's voltage dropped across the dipole length of the qubit, and iii) the resonator's characteristic impedance, or L over C ratio when modeled as a parallel LC circuit. A resonator that maximizes the cooperativity has the highest impedance at a given frequency; an example of such a resonator is a planar spiral inductor. We also show how this spiral inductor can be integrated with a transmission line scheme to enable high-fidelity quantum communication over distances greater than a meter [2].

Our theoretical findings have enabled us to design a circuit QED structure comprised of a superconducting high-Q microwave resonator and a silicon quantum dot charge qubit, which can be prepared in the energy splitting between two neighboring charge configurations. The quantum dot is a multi-terminal device structure providing a very large tunable operation frequency range (1 GHz to 100 GHz, as the potential can be adjusted from a double to a single well). It is optimized in terms of minimizing the distance between the resonator probes and the qubit to provide the highest achievable qubit-resonator coupling efficiency. Dispersive microwave measurements are under way to verify the coupling of our silicon-based charge qubit to a high-Q microwave resonator.

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Modeling and Low Temperature Operation of Silicon-Based CMOS Processes

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Silicon-based CMOS processes work relatively well at cryogenic temperatures, down to 20K and below. Additionally, the standard compact model formalisms such as the BSIM model set can be used to reproduce measured data at these temperatures with minimal changes to the core equation set [1,2]. The modifications due to the cryogenic temperature operation account for new physics absent at room temperature, such as the incomplete ionization and possible hysteresis effects, as well as enhanced existing physics such as impact ionization and impurity scattering that usually minimally affect operation at room temperature.

To show the performance of various CMOS processes at low temperatures, we will explain the measured behavior observed for these technologies. More specifically, we will show the relative performance of a bulk process and a silicon-on-sapphire technology, compared to the Sandia's CMOS7 process. These low temperature performance comparisons will clearly prove that the standard silicon processes are suitable for operation at low temperature, and there is no or minimal need for switching to more exotic processes for the cryogenic operation. Additionally, the measured current-voltage curves will be compared with their room temperature counterparts, and the standard MOSFET behavior. Such comparisons indicate that the basic device physics, electrostatics and the governing channel transport mechanisms are mainly unaltered at low temperatures, and therefore one observes cryogenic device performance that resembles that of the room temperature operation. Thus, standard compact models with minimal modifications to the core equation and parameter sets can be used to obtain simulated results that agree with measured curves even at these low temperatures.

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Extremely efficient clocked electron transport on helium using a silicon IC

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Electrons floating on the surface of superfluid helium have been suggested as promising mobile spin qubits. Approximately 3μm wide channels fabricated with standard silicon processing are filled with superfluid helium by capillary action. Voltages applied to underlying gates hold photoemitted electrons on the surface of the helium in the channels. The gates run under 120 parallel channels, with approximately one electron per channel. Electrons are detected by measuring the voltage they induce on a sense gate and buffering this signal with a cold HEMT preamp. An oscillatory potential applied to a neighboring gate moves electrons on and off the sense gate to allow lock-in detection. The underlying gates (3μm period) are connected as a 3-phase charge-coupled device (CCD). By applying an appropriate voltage sequence to the 3 phases, electrons are clocked along the 120 channels in parallel. No detectable transfer errors occur while clocking 10^9 pixels. One channel with its associated gates is perpendicular to the other 120, providing a CCD which can transfer electrons between the others. Again, no transfer errors were detected after transferring 10^9 pixels, including transfers between the two orthogonal CCDs. Fully scalable 2D control of an electron's position with only 5 gate leads is demonstrated.

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Posters

Microwave control of a single electron spin in silicon

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Electron spins in silicon are considered to be strong candidates for solid-state quantum bits. Silicon can be isotropically purified to eliminate host nuclear spins, thus providing long electron spin coherence times. Negligible spin-orbit coupling also ensures long relaxation times. Two fundamental requirements for such a qubit are the ability to read the spin state of an individual electron in single-shot and also the ability to control the spin state. To date, only single shot readout has been demonstrated in silicon [1]. Here we present the first instance of microwave control of an individual electron spin in silicon, detected via single-shot readout. This breakthrough has been achieved thanks to a novel CMOS-compatible device structure that combines a silicon Single-Electron Transistor (Si-SET) [2] with individually implanted phosphorus atoms [3] and an on chip microwave transmission line. Applying an oscillating current to the on chip microwave line produces an oscillating magnetic field (B1 field) at the donor implant site. By sweeping an in-plane magnetic field (Bo field) and performing projective single-shot measurements on the electron spin state, two well defined resonance peaks are observed. Future experiments will focus on coherent spin control through the demonstration of Rabi oscillations.

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Low Temperature Analog CMOS Electronics

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There are a number of advantages to developing CMOS circuits which are compatible with solid-state qubit technology. Some are fundamental, such as the low-capacitance coupling between a quantum device structure and the classical readout electronics. Others are more of a practical nature, as in using on-chip multiplexing to reduce the number of pins and associated wiring. Taking advantage of these features imposes severe constraints on the devices and circuits, however, since sharing the silicon with the quantum devices will require the CMOS to operate at the base temperature of the system. The power dissipation in the CMOS electronics must be held to an absolute minimum.

As a step towards developing the ability to employ classical analog circuits in this environment, we designed a variety of conventional CMOS opamps with their inputs, outputs, and power all multiplexed on-chip with digital CMOS logic and transmission gates. The operating currents are programmed through an external current source so that tradeoffs between power and performance can be measured. Circuits with both n- and p-channel input transistors as well as cascaded inputs to minimize input capacitance are included.

The circuits have been tested at both room temperature and 4.2K. The power supply voltage has been kept at 2V or lower for 4.2K testing to minimize hysteretic effects often observed in MOS transistors at low temperature. The programming current has been maintained at 200 nA for 4.2K testing, implying a total power dissipation of 800 nW. The opamps were configured as noninverting amplifiers with gain = 11 using external resistors, and compared under the same biasing conditions with room-temperature operation. The input-referred noise at 1 kHz is lower at room temperature, though by a factor of at most 3, and the p-channel input amplifiers had lower noise than their n-channel counterparts. An input noise voltage of 5-10 $\mu V/\sqrt{Hz}$ was typical at 4 K, over an order of magnitude larger than that measured with a cold GaAs HEMT preamp under similar conditions. However, for on-chip signals the CMOS circuit will have over an order of magnitude lower input capacitance.

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Atomistic simulations of coherent tunneling adiabatic passage in an imperfect donor chain

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Coherent Tunneling Adiabatic Passage (CTAP) has been proposed as a long-range physical qubit transport mechanism in solid-state quantum computing (QC) architectures [1]. CTAP offers a robust way to transfer an electron from one end of a chain of quantum dots or impurities to the other with minimal occupation at any other point along the chain. CTAP in a chain of impurities is of particular interest as it can in principle help reduce gate densities in QC architectures due to the natural confining potential of the impurities. However, in actual implementations the protocol is likely to be susceptible to atomic-scale donor placement errors and gate voltage fluctuations. We employed large-scale atomistic tight binding method on a prototype triple donor CTAP device containing 3.5 million atoms to show the existence of a voltage tuned adiabatic pathway [2]. We then showed how this adiabatic path is affected by donor placement errors and gate voltage fluctuations, and found that corrective voltages can be applied to minimize such errors. Finally, we derive an effective 3 x 3 model of CTAP that accurately resembles the voltage tuned lowest energy states of the multi-million atom tight-binding simulations, and provides a translation between an intensive atomistic Hamiltonian and a simplified effective Hamiltonian while retaining the relevant atomic-scale information. This method can help characterize multi-donor experimental structures quickly and accurately even in the presence of imperfections, overcoming the numeric intractability of finding optimal eigenstates for non-ideal donor placements.

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Focused Ion Beam Development for Single Ion Implantation

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We present experimental results and fabrication details of an effort at Sandia National Laboratories (SNL) to develop single ion implanted donor devices for quantum information processing. This program involves development along three parallel tracks – development of single ion detection capability using avalanche photodiodes (APD) detectors, integration with a nanostructured platform and the development of a focused nano-beam for spatially controlled implantation. In this workshop we will present details of the new nano-beamline (NBL) that has been developed at SNL using an existing 400 keV HVEE implanter. To date the new beamline has demonstrated a sub-micron beam spot for a variety of ion species including H+ and Sb+ through the use of Fischer slits and a magnetic Martin lens as the final focusing element. We are currently installing a series of improvements expected to dramatically decrease the spot size. These include a new vibration isolation system, new chamber designed to achieve greater de-magnification on target by reducing the spacing between the final focusing element and the target, and an additional quadrupole focusing magnet. In conjunction we have an ion optics modeling effort using ProLabs software to determine the final beam current and spot size on target by determining the best configuration of the focusing elements. Working with Gillespie and Associates we have expanded the modeling efforts to include second and third order corrections for both the electro-static and magnetic focusing elements. We predict a final beam spot size on the order of 20 to 100 nm with >1 ions/s on target calculated for a range of ions including P and Sb. Furthermore, we will describe a new nanoimplanter (nI) expected to be operational in early 2011 and its role in this work. The nI is a 100 keV focused ion beam with a 10 nm spot size and ExB filter to allow for multiple liquid metal ion sources (including P and Sb) be to explored.

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Combining Dynamical Decoupling with Robust Optimal Control for Improved Quantum Information Processing

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Constructing high-fidelity control pulses that are robust to control and system/environment fluctuations is a crucial objective for quantum information processing (QIP). We combine dynamical decoupling (DD) with optimal control (OC) to identify control pulses that achieve this objective numerically. Previous DD work has shown that general errors up to (but not including) third order can be removed from π- and $\pi/2$-pulses without concatenation [1]. By systematically integrating DD and OC, we are able to increase pulse fidelity beyond this limit. Our hybrid method of quantum control incorporates a newly-developed algorithm for robust OC, providing a nested DD-OC approach to generate robust controls. Motivated by solid-state QIP, we also incorporate relevant experimental constraints into this DD-OC formalism. To demonstrate the advantage of our approach, the resulting quantum controls are compared to previous DD results in open and uncertain model systems.

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Thermal Modeling of Circuits with Temperature Dependent Thermal Conductivities for Cryogenic CMOS

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Cryogenic operation of CMOS electronics will be necessary for future electrically controlled solid-state qubit implementations. Understanding local heating within circuits is critical for cryogenic circuit design due to the temperature dependence of transistor and noise behavior. Additionally, cooling circuits becomes harder at cryogenic temperatures due to decreased phonon scattering and thermal conductivity, leading to increased thermal noise and degraded circuit performance. To overcome these detrimental effects we need to understand self-heating of CMOS at cryogenic temperatures and learn circuit layout techniques that reduce self-heating.

We have investigated local heating effects of a CMOS ring oscillator and current comparator at T=4.2K. In two cases, the temperature near the circuit was measured with an integrated thermometer. A lumped element equivalent electrical circuit SPICE model that accounts for the strongly temperature dependent thermal conductivities and special 4.2K heat sinking considerations was developed. The temperature dependence on power is solved numerically with a SPICE package, and the results are within 20% of the measured values for local heating ranging from less than 1K to over 100K.

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A Comparison of Electrostatic Simulations to Measurements of Quantum Dot Structures

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We have compared simulations using solutions of Poisson's equation to detailed capacitance measurements on a double quantum dot structure. We tabulate the results and show which cases show good agreement and which do not. The capacitance values are also compared to those

calculated by a solution of Laplace's equation. Electron density is plotted and discussed. In order to understand relevant potential barriers we compare simulations at 50 Kelvin to simulations at 15 Kelvin. We show that the charge density does not differ greatly, but that the conduction band potential does. However, a method of estimating the potential at 0 Kelvin based on the charge distribution at 50 Kelvin is shown to be close to the potential at 15 Kelvin. This method was used to estimate potential barriers at 0 Kelvin in two quantum dot structures.

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Charge Sensing in Laterally Coupled Doubled-Top-Gated MOS Structures using Capacitance Modeling and simulation

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We investigate the effect of device geometry on charge sensing in laterally coupled doubled-top-gated MOS structures using a combination of semi-classical TCAD simulation and capacitance modeling. The model accurately renders the complex topography of the MOS double top gated structure. The approach agrees with the experimental results and uncertainty in the simulated projections due to variation from nominal device dimensions is estimated to be within 10%. We use the simulation approach to make projections of charge sensing coupling strengths for future designs and find that significant increases in coupling, by a factor of 2 to 3, could be achieved with smaller geometries as well as removal of parts of conducting lines between the charge sensor and quantum dot. We will furthermore discuss circuit feedback in to the quantum dot from external sensing circuitry using SPICE modeling combined with this capacitance network model.

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Low noise qubit gates in DQD systems

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Charge noise poses a significant challenge to the creation of solid state qubits. Even when quantum information is encoded in spin, as in a double quantum dot (DQD) singlet-triplet qubit, the fluctuating charge and errors in the controlling electronics is still a primary source of decoherence. We investigate the feasibility of achieving DQD qubit gates which are more robust to certain types of charge noise, specifically those we expect to be most dominant. A full configuration interaction (CI) method is used to compute the energies of one- and two-DQD systems as a function of dot shape and detuning voltage, and is able to identify regimes where exchange (z-rotation) and C-Phase gates are most robust to noise in the inter-dot detuning.

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Valley Degeneracy and Valley Drag on Silicon {111} Surfaces - Robert McFarland

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The 111 surface of silicon is predicted to retain the sixfold valley degeneracy of the ideal bulk crystal. We have developed a method for fabricating field effect transistors using vacuum as a dielectric in order to study electron transport on the bare hydrogen-terminated surface, free from the complications created by intrinsic disorder at Si-SiO_2 interfaces. The resulting devices display very high mobilities (up to 110,000 cm^2/Vs at 70mK, more than twice as large as the best silicon MOSFETs), enabling us to probe valley-dependent transport dynamics to a much greater degree than previously possible. Measurements made on a recent device over a density range of ~0.7-7*10^11/cm^2 reveal considerable information about the nature of this degeneracy and its role in 2D transport. In particular, we find (at n_s=6.7) that 1) low field Shubnikov-de Hass oscillations reveal a clearly sixfold degenerate system and allow us to establish an upper bound on the valley splitting of 0.2K 2) longitudinal resistivity at B=0 displays a strong temperature dependence, consistent with predictions that large valley degeneracy should enhance screening and 3) the Hall coefficient near B=0 is modified by the presence of multiple valleys, and we can use this correction to measure the intervalley Coulomb drag and its temperature/density dependence.

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 non trivial 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. 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 readout circuit is based on a current comparator where changes in current from an electrometer will trigger a digital output. These circuits were fabricated using Sandia's 0.35 μm CMOS foundry process. Initial measurements of comparators with an addition a current amplifier have displayed current sensitivities of < 1nA at 4.2K, switching speeds up to ~120ns, while consuming ~10μW. I will also discuss an investigation of noise characterization of our CMOS process in hopes to obtain a better understanding of the ultimate limit in signal to noise performance.

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Characterization of a lateral double quantum dot in a silicon MOS device

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We have constructed a double quantum dot defined by depletion gates in a silicon metal-oxide-semiconductor (MOS) structure. Electrons are accumulated at a Si-SiO_2 interface by applying a positive voltage to a global gate; negative voltages applied to smaller gates in the device deplete this 2D electron gas locally to form conduction channels and quantum dots. The device incorporates two point-contact-like channels for sensing the charge states of the double quantum dot. We present preliminary data taken to characterize the double quantum dot system, including both the transport current of electrons through the double quantum dot structure and charge sensing. Stability diagrams show that the device can be tuned from a regime in which it behaves as a single, large quantum dot with many electrons, through a regime where it behaves as two strongly coupled quantum dots, and into a regime where the two quantum dots are weakly coupled.

Defect studies in Si-based MOS structures for the development of spin-dependent transport devices

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Measurements are presented for ion implanted MOS capacitors used to optimize the processing strategy of spin-dependent transport FETs. Arsenic implantation is used as any spurious signals arising from microwave absorption of P donors in the bulk and in the P-diffused source and drain contacts in these FETs are avoided. The activation of donors as well as the minimization of oxide and interface traps are investigated. Preliminary low temperature measurements on the implanted FET are discussed and future work on this device is described. The properties of traps at SiO2/Si interfaces were examined in detail. Small-pulse deep level transient spectroscopy was also used to determine the effective electron capture cross-section of the interface states. This measurement will allow direct comparison of interface states determined by DLTS and other techniques.

Intervalley Coupling for Silicon Electronic Spin Qubits: Insights from an Effective Mass Study

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Orbital degeneracy of the electronic conduction band edge in silicon is a potential source of problems for the storage and manipulation of quantum information involving the electronic spin degree of freedom in this host material. This difficulty may be mitigated near an interface between Si and some barrier material, where intervalley scattering may couple states in the conduction ground state, leading to non-degenerate orbital ground and first excited states. The level splitting is experimentally found to have strong sample dependence, varying by orders of magnitude for different interfaces and samples. The basic physical mechanisms leading to such coupling [1,2] in different systems will be addressed. We will expand our recent study based on an effective mass approach [2], bringing new insights from a simple Si/barrier model. In particular, we will present a clear comparison between ours and different approximations and

formalisms adopted in the literature, and establish the applicability of these approximations in different physical scenarios.

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