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Poster Abstracts

Simultaneous conduction and valence band quantization in Si:P δ-layers

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Keywords: Si:P δ-layers, quantization, confinement, angle-resolved photoemission spectroscopy

δ-layers are ultra-sharp, ultra-dense doping profiles typically achieved in semiconductors. Here we focus specifically on phosphorus δ-layers in silicon (Si:P δ-layers) whose composition and structure have been studied down to the atomic limit by both secondary ion mass spectrometry and scanning tunnelling microscopy [1]. Angle-resolved photoemission spectroscopy has only recently provided direct access to the electronic properties of these Si:P δ-layers [2-4]. Confinement of the P dopants to a single atomic plane beneath the Si surface leads to a lowering and discretization of the conduction band (CB) resulting in two parabolic-like states dispersing across the Fermi level, referred to as 1Γ and 2Γ. We can tune the quantization of these CB states by adjusting the density and/or profile of the P dopant layer. Confinement of valence band (VB)-derived states between the P dopants and the Si surface additionally leads to quantization, which we can also tune by simply varying the position of the P dopant layer beneath the Si surface. This case of simultaneous quantization of electron and hole states is rather remarkable, and has never before been observed for traditional doped semiconductors.

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Negatively charged state on phosphorus atom in the silicon quantum computer architecture

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Keywords: Semiconductor impurity, effective mass theory

Negatively charged donor states (D-) play the important role in quantum computing devices based on nuclear and/or electron spins in silicon. In particular, read-out via the D- state is two orders of magnitude faster than via the neutral donor state (D0) due to the weaker bounding of the second electron with donor. Ability to perform manipulations with single donor orbital requires the knowledge of the bound electron wave function (and energy spectrum) and its modification under applied fields. Negatively charged donors have been extensively studied in bulk semiconductors, however, transport spectroscopy measurements of the field effect transistor indicate that D- states on impurities close to an interface differ qualitatively from D- states in bulk semiconductors.

In the present study, we investigated theoretically the D- state in silicon near the oxide interface in uniform electric and magnetic fields, both applied perpendicular to the surface. Wave functions and the energy spectrum of donor and interface states have been obtained analytically within effective mass theory. The key idea of our work is to take into account the anisotropy of the effective mass of the first electron (bound on Coulomb potential of the D+ center) that results in the aspherical and long-range donor potential for the second electron.

The hybridization of the negatively charged state between the potential of its donor atom and the triangular quantum well near the Si/SiO2 interface was studied. The parameters (electric and magnetic fields intensities, donor distance from the interface) which allow to control the electron density distribution in direction perpendicular to the interface were calculated. In general, the electron tunnels to the interface at the increase of the electric field, while the rise of the magnetic field makes it to pull back to the donor similar to the case of the D0 center. In the case of increasing the donor depth under the Si/SiO2 interface, our results for the D- state agree with those for bulk semiconductors.

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Si(001)-AsH3 : Arsine as Precursor for STM Patterned 2D Arsenic in Silicon

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Keywords: STM lithography, surface chemistry, Arsenic, Silicon

STM hydrogen desorption lithography has been developed and utilized to great effect, resulting in device fabrication with atomically precise 2D patterning of phosphorous atoms in silicon. Expanding this technique to include atomically precise 2D patterning of two unique species of donor impurity atoms could provide new possibilities for device structure and function. For example, this could lead to the realization of optically driven silicon-based quantum gates, as proposed by Stoneham, Fisher, and Greenland. Working towards this goal of STM lithography, using two species of donor impurity, we have used STM and DFT to examine the adsorption and dissociation of AsH3 on Si(001), from low coverage to saturation, and from room temperature to 500 °C. The behaviour of this system is compared to the well-studied Si(001)-PH3 system (precursor for 2D patterning of phosphorous in silicon). We find that the dissociation of AsH3 on the Si(001) surface follows a pathway different from that previously determined for PH3. This difference is attributed to kinetic limitations, and is used to explain the differences in the concentration and structure of saturation coverages. In addition to adsorption behavior, we also discuss the incorporation, encapsulation, and electrical transport of As delta-layers in Si, as well as the optimization of growth parameters required to utilize these delta-layers for atomic scale device fabrication.

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Fabrication of Acceptor Transport Devices in Silicon

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Keywords
Single-ion implantation, single-atom transistor, acceptors in silicon, charge transport spectroscopy

Our research focuses on the fabrication, study and characterization of individual acceptors implanted in silicon, in particular Al, Ga, In and Tl, with ionization energies 69, 73, 160 and 250 meV in the silicon band gap and nuclear spins 5/2, 3/2, 9/2 and 1/2 respectively. It is expected that the overlap of the hole wavefunction (p-orbital) with the nucleus will be small (compared to the s-orbital of an electron in a donor), reducing the hyperfine interaction between them and increasing the hole spin coherence time. Moreover, the hole spin can be manipulated with an electric field thanks to the enhanced spin-orbit interaction for holes occupying the p-orbital. We fabricate our devices implanting ions into the silicon channel with low doses. Implantation simulations performed with SRIM and Silvaco Athena give an estimation of the probability distribution of the final position of the implanted ions. Using these results, we can calculate the density of dopants in the active region, ideally achieving one dopant in a volume of 30 nm x 30 nm x 10 nm. Then, the implanted atoms need to be integrated into the silicon lattice and electrically activated with Rapid Thermal Annealing (RTA). This process will stimulate diffusion, reducing the final density of dopants. As the first steps of this project, test structures in silicon have been fabricated, implantation simulations have been performed and Ga atoms have been implanted in some samples. Our future plans include the fabrication of devices based on this scheme and electrical detection of single-acceptor signatures. We intend to present at the conference some preliminary low-temperature transport measurements of our first implanted devices.

This work is part of the research programme “Atomic physics in the solid state” with project number 14167, which is (partly) financed by the Netherlands Organisation for Scientific Research (NWO).

Si:P Chains and the Hubbard model

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Keywords: donor chains in Si
Hubbard model
electronic correlations

Atomically precise implantation of dopants in Si permits the construction of nanowires by design. We investigate the suitability of these interacting electron systems as simulators of a fermionic extended Hubbard model on demand. We describe the single particle wavefunctions as a Linear Combination of Dopant Orbitals (LCDO). The electronic states are calculated within configuration interaction (CI). Properties of these chains are affected by the interdonor distance R_0, in a non-monotonic way. Ground state (T=0K) properties such as charge and spin correlations are shown to remain robust under temperatures up to 4K for specific values of R_0. The robustness of the model against disorder is also tested, allowing some fluctuation of the implantation site around the target position. We suggest that finite donor chains in Si may serve as an analog simulator for strongly correlated model Hamiltonians. This simulator is, in many ways, complementary to those based on cold atoms in optical lattices---the trade-off between the tunability achievable in the latter and the survival of correlation at higher operation temperatures for the former suggests that both technologies are applicable for different regimes.

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Spin qubit manipulation of acceptor bound states in group IV quantum wells

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Keywords: acceptors, spin qubit

The large spin-orbit coupling in the valence band of group IV semiconductors provides an electric field knob for spin-qubit manipulation. This fact can be exploited with acceptor based qubits. Spin manipulation of holes bound to acceptors in engineered SiGe quantum wells depends very strongly on the electric eld applied and on the heterostructure parameters. The g-factor is enhanced by the Ge content and can be tuned by shifting the hole wave-function between the heterostructure constituent layers. The lack of inversion symmetry induced both by the quantum well and the electric fields together with the g-factor tunability allows the possibility of different qubit manipulation methods
such as electron spin resonance, electric dipole spin resonance and g-tensor modulation resonance. Rabi frequencies up to hundreds of MHz can be achieved with heavy-hole qubits, and of the order of GHz with light-hole qubits.

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Low magnetic field anomalies of spin relaxation in silicon in the low temperature limit

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Keywords:
Donor spin qubits, relaxation times

The electron spin relaxation rate of donors in silicon is predicted to follow a magnetic field dependence of $1/T_1 \propto B^5$ at low temperatures, where only spontaneous emission of phonons is relevant [1]. This behaviour has been observed in experiments on individual P donors [2,3]. However, these measurements also showed a deviation from the theoretical prediction at low magnetic fields (< 2 T). Here we present an extensive analysis of single donor relaxation rates at low fields, down to 0.5 T. To maintain a high spin readout contrast at low field we initialise using a Bayesian update, where a real-time feedback loop corrects for spin loading errors. Using a vector magnet, we investigate the dependence of the relaxation rate on the magnetic field direction. This allows us to disentangle valley-repopulation and single-valley contributions [1], and to study the potential impact of extrinsic relaxation mechanisms, such as evanescent-wave Johnson noise [4].
[1] F.A. Zwanenburg et al., Rev. Mod. Phys. 85, 961 (2013). [2] A. Morello et al., Nature(London) 467, 687 (2010). [3] Y.-L. Hsueh et al., Phys. Rev. Lett. 113, 245406 (2014). [4] L. S. Langsjoen et al., Phys. Rev. B 89, 115401 (2014).

Spin-orbit interaction and g-factor isotropy of holes in Si and Ge rectangular nanowires and nanowire quantum dots

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Keywords: Holes, nanowires, spin-orbit interaction, g-factor isotropy

In this study we develop a model describing holes in rectangular nanowires and nanowire quantum dots in silicon (Si) and germanium (Ge). Our findings on g-factor isotropy of strained systems give a good quantitative agreement with recent theoretical Phys. Rev. B 87,161305(R) (2013) and experimental
Phys. Rev. B 93 121408(R) (2016) studies. Further experimental studies of the system under consideration Nano Lett., 16 (1), pp 88-92, (2016), show that the g-factor of the ground state hole doublet can be anisotropic with respect to the direction of the external magnetic field, with opposing isotropies of the two lowest energy eigenstates. Our models allow us to qualitatively understand these experimental findings. In similarity with cylindrical nanowires, an electric field can induce a sizable spin-orbit interaction. Our findings suggest that the magnitude of this spin-orbit interaction is isotropic in case of Ge and highly anisotropic in case of Si with respect to the growth direction of the nanowire.

A 7-K noise temperature cryogenic CMOS LNA for scalable RF readout of spin qubits

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Keywords: Cryo-CMOS, 4 K, LNA, spin qubits

Solid-state qubits must be controlled and read out by classical electronic controllers to ensure proper operation. When scaling up to the thousands of qubits required for a practical quantum computer application, the interconnections between cryogenic qubits and room temperature controller become a limitation. As an alternative, the electronic controller can be placed at cryogenic temperature to simplify the wiring, while improving compactness and reliability.
In this work, we present the design of a cryogenic CMOS (cryo-CMOS) Low-Noise Amplifier (LNA) for RF spin-qubits readout, which represents the initial step towards a fully-integrated cryogenic CMOS controller for solid-state qubits. The proposed LNA was designed in a commercial 0.16-μm CMOS process. Measurements at 4 K show 7-K noise temperature, 57-dB gain, 300-MHz bandwidth (200 MHz – 500 MHz) and a 91-mW power consumption. The large bandwidth can enable the use of frequency multiplexing, thus enhancing the power efficiency by addressing multiple qubits simultaneously. With the achieved performance, the LNA can allocate 15 qubit channels (20 MHz per qubit) with a power consumption of 6 mW/qubit. Such design relaxes the limitations on power consumption at 4 K set by the cooling power of dilution refrigerators, thus enabling the readout and the integration of a large number of qubits in future quantum computers.

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NXP for chip fabrication.

Multi-electron multi-valley effective mass theory: Numerical considerations and applications

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Keywords: quantum dots, donors, simulation methods

Multi-valley effective mass theory (MVEMT) has been demonstrated to achieve quantitative agreement with experiment for single-electron properties of silicon quantum devices. These include donor energetics and tunnel couplings [1] as well as valley-splitting in the presence of interfacial disorder in MOS devices [2]. In this contribution, we adopt methods from quantum chemistry to enable the consideration of multi-electron effects within MVEMT. We study multi-electron effects relevant to the operation of qubits based on silicon quantum dots, phosphorus donors in silicon, and hybrids thereof. We will focus on describing methods for robust, efficient, and provably accurate solutions to the Shindo-Nara equations.

[1] Gamble, Jacobson, et al. Phys. Rev. B, Vol. 91, No. 23 (2015)
[2] Gamble, et al. App. Phys. Lett., Vol. 109, No. 25 (2016)

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Heavy holes in shallow undoped Ge/SiGe quantum wells and nanostructures

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Keywords: Germanium, quantum wells, spin-orbit, mobility

The following points justify the interest in strained Ge quantum wells for heavy holes spin qubits: large mobility/small effective masses for obtaining uniform and reproducible potential landscapes for quantum confinement; the possibility of long spin coherence times by isotope purification; the possibility of an all-electrically controlled qubit due to large spin-orbit coupling; working with holes, the absence of complications arising in the conduction band due to its multi-valley structure. Here we report the growth of shallow, undoped strained Ge/SiGe quantum wells of high structural quality by reduced pressure chemical vapor deposition. Magnetotransport characterisation at low temperature in Ge/SiGe heterostructure Hall Bar FETs show high mobility, low effective masses and strong spin orbit coupling from weak antilocalization features. We also observe clean pinch-off of the 2D hole gas in quantum point contacts devices fabricated in a dual layer gate architecture. These results bode well towards the development of CMOS compatible spin qubits in Ge double quantum dots.

Next steps towards a fault-tolerant qubit in silicon

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Keywords: Si/SiGe heterostructure, Si28, quantum error correction

Electron spin qubits in silicon are considered as a promising qubit for building a quantum computer due to their long coherence, fast operation and compatibility with current industrial CMOS technology. Despite the recent efforts in isotopic purification of Si to achieve longer coherence times, errors will inevitably happen due to charge noise and imperfect control. Therefore, quantum error correction is an essential ingredient to achieve fault-tolerant quantum computation. Though quantum error correction has already been implemented for superconducting qubits, NV centers and ion traps, there is no experimental study for electron spin qubits in silicon so far. In this work we present a linear array of 5 quantum dots fabricated on Si/SiGe heterostructures with Si28 quantum well. We aim to implement a quantum error correction repetition code where the logical qubit is encoded in three physical qubits and where one ancilla qubit consisting of two spins is used for the parity measurements.

This work is supported by an ERC Synergy grant, the Army Research Office, and the Spin Nano MCSA of the European Commission. We would like to thank Intel Corporation for providing Si/SiGe substrates.

Cryomultiplexing magnetotransport in silicon two-dimensional electron gases at milli-Kelvin temperatures and high magnetic fields.

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Keywords: Cryomultiplexing, transport

Obtaining statistics of key electrical metrics such as electron mobility and valley splitting, used to assess the uniformity of silicon heterostructures, aids in improving the quality of silicon qubits. To streamline the process of gathering these metrics, with a faster turnaround time between material growth and low temperature, high magnetic field characterization, we have developed a milli-Kelvin multiplexer aimed at increasing the throughput of magnetotransport measurements.

Here we present such measurements of Si 28 MOS quantum wells, fabricated in a Hall bar FET geometry. Despite the harsh switch action between Hall bar ohmics, these results demonstrate that quantum effects such as Shubnikov de Haas oscillations are reproducible, with and without the multiplexer, with minimal signal distortion even at high fields. We discuss the operation of the multiplexer setup, as well as the limitations and challenges of this approach towards a high throughput cryogenic platform for magnetotransport measurements.

Hyperfine-assisted fast electric control of dopant nuclear spins in semiconductors

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Keywords: phosphorus, nuclear spin, electric control, dot-donor system

Nuclear spins of dopant atoms in semiconductors are promising candidates as quantum bits, due to the long lifetime of their quantum states. Conventionally, coherent control of nuclear spins is done using ac magnetic fields. Using the example of a phosphorus atom in silicon, we theoretically demonstrate that hyperfine interaction can enhance the speed of magnetic control. Based on that result, we show that hyperfine interaction also provides a means to control the nuclear spin efficiently using an ac electric field, in the presence of intrinsic or artifical spin-orbit interaction. The electric control scheme we describe is especially fast in a hybrid dot-donor system subject to an inhomogeneous magnetic field. Reference: https://arxiv.org/abs/1707.00581

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Long-distance Spin Qubit Coupling Through High Kinetic Inductance Superconducting Nanowire Resonators

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Keywords: Si/SiGe quantum dots, superconducting resonator

The long lived qubits based on electron spins in Silicon quantum dots show great promise as elementary building blocks of a quantum processor. Proposals have been put forward for incorporating these qubits in circuit QED architecture as a means of scaling. However, the achievement of the strong coupling regime between spin qubits and superconducting resonators has proved challenging due to small dipole moments of electrons confined to quantum dots. We tackle this issue using high impedance NbTiN nanowire resonators, which generate higher zero point voltage fluctuations as compared with standard coplanar waveguide resonators used in the past. We present our work on coupling nanowire resonators with charge and spin states in gate defined quantum dots, focussing on achieving strong coupling between a nanowire resonator and a single electron spin in a double quantum dot in Si/SiGe heterostructure.

Decoherence of a two-qubit gate system in silicon

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Keywords: decoherence, two-qubit gate, charge noise, quantum dot

The rapid progress in the manipulation and detection of semiconductor spin qubits enables the experimental demonstration of a high fidelity two-qubit logic gate, which is necessary for universal quantum computing. Here, we study the decoherence of two electron spin qubits due to charge noise in a silicon double quantum dot (DQD) used for a two-qubit logic gate. We consider both detuning and tunneling fluctuations in the presence of $1/f$ charge noise. The qubit decoherence due to detuning and tunneling fluctuations show different detuning dependences, and decoherence can be dominated by detuning fluctuation or tunneling fluctuation depending on the condition of detuning and the tunnel barrier. By comparing with recent two-qubit logic gate experiments, we find that the decoherence can be dominated by charge noise induced tunneling fluctuation and the admixture of charge states. We discussed the important implications of the findings for the noise reduction operation of a spin qubit.

Withdrawn

A crossbar network for silicon spin qubits

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Keywords: silicon quantum computing, quantum dot spin qubits, scalability, 2D qubit array

The spin states of single electrons in gate-defined quantum dots satisfy crucial requirements for a quantum computer. These include extremely long coherence times, high-fidelity quantum operation, and the ability to shuttle electrons as a mechanism for on-chip flying qubits. In order to increase the number of qubits to the thousands or millions of qubits needed for practical quantum information we present an efficient architecture based on crossbar control, where only a limited number of control lines is needed. Our qubit grid design enables flexible qubit arrangement and crucially provides a mechanism for creating long-range entanglement, opening a path towards non-planar quantum error correction protocols. The qubit grid is based on a three-layer design to define qubit gates, and orthogonal barrier gates. We show that a double strip line on top of the structure can drive high-fidelity single-qubit rotations without excessive heating. Direct currents through the superconducting lines that define the barrier gates provide a self-aligned magnetic field distribution and enable qubit addressability and readout. Qubit coupling is based on the exchange interaction, and we show that parallel two-qubit gates can be performed at the detuning noise insensitive point. While the architecture requires a high level of uniformity, it stands out for its simplicity and provides prospects to be realized in the near future, such that large-scale quantum computation becomes within sight.

Kondo effect in a self-assembled SiGe quantum dot

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Keywords: SiGe self-assembled quantum dot, Kondo effect

SiGe self-assembled QDs and nanowires are gaining interest because of the p-type structures. The contact hyperfine interaction will be absent because of the p-orbital-like symmetry of holes, therefore the spin coherence time may be further improved. In addition, strong spin-orbit interaction is expected in the SiGe QD systems, which is useful for electrical coherent manipulation of spins. We investigate the transport properties of single hole transistors using a self-assembled SiGe QD at low temperatures. The differential conductance exhibits a zero-bias peak, which may be attributed to Kondo effect. We investigate the dependences of the zero-bias peaks on temperature and magnetic field, and find that both dependences are consistent with Kondo effect in QDs.

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Impact of valley phase and splitting on readout of silicon spin qubits

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Keywords: valley physics, readout, spin qubit

High fidelity readout is one of the main requirements for quantum computation. Spin qubits in silicon quantum dots are often readout via the Elzerman technique. Despite its success in few-qubit devices, this technique requires high magnetic fields to overcome the thermal broadening and external reservoirs. These together pose serious challenges for the integration in large qubit arrays. On the contrary, Pauli-spin blockade (PSB) readout has the potential to overcome these challenges. Here we study PSB readout in silicon quantum dots and investigate the role of the valley states. In silicon quantum dots the singlet-triplet splitting approaches the valley splitting and two types of tunnel couplings are present: intervalley and intravalley coupling. The valley phase difference sets their relative strength, and we study the impact on the readout fidelity in PSB-based protocols. We show the optimal detuning position for a given valley-phase. We find that for linear detuning-only pulses and valley splittings below 0.1 meV, a readout fidelity higher than 99.9% can be reached only for small valley phase differences. When the valley splitting is large, however, fast and high-fidelity readout exists for a broad parameter range.
To go beyond standard PSB, where the measurement time and fidelity is constrained by the spin relaxation time, we investigate novel schemes. We show that by the addition of a third dot, the relaxation time can be extended orders of magnitude. This can further improve the readout fidelity, and may be essential for remote readout schemes and for large qubit arrays.

Towards hot spin qubits with silicon quantum dots

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Keywords: quantum dots, temperature, spin lifetime, single shot readout

Electron spins in semiconductor quantum dots are one of the leading candidates for quantum computation. However, an important limitation is the low temperature where these systems currently operate. The limited available cooling power at temperatures below hundred milliKelvin poses serious challenges to scale up the number of qubits to the thousands or millions required for practical quantum algorithms. Instead, if the operating temperature can be increased beyond one Kelvin, the orders of magnitude increase in cooling power provides significant prospects to integrate all the essential electronics on the qubit chip.

Here, we work towards such hot-qubit operation and start to investigate the temperature dependence of the spin relaxation time. We have fabricated quantum dot devices on isotopically purified silicon that can host up to four qubits in a linear array. The linear array can be sensed through a nearby SET. We measure the stability diagram of the quantum dot system and show that we can clearly sense transitions from all the four quantum dots. We deplete one quantum dot to the few electron regime and after tuning the tunnel coupling with the reservoir we measure the (0,1) charge transition in single shot mode. By applying voltage pulses on the qubit gate, we are able to readout the spin state in single shot measurements. Next steps include mapping out the parameter space to evaluate the prospects for hot qubits in an integrated silicon chip.

Depletion-mode Quantum Dots in Intrinsic Silicon

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Keywords: Depletion-mode Quantum Dots in Si, Hole Transport

We report the fabrication and electrical characterization of depletion-mode quantum dots in a two-dimensional hole gas (2DHG) in intrinsic silicon. We use fixed charge in a SiO2/Al2O3 dielectric stack to induce a 2DHG at the Si/SiO2 interface. Gate fabrication features one-fold layer metallization process. Transport spectroscopy reveals regular Coulomb oscillations with charging energies of 10 − 15 meV and 3 − 5 meV for a few- and many-hole regimes respectively. This depletion-mode design avoids complex multilayer architectures requiring precision alignment and allows to adopt directly best practices already developed for depletion dots in other material systems. We also demonstrate a method to deactivate fixed charge in the SiO2 /Al2O3 dielectric stack using deep ultraviolet light, which may become an important procedure to avoid unwanted 2DHG build-up in Si MOS quantum bits.

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Magnetic coupling and control of electron spins in silicon

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Keywords: electron spin resonance, spin qubits, quantum dots, two-qubit interactions

Two-dimensional arrays of gate-defined quantum dots are a promising approach for the realization of a scalable quantum processor and have become within reach of current fabrication technology. In particular, electron spin qubits in isotopically purified silicon hold the promise of extremely long coherence times and flexible integration. The possibility and straight-forward integration of global control and parallel operation of qubits that is central in error correction schemes such as the surface code make electron spin resonance (ESR) a powerful ingredient to the concept of such arrays. We discuss opportunities and challenges of the integration of ESR control into a 2D architectures, including microwave delivery, magnetic field and g-factor inhomogeneities, and ESR pulses and sequences. In proof-of-principle experiments on few-qubit devices, we aim to investigate the limitations of magnetic control and explore other contributions to the magnetic environment of the electron spin qubits, such as the magnetic dipole-dipole interactions in a double quantum dot and the interaction with remaining nuclear spins in the isotopically purified host crystal.

Cobalt micro-magnet integration on silicon MOS quantum dots

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Keywords: micro-magnet, MOS quantum dots, transport measurements, magnetospectroscopy

Integration of cobalt micro-magnets on silicon metal-oxide-semiconductor (MOS) quantum dot devices has been investigated. The micro-magnets are fabricated in a lift-off process with e-beam lithography and deposited directly on top of an etched poly-silicon gate stack. Among the five resist stacks tested, one is found to be compatible with our MOS specific materials (Si and SiO2). Moreover, devices with and without additional Al2O3 insulating layer show no additional gate leakage after processing. Preliminary transport data indicates electrostatic stability of our devices with integrated magnets.

This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.

Spin relaxation of a donor electron coupled to interface states

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Keywords: spin relaxation, donor, quantum dot, spin-orbit interaction

An electron spin qubit in a silicon donor atom is a promising candidate for quantum information processing because of its long coherence time. To be sensed with a single-electron transistor, the donor atom is usually located near an interface, where the donor states could also be coupled with interface states. Here we study the possible spin relaxation mechanisms arising from the coupling of a donor to confined interface states. We find that both Zeeman interaction and spin-orbit interaction can hybridize spin and orbital states, and leading to phonon-assisted spin relaxation for donors coupled to interface states in addition to the spin relaxation for a single donor in bulk silicon. The spin relaxation due to Zeeman interaction and spin-orbit interaction show the same B^5 dependence on the magnitude of the applied magnetic field, but show different angular dependences on the orientation of the applied magnetic field. We find that there are peaks in the B-dependent spin relaxation (spin relaxation hot spots) due to strong hybridization of orbital states with opposite spin. We also find spin relaxation dips (spin relaxation cool spots) due to the interference of different spin relaxation paths. Qubit operation for B near a dip may be used for the preservation of quantum information during the transfer of spin qubit between donor atoms via interface states.

Further investigation of the deep double donor interstitial magnesium in silicon.

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Keywords: Magnesium, isoelectronic, interstitial

The deep double donor levels of substitutional chalcogen impurities in silicon have unique optical properties which may enable a spin/photonic quantum technology (Sci. Adv. in press) [1]. The interstitial magnesium impurity in silicon is also a deep double donor but has not yet been studied in the same detail as have the chalcogens. In this study we look at the neutral and singly ionized Mg absorption spectra in more detail, looking in particular for the 1sA1 to 1sT2 transitions which are very strong for the chalcogens. We have also verified the existence of a Mg-pair isoelectronic bound exciton by observing the "isotopic fingerprint" of its photoluminescence spectrum in enriched 28Si.

[1] https://arxiv.org/abs/1606.03488\\

Effective mass theory simulations of exchange coupled donors in silicon

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Keywords: 31P donors in Si, exchange interaction, effective mass theory, Hartree-Fock method

Multi-qubit quantum logic gates are the final step to demonstrate the the viability of donor spin qubits in silicon for quantum computation applications. Proposed two-qubit gates rely on the electron-electron exchange interaction which is highly sensitive to the relative placements of the donors in the silicon lattice. For two proximal phosphorus donors an inversion of the hierarchy of the valley-orbital split states has been observed, i.e. the crossing of the bonding combination of T2 states below that of the antibonding A1. Here, we use the Hartree-Fock method within multivalley effective mass theory to model the two-electron wavefunction for different donor configurations and benchmark our results with experimental data.

Ion-implanted 31P donor devices for 2-qubit logic gates

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Keywords: logic gates; qubits; 31P donors in silicon

Donor spin qubits have been extensively studied for future applications in quantum computing. Experiments including electron spin resonance (ESR) and nuclear magnetic resonance (NMR) have led to demonstration of coherence times as long as 30 seconds. Building on those achievements, we report on progress towards two-qubit operations. An increased implantation dose of Phosphorus atoms increased the probability of finding two exchange-coupled donors. The charge stability diagram of newly fabricated devices revealed a high number of donors in the vicinity of a single-electron transistor (SET). Electron spin resonance experiments are underway to benchmark the device performance and identify an exchange-coupled pair of implanted Phosphorus atoms.

Principal Investigations of Acceptor Qubits in Silicon

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Keywords: Acceptor in silicon, Spin-orbit coupling

In the field of quantum information technology, dopant spins in silicon have the advantage of long coherence time and a wealth of experience in fabrication techniques [1]. While a number of breakthroughs have been accomplished in donor-based quantum bit (qubit) systems, the small dipole moment of donor spins makes inter-connection of many qubits challenging. Acceptor spins, on the other hand, possess spin-orbit coupling, which can be exploited for fast quantum-gate manipulations [2] and effective long-range inter-qubit coupling [3]. Recent acceptor qubit proposals [4] indicate the possibility to reach long coherence times, while maintaining the dipole moment between the spin-orbit states. However, static and dynamic properties of acceptor spins have yet to be unveiled in experiments.

Here, we present a comprehensive investigation of the spin dynamics of acceptor atoms in silicon. By means of the paramagnetic resonance technique, we investigate the coherence of acceptor spins in silicon and obtain a coherence time T2 of 0.04 ms at <100 mK for boron spins in isotopically purified silicon (99.99+ % 28Si). This T2 is comparable with or even longer than the electrical-drive qubits in previous reports [2,3]. We also observed T2 of > 0.7 ms for the same silicon crystal subjected to biaxial stress, indicating potential long coherence of a novel electrical-drive qubit defined by a boron atom in silicon. Separately, we use a state-of-the-art boron-doped CMOS transistor to demonstrate the strong influence on the acceptor spin-orbit states when the level configuration is altered with an external magnetic field. We probe two coupled boron atoms and use spin-dependent tunneling induced by Pauli spin-blockade for spin-readout. Analysis of the full two-acceptor excited state spectrum shows that we can rotate the quantization axis of the angular momentum with the magnetic field. Furthermore, the relaxation rate in the acceptor system reveals a strong mixing between heavy and light hole states when they are brought in resonance. This implies that tailoring the acceptor spin level configuration by the external field enables us to tune the spin-orbit interaction to a suitable strength. The demonstrated coherence and controllability of acceptor spins in silicon offer a promising passage to realise a scalable solid state qubit.

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Cryogenic DRAM-based voltage controller integrated with a Si/SiGe quantum dot

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Keywords: DRAM, Si/SiGe quantum dot, scaling, system-in-package

In the pursuit of a fault tolerant quantum computer, a large number of physical Si spin qubits needs to be prepared and connected with classical electronics for voltage control and measurement. While tools that are used today for the control and measurement of a limited number of qubits are sufficient, scaling up demands a more efficient way of routing in order to reduce the number of physical wires from room-temperature to the 20 mK stages. (De)multiplexing and sample-hold strategies, using a Manhattan-style architecture and DRAM circuits, can control the voltage for every gate of a quantum dot with fewer control lines [arXiv:1612.05936]. This allows qubit voltages to be controlled efficiently and independently as the necessary charge is stored in dedicated capacitors for each gate [Appl. Phys. Lett. 102, 13107 (2013),arXiv:1408.2872]. Furthermore, advanced packaging such as system-in-package(SiP) will allow a further scaling advantage as a result of circuit compactness and design and process optimization for each chip.

In this work, we aim at voltage control of a single Si/SiGe quantum dot by using a DRAM circuit within a SiP integration.

The Si/SiGe quantum dot has been fabricated on top of a relaxed SiGe buffer on top of a Si substrate, with a stack of 10 nm of strained Si, 30 nm of SiGe, 15 nm of Al2O3, and 19 nm of Cr/Au for the gates. The plunger gate of the Si/SiGe quantum dot was connected by wire-bonding to a DAC, targeting a few hundreds of mV, through DRAM circuits employing a NMOS transistor having a L/W of 1 by 1 um, tox of 50 nm, and a 100 pF MOS capacitor. Clear Coulomb blockade peaks appear at 20 mK. The charged capacitor can hold the charge for hours with only mV/hr shift in charge value. The main charge leakage is caused by the 100 pF capacitor.

This work shows the potential of scaling up of a spin qubit array by means of DRAM cells for storing voltages. We envision connecting the DRAM circuit to a multiplexing circuit so that only a limited number of wires are needed to define a large number of qubits.

Else Kooi Laboratory, Intel Corporation

High-Q lumped-element resonators for gate-based dispersive readout

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Keywords: Silicon quantum dot, dispersive readout, high-Q resonator.

Semiconductor-based quantum computing architectures require sensitive electrometers to readout the state of the qubits. Typically, this is achieved with high-precision using external electrometers. With the purpose of reducing the number of circuit elements and facilitate scalability, a compact alternative for quantum state readout has been proposed: In-situ gate-based dispersive readout. Gate-based sensing couples the qubit to a resonant circuit via a gate and probes the qubit's state via its radio frequency polarizability. So far this technique has been successfully used to determine averaged spin dynamics in GaAs [1] and thermally averaged spin distributions in Si [2, 3]. However, single-shot dispersive readout of an electron spin state, which is a crucial requirement for error correction protocols, has not been performed yet.

To facilitate time-resolved gate-based reflectometry, large coupling of a high-Q resonator to the quantum system is desired. Here, we present results on gate-based sensing of silicon corner state quantum dots with large gate-couplings. For the purpose of enhancing the Q factor of the resonator, we study the origin of the losses in the circuit and propose an optimised resonator configuration. Additionally, we fabricate and characterise NbN lumped-element inductors. We show that resonators with these NbN inductors have high uncoupled Q-factors at liquid helium temperatures. Overall our results pave the way to high-Q lumped-element resonators for high-sensitivity gate-based readout.

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Impact of Zeeman splitting electrical tunability on Rabi frequency of Si hole qubits

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Keywords: Hole qubit, electrical spin manipulation, g-factor modulation, Rabi frequency anisotropy

We characterize the electrical manipulation of hole spins confined in Silicon quantum dots in terms of g-factor modulation. The Zeeman splitting anisotropy as a function of the magnetic field direction provides information on the underlying spin-orbit coupling.
The device is then operated as a spin-orbit qubit to measure the full angular dependence of the Rabi frequency. The Rabi oscillations are originated by two kinds of mechanisms, one linked to the tunability of the dot's confinement potential, the other due to intrinsic spin-orbit interaction; the former is detectable, the latter is undetectable through the gate-voltage dependence of the Zeeman response.
We demonstrate that a formalism based on Landé g-matrix voltage modulation allows to disentangle these two mechanisms. Finally, the anisotropy of the Rabi frequency provides the experimental way to quantify either of them.

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An extended Hubbard model for mesoscopic transport in donor arrays in silicon

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Keywords: donor arrays, transport, quantum simulation, localization

Arrays of dopants in silicon are promising platforms for the quantum simulation of the Fermi-Hubbard model. We show that the simplest model with only on-site interaction is insufficient to describe the physics of an array of phosphorous donors in silicon due to the strong inter-site interaction in the system. We also study the resonant tunneling transport in the array at low temperature as a mean of probing the features of the Hubbard physics, such as the Hubbard bands and the Mott gap. Two mechanisms of localization which suppresses transport in the array are investigated: The first arises from the electron-ion core attraction and is significant at low filling; the second is due to the sharp oscillation in the tunnel coupling caused by the inter-valley interference of the donor electron's wavefunction. This disorder in the tunnel coupling leads to a steep exponential decay of conductance with channel length in one-dimensional arrays, but its effect is less prominent in two-dimensional ones. Hence, it is possible to observe resonant tunneling transport in a relatively large array in two dimensions. Finally, we discuss a proposal of using transport measurement to probe topological edge states in a one dimensional superlattice of Si:P.

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Electrical Transport Measurements with Atomically Precise Probes

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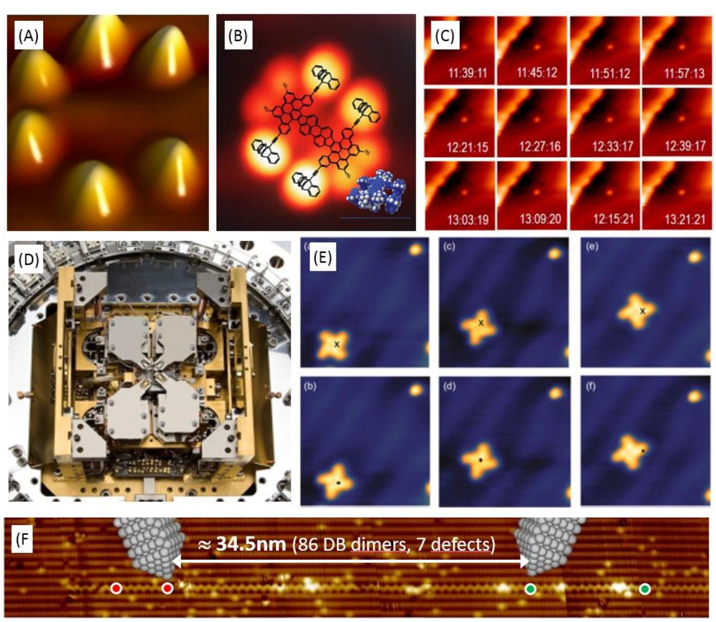
A major challenge in the development of novel devices in molecular and atomic scale electronics is their interconnection with larger scaled electrical circuits. Local electrical probing by multiple probes with atomic precision can significantly improve efficiency in analyzing electrical properties of individual structures without the need of a full electrical integration.

The LT NANOPROBE merges a SEM navigated 4-probe electrical transport measurement system with four individual ultimate stability SPM's with precision in the pm range. This excellent stability allows for atomic resolution in STM and nc-AFM (QPlus) and expands applications towards the creation of atomically precise structures and their direct analysis by electrical transport measurements and SPM based spectroscopy methods.

The system - including simultaneous SEM probe navigation - is operated near thermal equilibrium at T< 5K and has been developed towards an extremely low thermal drift, which is the most important ingredient to allow for enough measurement time on atomic structures, a precision regime that is virtually inaccessible at room temperature.

We will present the technical concept and measurements that prove the performance level of the instrument, specifically low thermal drift and pm stability. As an exciting application, we will show atomic scale lateral transport measurements on dangling bond dimer rows created on hydrogenated Ge(001), in which probes are as close together as 30nm and positioned for transport measurements from atom to atom.

We will also show the newest technology improvements, such as high frequency capabilities and optical access for pumped probe experiments. Future technology challenges as well as applications and scientific drivers for this type of scientific instrumentation will be discussed.



(A) STM atom manipulation on Au(111) @ T<5K. Data Courtesy by Ch. Joachim et al., PicoLab, CNRS, France

(B) High resolution STM on molecules during the NanoCar race. Data Courtesy by Ch. Joachim et al., PicoLab, CNRS, France

(C) Drift measurements STM on Au(111) @ T<5K. Image size 20 nm^2 , measurement time of ≈ 2hrs, lateral drift < 1.3Å/h.

(D) LT NANOPROBE stage, with 4 dedicated shared stack SPM scanners.

(E) STM manipulation of acetylbiphenyl molecules on Au(111) @ T<5K. Data Courtesy by F. Eisenhut et.al. ; Eur. Phys. J. Appl. Phys. (2016) 76.

(F) Transport on dangling bond dimer rows on hydrogenated Ge(111). Data courtesy by M. Kolmer, *NANOSAM, Krakow, Poland*

Enhancement-mode two-channel triple quantum dot from an undoped Si/Si0.8Ge0.2 quantum well hetero-structure

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Keywords: Si/SiGe heterostructure, enhancement-mode

Recently, single- and double-dot characteristics of an enhancement-mode quantum dot device fabricated from an undoped Si/Si0.8Ge0.2 hetero-structure were reported in Ref. [1]. As compared to Si/SiGe hetero-structures with a Ge concentration of 30% typically encountered, a 20% Ge concentration offers higher electron mobility [2], and the fabrication process flow is simplified to incorporate a single accumulation metal-gate layer. We report a number of new results for the device which consists of two channels (upper and lower) formed with two separate accumulation gates. With other gates, a double-dot (in upper channel) and single-dot (in lower channel) can be formed under the accumulation gates energized positively. We demonstrate charge sensing of the upper double-dot with the lower single-dot. We also discuss the formation and tunability of a tunnel-coupled triple-dot formed by coupling the lower and upper channel dots (see typical charge stability diagram below which shows three distinct slopes).

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Achieving High Fidelity Single Qubit Gates in Strongly Driven Silicon Quantum Dot Qubits

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Keywords: Si quantum dot hybrid qubit, Si quantum dot charge qubit, strong drive regime, $1/f$ noise

Performing qubit gate operations as quickly as possible can be important to minimize the effects of decoherence. For resonant gates, this requires applying a strong ac drive. However, strong driving can present control challenges by causing leakage to levels that lie outside the qubit subspace. Strong driving can also present theoretical challenges because preferred tools such as the rotating wave approximation can break down, resulting in complex dynamics that are difficult to control. Here we analyze resonant X rotations of a silicon quantum double dot hybrid qubit as well as a quantum double dot charge qubit within a dressed-state formalism, obtaining results beyond the rotating wave approximation. We obtain analytic formulas for the optimum driving frequency and the Rabi frequency, which both are affected by strong driving.
While the qubit states exhibit fast oscillations due to counter-rotating terms and leakage, we show that they can be suppressed to the point that gate fidelities above 99.99% on both qubits are possible, in the absence of decoherence. When coupled to $1/f$ charge noise, we further show that, by applying strong driving, gate fidelities in a silicon quantum double dot charge qubit can be above 99.9%. This suggests that high-fidelity gates should also be possible in silicon quantum dot hybrid qubits.

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Double quantum dots in Ge hut wires

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Keywords: Ge hut wires, double quantum dot, charge sensing

Holes confined in quantum dots are promising candidates for the realization of spin qubits due to the combination of a strong spin orbit coupling and a weak hyperfine interaction. In our group we study holes confined in SiGe self-assembled nanostructures [1]. Here we focus on quantum dots formed in so-called Ge hut wires (HWs) [2]. Holes confined in HWs are of almost purely heavy-hole character [3] implying very long dephasing times. Furthermore, heavy holes have an additional attractive characteristic; despite their name, their effective mass in the transport direction is actually rather light [4].

The focus of the work presented here is on the realization of double quantum dots in HWs which have been created by adding top gates onto the wire [5]. First signatures of Pauli spin blockade were observed, serving as an important ingredient for the realization and readout of spin ½ qubits.
By creating a parallel double quantum dot system between two neighboring HWs an alternative readout scheme via charge sensing has been realized. The integration of the device into a reflectometry setup allowed for the extraction of hole tunneling times between the two wires [6], which were found to be much shorter than the expected spin relaxation time [7].
All this together brings us a step closer towards measuring the spin lifetimes and thus evaluating the potential of hole spin qubits confined in Ge.

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Single Shot Spin to Charge Conversion in Si/SiGe Quantum Dots Using Latched Readout and Cryogenic Amplification

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Keywords: single shot readout, spin to charge conversion, low noise amplifiers

Achieving high signal-to-noise readout of multi-electron Si/SiGe spin qubits is critical for the rapid development of this technology for quantum applications. We demonstrate single shot qubit measurements of a triple dot device with a spin to charge conversion signal-to-noise of greater than 10 in 5 μs by using latched readout [1-4] in combination with a cryogenic HEMT amplification chain. This signal-to-noise ratio corresponds to a measurement imprecision < 1E-6. The latched readout sequence utilizes an additional charge state such that (1,1) singlets are transferred to the (1,0) state via the non-blockaded (2,0) state whereas (1,1) triplets are forced to remain in (1,1). Compared to simply performing spin to charge conversion to (2,0) for singlet states, the (1,0) final charge state for singlets in the latched readout sequence amplifies the singlet-triplet differential signal because the spin sates are mapped to charge states that differ in electron number rather than just a difference in their spatial distribution. Short integration times are enabled through the use of a two-stage, AC-coupled, cryogenic HEMT amplifier with an input referred 250 pV/rtHz noise floor and 10 MHz bandwidth. Compared to the use of a room temperature transimpedance amplifier, the cryo-HEMT has a significantly reduced parasitic capacitance which improves the bandwidth considerably. Decreasing integration time not only speeds up measurement throughput, but also increases measurement accuracy because of finite charge/spin/valley relaxation times. In combination, these improvements enable both higher quality qubit measurements and more rapid device testing.

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Triple-Quantum-Dots with Overlapping Gates for Si/SiGe Qubits

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Keywords: Si/SiGe, Fabrication, Overlapping Gates, Quantum Dots

Silicon is an attractive host material for quantum bits due to its weak spin-orbit coupling and hyperfine interaction, allowing for long spin relaxation times. However, to achieve a high fidelity qubit, the decohering effects of charge noise must be mitigated. We present data from devices with potential to reduce the decoherence from charge noise. A linear triple-dot design is used to explore different types of qubits. Of particular interest are the charge quadrupole qubit [1] and the quantum dot hybrid qubit [2,3], both of which can operate in charge noise insensitive regimes. Additionally, the devices utilize a three-layer overlapping aluminum gate architecture [4, 5], which may lead to a reduction in charge noise because of the reduced volume of gate oxide. This architecture allows for high tunability of tunneling rates, and for closely spaced dots, which is in line with the requirements for the charge quadrupole qubit. The design is also scalable in a one-dimensional array, allowing for multi-qubit devices in the near future. We present charge sensing measurements of a double quantum dot using fast cryogenic amplification [6]. Magnetospectroscopy measurements indicate that the dot occupations can be tuned to the one-electron limit.

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Optical characterization of Si:Se+ for future integration into photonic cavity-QED structures

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Keywords: donor spin qubit, double donor, transition dipole moment, phonon sideband

Deep donors in silicon possess favourable spin properties, akin to shallow donors such as 31P, but additionally offer spin-selective mid-infrared optical access to their lowest excited valley-orbit states. In particular singly ionized selenium, Si:Se+, has been shown to be a promising spin qubit. It has been proposed to strongly couple the 2.9 µm spin-selective optical transition of a single selenium donor to a silicon photonic cavity for single-shot spin readout at 4 K. Alternatively, spin dependent single photon emission of the selenium donor has been proposed as another possible spin qubit readout method. In this present work, using transmission and photoluminescence measurements on bulk samples, we have tightened our estimate on the transition dipole moment and have measured the phonon sideband of the spin-selective 2.9 µm optical transition of singly ionized selenium. These measurements provide useful information for the design of photonic cavities for strong coupling as well as for the development of Si:Se+ as a single photon emitter.

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A hybrid spin quantum memory in silicon

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Keywords: hybrid systems, quantum memory, bismuth

The notion of 'Hybrid Quantum Systems' has generated a considerable amount of excitement in recent years as it offers the potential to connect different types of quantum systems together to exploit their respective strengths [1]. For example, superconducting qubits have emerged as an excellent technology for performing quantum logic gates and fabricating large qubit arrays, but their coherence times remain typically in the tens of microseconds [2]. On the other hand, the electron spins of donors in silicon have been found to have coherence times extending up to 3 seconds [3], and their states and can be stored and retrieved using coupled nuclear spins [4], offering coherence times of up to 3 hours [5]. Combining these systems together leads to the possibility of a quantum computing architecture using superconducting qubits for processing and spins for memory, interfaced using a superconducting resonator as a quantum bus [6].

Of the donors in silicon, bismuth (209Bi) possesses the largest hyperfine constant (A/h = 1.475 GHz) and the greatest nuclear spin (I = 9/2), producing a zero-field-splitting of 7.375 GHz - within the typical frequency range of choice for superconducting qubits and resonators. It is therefore a natural impurity to use in a hybrid quantum memory, as only modest magnetic fields are required. The large Hilbert space of the Bi:Si system produces desirable features such as the so-called "clock transitions" [3], where (to first order) the spin resonance frequency becomes insensitive to magnetic field or hyperfine fluctuations, facilitating electron spin coherence times several seconds long.

Here we present efforts towards the implementation of an electrically-controlled spin quantum memory using 209Bi in highly-enriched 28Si. A 'voltage-biasable' lumped-element LC resonator (allowing the simultaneous application of large 'DC' electric fields and AC magnetic fields to the bismuth donors) with ultra-high quality factor has been fabricated directly on a doped silicon chip. Simulations reveal that modest voltages (< 10 V) applied to the resonator are expected to produce Stark shifts of the Bi spin ensemble of up to 10 MHz. This represents a sizable detuning between the spin system and resonator, as required in quantum memory protocols [7]. This raises the prospect of an electrically-controlled hybrid quantum memory using linear resonators, which exploits the seconds-long spin coherence times of the Bi:Si system. The design has numerous advantages over conventional architectures [1] that employ SQUID loops to control the spin-resonator detuning, including ease of fabrication, reduced gate complexity and higher quality factors.

Quantum Computing using Spin Qubits in Ge Phononic Crystals

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Keywords: Phononic Crystals, Quantum Computing, Germanium

We propose qubits based on shallow donor spins in germanium phononic crystals. The spin-lattice coupling of electrons in germanium, induced by the spin-orbit interaction, is many orders of magnitude stronger than in silicon. This allows a quantum computer system to be constructed utilizing this coupling, to create a long-range interaction between the donor spins. If the Zeeman frequency of the spin qubits falls within a phonon band gap of the crystal the spin lifetime will be significantly increased. Through careful design of the phononic crystal we may tune the band gaps to completely suppress the single-phonon channel of spin relaxation. Our simulations, based on the effective Hamiltonian describing the spin qubit interacting with acoustic phonons, demonstrate viability of our proposal. The suppression of the spin relaxation by the phononic band gap leads to substantially longer spin lifetimes, allowing the possibility of complex quantum computing operations to be performed. The long-range interaction of the spin donors would allow for placement of donors with separations on the order of 100nm. Additionally, the periodic structure combined with the long interqubit interaction range would allow for precise, individual control of the qubits within the system.

Dispersive readout of accumulation-mode SiMOS quantum dots

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Keywords: Silicon quantum dots, dispersive readout, spin qubit

Silicon metal-oxide-semiconductor (SiMOS) based architectures are an excellent platform for spin qubits since they possess long coherence times, high fidelity control, and have been used to demonstrate multi-qubit logic gates [1]. Current architectures feature spin control via electron spin resonance (ESR) and sensing is achieved via an on-chip single electron transistor enabling single-shot spin readout. In-situ charge detection via radio-frequency dispersive readout methods promise enhanced scalability by eliminating the need for separate charge sensors. We report [2] dispersive readout measurements on an accumulation-mode silicon device consisting of stacked Al/AlOx gates above a thin SiO2 gate oxide. The tunnel capacitance is detected, however, additional accumulation of a 2DEG under the sensing gate adds a competing MOS capacitance (C2DEG) which complicates the dispersive detection of a single-electron tunnelling event. We propose a multiple quantum dot architecture to eliminate C2DEG by using a modified confinement barrier, and we report preliminary studies on these devices.

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Dynamics of a nuclear spin bath in enriched silicon

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Keywords: electron spin decoherence, magnetic noise, nuclear diffusion

Electron spin qubits in silicon are known to have very long coherence times, especially in isotopically-enriched materials with few nuclear spins. As a variety of silicon qubit devices are being explored experimentally, it is necessary to have a proper theoretical understanding of the noise characteristics as induced by the nuclear spins that are present in order to know when other of sources of noise should be suspected. We present a quantitative study of nuclear spin dynamics for moderately sized baths O(100 spins) over a range of timescales. We approximate the quantum dynamics by adapting the cluster-correlation (CCE) expansion technique [Phys. Rev. B 78, 085315] to calculate "flip-flop" probabilities. We improve the accuracy of the simulation for longer timescales by introducing random, sparse projective measurements throughout the time evolution as a semiclassical approximation. In this way, we are able to estimate the spectral density of noise induced by a nuclear spin bath for a wide range of frequencies and study the variation for different instances of nuclear spin locations. We present results of our modified CCE technique, comparing it to exact numerical simulations where possible and known analytical solutions.

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Microwave induced frequency shift and its quadrature compensation for Si/SiGe spin qubits

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Keywords: quantum dot qubit, isotope purification, fidelity

For quantum dot (QD) based spin-1/2 qubits, dephasing has been known to be a primal limiting factor of qubit fidelity. However, for the recent isotopically enriched silicon-based qubits with

extremely long dephasing times, other factors such as non-idealities of qubit control can also limit the fidelity.

Here, we report the microwave induced qubit frequency shift and its impact on the single-qubit fidelity. Our device are Si/SiGe QDs with an on-chip cobalt micro-magnet. When a microwave burst is applied to the QD, in addition to the expected spin rotation by electric dipole spin resonance, we observe microwave power dependent qubit resonance frequency shift. As the frequency shift is not proportional to the microwave power and different from the standard Bloch-Siegert shift, several possible mechanisms will be discussed in the poster presentation.

Randomized benchmarking measurements show that this frequency shift adversely affects the single-qubit control fidelity (~99.8 % for Rabi quality factor ~900). To mitigate the influence of the frequency shift, we introduce a quadrature microwave compensation and experimentally confirm that it improves the fidelity to above 99.9 %.

This work was supported in part by CREST, JST (JPMJCR15N2, JPMJCR1675) and the ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

Designs for electrically driven spin qubits based on silicon-MOS quantum dots

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Keywords: Si-MOS, Electric Dipole Spin Resonance

Recently, both one- and two-qubit logic gates with high control fidelity have been demonstrated using silicon metal-oxide-semiconductor (Si-MOS) quantum dots formed in silicon-28 enriched substrates. These qubit manipulations utilise electron spin resonance (ESR), a technique that can control spin qubits using an oscillating magnetic field generated via a microwave strip-line.

The electrical control of single spin qubits based on semiconductor quantum dots provides an alternative approach for scalable quantum computing, due to the fact that electric fields can be generated easily and can be more spatially focused than magnetic fields. By incorporating a permanent magnet, the qubits can be driven using an oscillating electric field, via electric dipole spin resonance (EDSR). Here we present a number of design considerations and simulations on a microwave coplanar waveguide for Si-MOS quantum dot qubit devices. At 1mW input, a Rabi frequency of 10 MHz is generated by EDSR with minimal noise. The Rabi frequency can be further maximised by changing the quantum device architecture and applying microwave signals on various metallic control electrodes.

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Withdrawn

Atomic-precision spatial metrology of phosphorous donors in silicon by STM imaging of wave functions

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Keywords: STM, Si:P, Wave Functions, Spatial Metrology

Shallow dopants in silicon are promising candidates for the implementation of quantum processors. One of the key challenges in silicon based quantum computing is to find the exact dopant positions after the fabrication and overgrowth processes, which would greatly help in the design and optimisation of highly precise quantum logic gates. Here we present an atomically-precise metrology based on low temperature STM measurements [1] in conjunction with a fully quantum, large-volume treatment of the STM-dopant system, which demonstrates the pinpointing of the position of subsurface phosphorous (P) and arsenic (As) dopants in silicon down to individual lattice sites [2]. Through quantitative modelling of STM images based on multi-million atomistic tight-binding simulations [3] and determination of accurate STM tip state, a clear identification of the exact 3D locations of single phosphorous and arsenic donors down to depths of 5 nm below the Si surface is demonstrated [2]. For pairs of closely spaced phosphorous donor atoms, we simulate STM images from the quasi-particle wave functions computed from single and two-electron states, demonstrating that the developed spatial metrology technique is applicable to find the locations of both donor atoms in the silicon lattice [4].

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A Phosphorus in Silicon Adiabatic Quantum Computer

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Keywords: Si:P, Adiabatic Quantum Computation

The exceptionally long quantum coherence times of phosphorus donor based qubits in silicon [1,2], coupled with the connection to silicon-based nano-electronics, makes them attractive candidates for quantum information processing [3]. Here we present protocols for a digital version of adiabatic quantum computation based on 3D STM fabricated [4] phosphorus donor qubit arrays [3], which allows for the initialization, control, and measurement of the qubits and the implementation of non-planar couplings. We show how to encode a variety of QUBO problem Hamiltonians on the architecture.

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A 3x3 array of 28Si quantum dots.

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Keywords: silicon quantum dot, 2D array, quantum computing

In order to push silicon quantum dots from the few-qubit regime towards large-scale quantum computation, the development of an extensible qubit structure is key. Such building blocks must involve the second dimension to make it scalable. In this work, as a first step, we aim to tackle the challenging task of realizing a 3x3 array of purified 28Si quantum dots in order to demonstrate the operation and control of such an array. We will describe the different variations on the device architecture, the fabrication process and the initial proof of concept of the integration scheme. Selection of the appropriate substrate will be discussed with its impact on the expected physics of the device. We will describe some of the planned experiments needed to understand and gain control of the device. Such experiments include loading of electrons in the 9 dots, shuttling of the electrons from their loading dot to any position in the array, coherent shuttling of electrons throughout the array and Pauli spin blockade between a variety of pairs of quantum dots. These experiments pave the way to parallel qubit operation in a single array and demonstrate the basic capabilities required to scale up the technology to larger arrays containing thousands of dots.

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Reflectometry readout of Ge quantum dots

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Keywords: Ge hut wires, RF reflectometry

Group IV materials have attracted great interest for realizing spin qubits, especially since coherence times of almost one second were reported for an electron spin in isotopically purified Si [1]. In our group we are working with holes confined in quantum dots formed in Ge hut wires [2, 3]. Due to the recently shown, almost purely heavy-hole character of the confined hole states [4], long dephasing times are expected. This, together with the fast spin manipulation times of holes [5], makes the realization of a Ge hole spin qubit very attractive.

For measuring spin qubits, fast readout schemes are needed. Here we will present our RF reflectometry setup integrated into a dilution refrigerator. The high signal to noise ratios enable single shot readout measurements, which were performed in order to extract the tunneling times between two capacitively and tunnel coupled hut wires. The extracted tunneling times, of less than 10μs [6], pave the way towards projective spin readout measurements.

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Isotopically enriched Si-28/SiGe heterostructures with nearly atomic-scale roughness

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Keywords: Silicon isotope purification, Si/SiGe quantum-well structure, Surface and heterointerface

Isotope enrichment of silicon by zero-nuclear-spin Si-28 is essential for prolonging coherence time of electron-spin qubits in quantum dots (QDs). Si-28/SiGe quantum-well (QW) structures were epitaxially grown by employing isotopically purified 28SiH4 gas-source. A continuous growth from graded SiGe buffer layers was investigated with varying dominant growth parameters. For the Ge composition of xGe ~ 30%, the regrowth of Si-28 QWs was circumstantially explored on SiGe virtual substrates that were planarized by chemical mechanical polishing. The top surface of the resulting structures represents a strain-induced cross-hatch pattern with surface roughness reduced at the level of ~1 nm. The 28Si-QW interface defined at controlled temperature is found to be abrupt with an atomic-level fluctuation. Furthermore, a comprehensive study based on x-ray diffraction and Raman scattering spectroscopy shows that the 28Si-QW layer is coherently strained with experiencing a fully relaxed SiGe buffer layer. The well-defined 28Si-QW layer may leads not only to suppress the formation of unintentional QDs but to tune the magnitude of valley splitting.

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Cryo-CMOS circulators for spin and superconducting qubits

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Keywords: Cryo-CMOS, circulator, spin/superconducting qubit readout, directional coupler

Circulators are required in readout and control systems for both spin and superconducting qubits. Currently, discrete ferrite components are used, however they are bulky and not suitable for integration. Also, Hall effect circulators have been recently demonstrated, however they require large external magnetic fields for proper biasing. In this work, we propose cryogenic circulators in a standard CMOS process that can be integrated into a full CMOS classical interface for the control of multi-qubit quantum processors. Both active and passive topologies are explored to implement a low-noise, low power CMOS circulator operating at cryogenic temperatures. The active version is based on differential transconductors to realize gyrators, exploiting the inherent transistor non-reciprocity. The non-reciprocity in the passive version is instead realized by connecting passive mixers, with non-overlapping LO phases, across LC all-pass filters. S-parameters and noise figure are simulated for both active and passive circulators in a 40-nm bulk CMOS technology and with 50 Ω impedances at all three ports. At 300 K, the simulated bandwidth (BW) is larger than 1 GHz and the isolation varies between 10-15 dB across the BW, with an expected similar performance at 4.2 K. At 300 K, the noise figure (NF) of the active circulator is ~4 dB, dominated by transconductances, while for the passive structure the NF is as low as ~1.3 dB, dominated by channel resistance of the switches used in the passive mixers and Q factor of the LC passives. At 4.2 K, the expected noise figures reduce to 0.5 dB and 0.7 dB for active and passive structures respectively, mainly due to a decrease in the thermal noise and on-resistance of the switches. The active and passive circulators dissipate 10 mW and 50 mW, respectively. The designed circuits could be used to replace discrete components by single integrated circuits, thus ensuring compactness, enabling integration and hence addressing scalability of qubit readout and control systems.

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Impact of gate-induced strain on silicon MOS quantum dot tunnel barriers

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Keywords: quantum dots, Silicon MOS, nanoscale tunneling

Gate defined quantum dots in silicon are extremely sensitive to disorder in the local environment of the quantum dot. In the Si MOS system, this disorder can be caused by several different sources including charge defects in the oxide, substrate impurities, and strain. One significant source of inhomogeneous strain in silicon quantum dots is induced by MOS gate materials. At cryogenic temperatures, this gate-induced strain leads to local modifications of the conduction band strong enough to form unintentional quantum dots and to affect the tunnel coupling between dots [1,2]. To realize the potential of quantum devices, gate-induced strain must be understood and mitigated or exploited. In this work, we investigate the role of gate-induced strain in quantum dot devices by comparing measurements of the 4-terminal I-V characteristics of tunnel barrier devices at 2K. The devices are fabricated on bulk silicon wafers with Al and poly-silicon gate electrodes separated by tunnel gap lengths ranging from 20-40nm and gate widths ranging from 50 to 500 nm. We will compare the measured transport characteristics between different devices with the goal of quantifying the level of strain and validating simulations.

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Reducing charge offset drift in Si/SiO2 based single-layer single electron devices using a poly-Si top gate

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Keywords: Si single electron device, charge offset drift

Practical applications of single electron devices (SEDs) require that the operating point of each SED remains stable in time. However, a low-frequency time instability known as charge offset drift is present in real SEDs. Experimentally, it is well established that the charge offset drift is large in Al/AlOx based SEDs ($\Delta Q\_0>1e$) and minimal in mesa-etched Si/SiO2 based silicon on insulator (SOI) devices (($\Delta Q\_0<0.01e$) [1]. This result has been interpreted to be a consequence of intrinsic material properties. Specifically, the level of interaction between TLS defects present in the amorphous insulators, AlOx and SiO2, is distinctly different [1]. In contradiction to this interpretation our recent measurements on Si/SiO2-based single-layer SEDs fabricated on bulk wafers show appreciable charge offset drift. To begin to understand the origin of this drift, we have fabricated single-layer SEDs both with and without a poly-Si top gate on a same wafer (resistivity 5-10 ohm.cm, Boron doped <100>). We find that SEDs with the top gate have significantly less charge offset drift. First, they have very few isolated discrete jumps; second, the local fluctuations (root-mean-square deviation) about a stable mean value are reduced by more than half. We will discuss these results in the context of the origin of charge offset drift in the Si/SiO2 material system and the role being played by device structure.

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AC Signal Characterization for Optimization of a CMOS Single Electron Pump

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Keywords: Charge pump; Transfer function;

Devices which can manipulate single electrons are of great interest to the quantum information community. These same devices can also be used to pump single electrons at a set rate, a useful property for an electrical current standard. Pumping single electrons using multiple AC signals requires coordination and characterization of the signals at the device. To characterize and optimize our two AC signals, we pumped electrons using a 2-gate ratchet style measurement. Fitting this data at various frequencies from 5 to 500 MHz revealed a difference in both the attenuation and phase between our two AC lines. This method reveals in situ the transfer function and phase difference at the device. Using this data, we corrected for the difference in signal path length and attenuation by applying an offset in both the phase and the amplitude at the signal generator. We then switched to a 2-gate turnstile measurement to test the optimization parameters. Operating the device with the parameters determined from the 2-gate ratchet measurement led to much flatter, more robust charge pumping plateaus. This method was useful in tuning our device up for optimal charge pumping, and may prove useful to the semiconductor QD community to determine signal attenuation and path differences at the device.

This work was performed in part at the NIST Center for Nanoscale Science and Technology.

Implications of the spin-orbit effect for singlet-triplet qubit operation

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Keywords: singlet-triplet, qubit, spin-orbit, ac-control

Spin-orbit effects in silicon have long been considered of minor importance for the operation of spin qubits. Contrary to this belief, recent and growing amounts of evidence in systems like spin 1/2 and atomic-precision devices seem to indicate otherwise, but the exact mechanisms and implications are not well understood. In this work, we use a metal-oxide-semiconductor and poly-Si (metal-free) double quantum dot singlet-triplet qubit as a sensitive probe of the spin-orbit effect. We first show that a strong magnetic field enables rotations between the singlet S and unpolarized triplet T_0, an effect which amounts to an effective g-factor difference between the two quantum dots and is affected by gate voltages. Two-axis control and single shot readout of the qubit is used to study AC resonant control in the deep detuning regime and achieve few microsecond Rabi flip times. Perhaps surprisingly, singlet-triplet qubits “just turn” without engineering feats. Secondly, we investigate a different effect of the spin-orbit interaction on the $S-T_{-}$ transition and its impact on schemes like dynamic nuclear polarization. Our results shed light on the implications of spin-orbit interaction for the operation of spin qubits in silicon.

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Measurement-free implementations of small-scale surface codes for quantum dot qubits

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Keywords: quantum error correction, surface codes

The performance of quantum error correction schemes depends sensitively on the physical realizations of the qubits and the implementations of various operations. For example, in quantum dot spin qubits, readout is typically much slower than gate operations, and conventional surface codes that rely heavily on syndrome measurements could therefore be challenging. However, fast and accurate reset of quantum dot qubits---without readout---can be achieved via tunneling to a reservoir. Here, we propose small-scale surface code implementations for which syndrome measurements are replaced by a combination of Toffoli gates and qubit reset. For quantum dot qubits, this enables much faster error correction than measurement-based schemes, but requires additional ancilla qubits and non-nearest-neighbor interactions. We have performed numerical simulations of two different coding schemes, obtaining error thresholds on the order of 10^{-3} for a 1D architecture that only corrects bit-flip errors, and 10^{-4} for a 2D architecture that corrects bit- and phase-flip errors.

The simulations for this work were performed using the University of Wisconsin Center for High Throughput Computing. The authors thank Dan Bradley for the technical support, and M. A. Eriksson, M. Saffman and Yuan-Chi Yang for helpful discussions. The authors acknowledge support from the Vannevar Bush Faculty Fellowship program sponsored by the Basic Research Office of the Assistant Secretary of Defense for Research and Engineering and funded by the Office of Naval Research through grant N00014-15-1-0029.

Noise spectroscopy and randomized benchmarking of a silicon quantum dot qubit

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Keywords: Noise spectroscopy, Stark shift, randomized benchmarking, silicon quantum dot

Spin-based quantum dot qubits in semiconductors have high potential for scalable quantum information processing [1] due to their relative immunity to electrical noise and compatibility with well-established semiconductor manufacturing. Extremely long spin coherence times are possible in isotopically purified silicon [2], and quantum dot qubits have now been constructed with fidelities that meet certain fault-tolerance thresholds [3]. A two-qubit logic gate based on silicon metal-oxide-semiconductor (SiMOS) quantum dots [4] has also been demonstrated. In the effort to scale up this qubit architecture, we must engineer devices and a local environment which can sustain fault-tolerance thresholds for multi-qubit systems when operating error correction protocols such as the surface code [5]. This requires a detailed understanding of the possible sources of noise or decoherence experienced by SiMOS qubits. Here, we employ a silicon quantum dot qubit as a probe to enable noise spectroscopy via CPMG pulse sequences. We compare the sensitivity of this qubit to electrical noise with that of a phosphorus donor qubit [6] in the same environment and measurement set-up. Our results show that, as expected, a quantum dot qubit is more sensitive to electrical noise than an implanted phosphorus donor qubit due to the larger Stark shift of the quantum dot. At low frequencies we observed a coloured noise spectrum, with an exponent of -2.5 for f < 2 kHz which we attribute to DC magnetic drift, and an exponent -1 for f in the range 2 - 10 kHz which we attribute to charge noise. We have also characterized this qubit's relaxation time (~1s), T2* time (~30 microseconds), and coherence times, and have performed Clifford-based randomized benchmarking (RBM). While this qubit device has a shorter dephasing time than that previously reported in [3], its average control fidelity determined via RBM is higher (>99.83%), due to the higher bandwidth available in the RBM pulse sequences here.

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Alternative method for interconnecting STM written quantum electronic devices

Generation and annealing of electron traps in high-mobility MOSFETs

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Keywords: MOS, Shallow traps, high mobility, annealing

Spins confined in metal-oxide-silicon (MOS) heterostructures are promising qubits, enjoying long coherence times, a large valley splitting and the potential for integration with the existing CMOS fabrication infrastructure. An important challenge in fabricating MOS quantum devices is to understand and reduce defects at the Si/SiO2 interface, namely shallow electron traps (< 4 meV below the conduction band), which can interfere with the manipulation of single electrons, and are invisible to conventional MOS characterization techniques. These shallow electron traps can be created by high energy photons and electrons during the fabrication process, especially by electron-beam (e-beam) lithography, the "work-horse" of quantum device fabrication in research labs. To this end, we have fabricated silicon MOSFETs with the highest reported electron mobility (23,000 cm^2/Vs) with an oxide thickness of 30 nm or thinner. We investigate the effect of e-beam irradiation (10 kV, 40 uC/cm^2) and a subsequent forming gas anneal on these devices, and report their shallow trap density using electron spin resonance (ESR) techniques. Additionally, we compare these results to more typical metrics of the oxide interface, namely low temperature transport measurements of the electron mobility and percolation thresholds. We find that the forming gas anneal is sufficient to recover a high mobility after the e-beam irradiation (14,000 cm^2/Vs) and that the forming gas anneal returns the density of shallow traps to the baseline (unexposed) density. We also show that our devices' T=0 percolation threshold quantitatively agrees with our lowest temperature ESR measurements of shallow traps, demonstrating agreement between two independent methods of assessing the silicon/oxide interface.

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Significance of Accurate Electronic Structure Calculation Methods in Designing Silicon Donor Qubits

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Keywords: Donors in silicon, wave function, density functional theory, tight binding

Recent demonstrations of long-lived spin qubits with high gate fidelities have enhanced the prospects of silicon donor qubits in quantum computing. Designing prototype silicon qubit devices requires accurate computational methods to model their electrostatic potential landscape, donor electron wave functions, and spin dynamics. Here, we examine the sensitivity of device design to the underlying electronic structure model used for the donor, within the context of a computational workflow. We observe a significant discrepancy in the spatial distribution of donor wave function amplitude computed using density-functional theory versus tight-binding methods, for the case of doped silicon nanocrystals. While both methods can be used to match experimental values for the hyperfine coupling, differences in the electronic wave function amplitudes suggest that more complicated interactions, such as electron-exchange, may become unreliable. Hence, an accurate understanding of the donor wave function is critical to device design, as it serves as a handle to vital parameters in donor based quantum computer architectures.

This work used computational resources of the XSEDE allocation TG-DMR110037 and of the National Energy Research Scientific Computing Center which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. A portion of this research was conducted at the Center for Nanophase Materials Sciences (CNMS), which is a DOE Office of Science User Facility.

Why tunnel gates are better than tilting gates in quantum dot quantum computing

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Keywords: exchange interaction, charge noise, barrier control, symmetric operation

We present a theory for the symmetric operations (tunnel gates) for controlling exchange interaction between electron spins in a double quantum dot. Both Hubbard model and a more realistic confining-potential model are used to investigate how the tilting and barrier control affect the effective exchange coupling in two different regimes, detuning regime and symmetric regime. We show that the exchange coupling is less sensitive to the charge noise in the tunnel barrier, and it allows the exchange coupling control on a sweet spot where the exchange interaction has zero derivative with respect to the detuning. Both Si and GaAs quantum dots are considered and we compare our results with experimental data to show qualitative agreements.

Hysteresis Correction and its Relationship to Creep and Drift in Scanning Tunneling Microscope Tip Positioning

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Zyvex Labs

Keywords: Scanning Tunneling Microscopy, Hysteresis, Piezo Creep

Single phosphorus atoms in silicon qubits with geometries as defined by Scanning Tunneling Microscope (STM) lithography is a promising architecture. However, as the number of qubits increases to occupy a surface area of 1µm2 or greater, positioning errors which increase nonlinearly with lateral step size will become difficult to compensate for in multi-tier systems. While methods for correcting positions are available such as lattice registration, artificial fiducial registration, and closed loop positioning, this model-based compensation for position uncertainties greatly reduces patterning time for highly scaled devices.

This work shows that the hysteresis error for the commonly used Scienta Omicron VT STM to be approximately 0.03r2 µm where r is the size of a lateral step. Furthermore, it is shown that creep corrections, described previously, depend upon the state of the hysteresis with observed creep coefficients varying by over 10%. A real-time correction algorithm with 20-bit precision and 50 µs update time will be described. This algorithms reduces positioning errors for 2µm steps from >100nm down to <20nm. Furthermore, correcting hysteresis reduces the variability of optimal creep correction coefficients. Results will be shown for lateral motion as well as settling times in Z as shown below, with the effects of position correction on complex patterns shown.

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Evaluation and reduction of impurity contributions during deposition of isotopically enriched 28Si thin films

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Keywords: Enriched 28Si, chemical purity, UHV ion source, MOSFET

Both nuclear spins (mainly due to 29Si) and chemical impurities can reduce the coherence time for qubits in silicon, however, experimental study of this phase space is limited. With the objective of producing both isotopically enriched and chemically pure 28Si thin films to study the impacts of purity and enrichment on coherence, we have evaluated the vacuum contributions to 28Si chemical purity in our system. Highly enriched epitaxial 28Si thin films are routinely grown via mass selective ion beam deposition with an isotope fractions up to 99.99998 % (0.127 ppm 29Si). However, the chemical contamination levels of nitrogen, oxygen and carbon are much higher in the film than semiconductor grade silicon, one consequence being poor oxide quality during device fabrication. The impurities in the film are largely due to poor vacuum (≈10-8 Torr) in the ion beam system. To improve the chemical purity, we designed and built a replacement UHV version of the ion source. The source produces well-formed ion beams, maintaining the high enrichment, and is estimated to allow us to reach >99.999 % total purity with ongoing improvements. So far, our total purity is estimated to be ≈99.97 %. Good isolation oxides have been grown on 28Si films deposited from this new source, enabling MOSCAPS and gated Hall bar devices to be fabricated. The electrical measurements from these devices fabricated from 28Si will be presented.

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Hall measurements and STM analysis of Al delta layer heterostructures in silicon

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Keywords: Al delta layer, 2D hole gas

Using in situ aluminum doping, an Si/Al/Si hetero-structure is studied by STM (scanning tunneling microscopy) after each fabrication step and then patterned and contacted ex situ for electrical measurements. The dominant carrier type in our work is holes, making it complimentary to the n-type delta layers prominently fabricated using phosphine gas doping. Unlike the phosphorus case, ultra-shallow p-type junctions with a narrow doping profiles and high doping concentration (>3 x 1014 cm-2) have not been widely studied. Development of an acceptor qubit in silicon is of interest due to the large spin-orbit coupling and no valley degeneracy. Using Hall measurements at 4 K and up to 3 T, these Al delta layer samples had hole concentrations of ≈8 x 1013 cm-2 and Hall mobilities of ≈14 cm2/V•s. STM images show the aluminum forming a well ordered 1x1 array on the surface prior to activation and then one-dimensional chains in the first surface layer after activation. Moderate thermal processing was required for electrical contacting, but Hall measurements at various angles confirm that the hole gas is two-dimensionally confined.

This work is supported in part by NIST-IMS for single atom devices. This work performed in part at the NIST Center for Nanoscale Science and Technology.

Extending the coherence of a quantum dot hybrid qubit

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Keywords: Charge noise, spin qubits, decoherence

Charge noise fluctuations that cause the detuning of a qubit and hence its frequency to vary are the dominant source of dephasing in many semiconducting qubits, including quantum dot hybrid qubits (QDHQ) [1,2]. In this work we show that by appropriately tuning the internal parameters of a QDHQ and intelligently choosing its operating point, the qubit frequency can be made essentially independent of detuning, so that the resilience of a QDHQ to charge noise can be increased by more than an order of magnitude, improving the free induction decay time T_2^* to 177 ns and the Rabi decay time to more than 1 μs. We also show that for the longest Rabi decay times the decoherence is no longer limited by the qubit frequency being changed by charge noise-induced detuning, but instead by fluctuations in the detuning dependent (and therefore affected by charge noise) effective coupling between the qubit states that drives the Rabi rotations [3].

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High Bandwidth Electron Spin Readout with the Radio Frequency Single Electron Transistor

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Keywords: spin qubit, STM, reflectometry

Qubit state readout is an essential step for quantum computation and must introduce minimal errors if full error correction is to be achieved with a surface code architecture. The lowest errors during readout will only be possible if the readout is not only high fidelity, but also high bandwidth. Typically, for electron spin qubits in Si-P donor based systems, a single electron transistor (SET) is used as a charge sensor to perform single-shot electron spin readout. Previously, spin readout fidelities above 99% have been achieved with a dc measured SET, but only by limiting the bandwidth to 100 kHz [1].

Here, we demonstrate using a radio frequency SET (rf-SET) and characterize its bandwidth, shot-noise and readout fidelity. At the full bandwidth of the rf-SET circuit, 9.5 MHz, we demonstrate single-shot electron spin readout at B=1.5 T with an effective signal-to-noise ratio of 7.2. For electron charge state detection the power broadening is no longer limited by the electron spin state splitting, allowing us to achieve an effective signal-to-noise ratio of 15.5 by increasing the driving power before being limited by heating of the rf-SET. Optimized single-shot readout of electrons, with 50 kHz tunnel rates, achieved measurement fidelities above 98% limited by the base electron temperature (200 mK).

Importantly, we have shown that the high bandwidth readout has multiple benefits: it enables the measurement of faster electron transitions, has greater statistics for experiments employing electron spin readout, and faster qubit gate operations. Collectively these lead to lower errors on both measured and idling qubits during readout operations.

[1] Watson, et al., Phys. Rev. Lett. 115, 166806 (2015)

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Theory of spin-orbit coupling at the silicon MOS interface

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Keywords: spin-orbit coupling, MOS interface, singlet-triplet qubit

While spin-orbit (SO) coupling in bulk silicon is relatively weak in comparison to other semiconductors such as GaAs, recent measurements of quantum dots indicate enhanced SO coupling at a silicon interface [1-3]. As we have demonstrated recently [4], this coupling is controllable and strong enough to enable full electrical control of a singlet-triplet qubit in a silicon MOS double quantum dot (DQD), without the need for micro-magnets or an Overhauser field gradient. Here, we show how this interface SO coupling mechanism manifests in a DQD through a range of physical mechanisms. This work fully explains the angular dependence on applied magnetic field and how SO coupling is exhibited in the various operating regimes of this device. Through detailed numerical modeling that includes valley-orbit coupling and interface effects, we estimate the amount of intrinsic variability of SO coupling due to realistic interface statistics.

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[2] Veldhorst, et al. Phys. Rev. B 92, 201401(R) (2015)
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Localized implantation of phosphorus atoms into Si/SiGe heterostructure for donor-dot qubits

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Keywords: donors, quantum-dot, SiGe, qubit

Coupling a donor atom to a quantum dot can create a qubit with the advantages of both. Donors bound in silicon have long coherence and relaxation times for their electron and nuclear spins. Combining donors with a gate-defined quantum dot can create a qubit with increased speed and enhanced coupling to nearby qubits. Recent work in an MOS device has shown coherent coupling of electron spins between a phosphorus donor and a quantum dot, as well as rotations driven by the donor nuclear spin [1]. A Si/SiGe heterostructure with a donor-dot device may be advantageous due to reduced charge noise from surface defects as the quantum well is offset by a SiGe layer. Here, we implant phosphorus donors through a 120 x 120 nm hole in PMMA resist on Si/SiGe, aligned to palladium alignment markers capable of withstanding high-temperature processing. A double-dot gate design is then patterned on top of the implanted region, with the donors implanted directly under one of the two dot regions. These devices have been fabricated, measurements are ongoing, and we present our progress.

[1] Coherent coupling between a quantum dot and a donor in silicon, P. Harvey-Collard, et al., https://arxiv.org/abs/1512.01606

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Design and characterization of a device for hosting singlet-triplet qubits with atomic precision donors in silicon

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Keywords: donor qubit singlet-triplet

We present the design, fabrication, and characterization of a device for hosting capacitively-coupled singlet-triplet donor qubits in silicon fabricated by scanning tunneling microscope lithography. The layout is geometrically compact and robust as each pair of dots can be independently controlled via one gate and one reservoir that also measures the singlet-triplet state of the qubit by dispersive readout [1]. We verify the STM-patterned positions of each dot by comparing measured values of the relative couplings between each dot and gate to those predicted by a finite-element electrostatic model. We measure singlet-triplet states with dispersive readout and observe a S0 to T- decay time of 2 ms at zero detuning and 3.3 T applied magnetic field. The design represents a scalable device building block in one dimension with minimal gate leads (two per qubit) based on atomic precision lithography and dispersive readout.

High-fidelity gate control of silicon quantum dot qubits using shape-optimized microwave pulses

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Keywords: GRAPE optimization, randomized-benchmarking, gate set tomography, Si-MOS quantum dot

In a fully functional quantum computer elementary qubit control gates will need to reach certain fault tolerant thresholds. Single qubits in silicon MOS quantum dots have achieved 99.6% gate control fidelity [1] which satisfies one error threshold requirement for surface codes. However, by attaining even higher fidelities, one could envision surface code quantum computing with a smaller number of qubits. Here, in experimental measurements on SiMOS quantum dots, we show that pulse-shape optimised qubit gates, based upon GRAPE techniques from NMR [2], can improve the single qubit control fidelity from 99.83% to 99.96%, a factor of 4 improvement compared with simple microwave square pulses. The fidelity is assessed using randomized benchmarking combined with state tomography measurements, where we also observe errors arising from non-unitarity processes [3]. We have also applied a gate set tomography sequence [4], which has previously been used to characterize silicon donor qubits [5], and we extract control gate fidelities over 99.83%. Both the results seen in unitarity decay rates from randomized benchmarking, and goodness of fit from gate set tomography, show that pulse-optimised control gates are less affected by non-Markovian noise compared with simple square-pulse gates.

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[5] J. P. Dehollain et al., New Journal of Physics 18, 103018 (2015).

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Adiabatically-controlled two-qubit gates using quantum dot hybrid qubits

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Keywords: two-qubit, quantum control, quantum dot hybrid qubit

With its recent success in experimentally performing single-qubit gates, the quantum dot hybrid qubit is an excellent candidate for two-qubit gating. Here, we propose an operational scheme which exploits the electrostatic properties of such qubits to yield a tunable effective coupling in a system with a static capacitive coupling between the dots. We then use numerically calculated fidelities to demonstrate the effect of charge noise on two-qubit gates with this scheme. Finally, we show steps towards optimizing the gates fidelities, and discuss ways that the scheme could be further improved.

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Interface induced spin-orbit interaction in silicon quantum dots and anisotropic dephasing time

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Keywords: Si QD, Spin-orbit, Dephasing

Spin qubits hosted in Silicon (Si) quantum dots (QD) are among the most promising candidates for building large-scale quantum computer, because of their compatibility with the CMOS technology. On top of that, Si offers a nuclear spin free environment for electron spins and hence spin dephasing time of 120 μs has been achieved in an isotopically purified Si QD, formed at a Si/SiO_2 interface. However, recently a variation in T_2^*, up to four times, is observed among three neighboring QDs, on the same Si/SiO_2 sample. We relate these T_2^* times with the sensitivity of the electron g-factor to the fluctuation in the vertical electric field, due to electrical noise. We identify that monoatomic steps at the interface control the strength of the Dresselhaus spin-orbit interaction (SOI) in Si QDs and result in variations in the T_2^* times. Finally we predict that by using the anisotropic nature of the Dresselhaus SOI, the variability in T_2^* times can be suppressed and also T_2^* >1 ms can be achieved by aligning the external magnetic field towards specific crystal orientation, if other noise sources do not significantly contribute.

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Design Considerations of Cryo-RFICs for Superconducting Qubits Readout

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Keywords: readout of superconducting qubits, cryogenic readout platforms, Cryo-RFIC

Solid-state superconducting circuit quantum bits (qubits) are one of the most promising platforms for the implementation of fault-tolerant quantum computers (FTQC) owing to their potential for scalability. Recently, networks of up to 17 superconducting qubits have been demonstrated. However, a useful FTQC calls for orders-of-magnitude larger networks of physical qubits and the necessary extensible control and readout hardware, to be able to address the qubits individually. Currently, qubits are operated below 100 mK and the control and readout signals are generated using commercial-off-the-shelf (COTS) electronics equipment, operating at room-temperature. For few qubits, such schemes are feasible, however, as the number of physical qubits on a single device is rapidly increasing, the usage of COTS becomes prohibitive from a cost, reliability and system complexity perspective, hindering the scalability of quantum computers.

An active area of research is, therefore, to replace COTS with customized platforms or even microwave/RF integrated circuits (RFICs), which can lead to a significant reduction of form factor, power consumption, and system cost/complexity. If operating at deep-cryogenic temperatures (<4 K), RFICs (Cryo-RFICs) can be placed in close proximity to qubits, thus enabling compact quantum error correction (QEC). Moreover, RF front-end and digital back-end can be integrated on a single silicon die, offering further size, cost, and power reduction.

One of the caveats of Cryo-RFICs, as opposed to COTS electronics, can be excessive noise and reduced accuracy, which arises from the restricted power consumption budgets at cryogenic temperatures. It is, therefore, crucial to identify the trade-offs at the system-level design and its impact on the qubit (control/readout) fidelity, to be able to implement practical and power efficient Cryo-RFICs. In this work, we focus on the readout electronics chain of superconducting qubits within the circuit QED framework. Through simulating the system dynamics, we analyze a demonstrative case of multi-qubit non-demolition, single-shot, high-fidelity (>99.9%) readout, featuring frequency domain multiplexing (FDM). We analyze the impact of the interrogating (probe) microwave-pulse source imperfections (amplitude/frequency/phase errors and noise, spurious harmonics and intermodulation distortions) and the homodyne demodulation chain design requirements (RF amplifiers gain and noise distribution, ADC speed and resolution etc.).

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Quantum-limited measurement and gates on spin qubits via curvature coupling to a cavity

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Keywords: TQD spin-qubit, SC resonator, longitudinal QND readout and control

Existing schemes for semiconductor spin qubit readout involve either spin-to-charge conversion or electric dipole coupling to a superconducting resonator. The former requires destructive readout while the latter suffers from enhanced qubit dephasing together with low qubit-cavity coupling, limiting the potential performance of quantum measurement and qubit-qubit entanglement generation: an open challenge in semiconductor quantum computing. Here we propose a new type of coupling to a superconducting resonator based on spin-qubit energy curvature vs. gate voltage which enables quantum non-demolition readout while the qubit resides in its full sweet spot and with zero dipole coupling (offering resilience to charge noise). Specifically, for an encoded spin qubit, a readout strength of tens to hundred MHz can be reached, at least 10 times larger than previously proposed schemes. We show how this curvature interaction generates “dispersive-like” spin-dependent resonator energy shifts, similar to circuit QED, but avoiding the Purcell effect. With the addition of gate voltage modulation, a longitudinal readout can also be switched on, selectively generating entanglement-by measurement for an n-qubit subsystem [1]. We also propose [2] a two-qubit entangling gate between encoded spin qubits based on the modulated longitudinal coupling which offers gate speeds of 10s of nanoseconds. This approach allows always-on, exchange-only qubits, for example, to stay on their ``sweet spots'' during all gate operations, minimizing sensitivity to charge noise [2].

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Investigating CMOS Based Local Bias Voltage Generation for Solid-State Qubit Potential Well Creation

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Keywords: Commercial 65nm CMOS, Cryogenic circuit design, Digital-to-Analog Converter, Bias voltage generation

Operation of a general purpose Quantum Computer requires millions of physical Qubits [1]. In order to reach this number a truly scalable electrical control approach and a corresponding rise in control and read-out capabilities will be necessary. As interfacing more and more Qubits is required, a natural approach is to integrate as much control and read-out capability as possible close to the Qubits. Therefore, it seems reasonable to use (semiconductor based) integrated circuits (ICs) located in the same cryogenic environment as the Qubits inside a dilution refrigerator. This gives rise to highly specific requirements and challenges calling for novel circuit approaches and architectures as well as application specific designs [2]. A proof of concept IC implementation is ongoing in order to demonstrate solid-state Qubit control by an adjacent placed CMOS Chip in the temperature regime around 100 mK using a commercial 65 nm technology. One major challenge is the broadly unexplored device behavior and lack of modeling of classical bulk CMOS processes at cryogenic temperatures below the freeze-out point of dopants (<30 K) [3]. Furthermore, today's low cooling power budget of dilution refrigerators at the lowest sub 1 K temperature stage of about 1 mW poses an additional challenge to the system solution and circuit design. First IC design approaches will be shown utilizing a 13 bit charge-redistribution DAC topology with 20 multiplexed output channels to deliver extremely stable DC output voltages (1 V dynamic range; voltage uncertainties of less than 30 µV) to form the potential well for gate defined lateral quantum dots (e.g. GaAs or SiGe based). First simulation results indicate the possibility of operating multiple GaAs based Spin Qubits (each requiring up to 10 distinct DC voltages) in parallel within the given cooling power budget. Promising early stage results of noise performance simulations are discussed and the next required steps towards a fully integrated proof-of-concept setup are introduced.

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Atomically-precise fabrication on silicon: Optimization of dangling bond properties and incorporation of acceptor dopants

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Keywords: Si(100) surface defects, boron dopants, ab initio simulations, scanning tunneling microscopy

STM-based lithography on silicon surfaces has been used to demonstrate both the functionalization of Si dangling bonds, and the incorporation of donor dopant atoms with near-atomic precision. Here we employ ab initio simulations to study the properties of dangling bonds on Si(100), and use simulations together with STM to study the adsorption of boron onto these dangling bonds. For dangling bonds, we show that their properties vary dramatically based on the thickness of the Si sample; we also show that the effect of strain is dependent on sample thickness [1]. We find that only for extremely thin Si samples (1-2 nm) can neutral DB states be isolated from bulk valence states; strain enhances this isolation only in these thin samples. Turning to the incorporation of dopant atoms, we explore the use of diborane precursors to attach boron atoms to the silicon surface. We demonstrate successful adsorption at both room and elevated temperatures, and show how early stages of decomposition of diborane have many similar steps to decomposition of phosphine and alane, but that important differences occur, especially at the final stages of decomposition. [1] P. Scherpelz and G. Galli, Physical Review Materials (Rapid Communication), accepted (2017). arXiv:1702.07747.

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Single-shot Readout of Spin states in a FDSOI Split-Gate Device with Built-in Charge Detector

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Keywords: spin qubits, single shot read-out, CMOS devices

The building block of quantum information is the quantum bit (qubit) which is made out of a two-level quantum system. In contrast with a classical bit the information is encoded in a superposition of 0 and 1. Along with entanglement, this property can be harnessed by specifically designed algorithms to achieve a computational acceleration for applications such as cryptography, searching large databases or simulation of quantum processes. In silicon-based quantum devices, the qubit is formed by the spin degree of freedom of charge carrier (electron or hole) trapped in quantum dots. Tremendous progress has been achieved in this field in the past five years [1]. We recently demonstrated two-axis control of the first hole spin qubit in Si transistor-like structures using a CMOS technology platform [2,3]. However, the qubit state was then evaluated by averaging repeated destructive measurements followed by qubit re-initialization. In order to perform fault-tolerant quantum computation with dynamic error correction codes [4], the single-shot (real-time) detection of the spin state is required [5]. This is achieved by coupling a Quantum Dot (QD) with a charge detector allowing non-invasive probing of the QD charge state, and a strategy for spin to charge conversion.

We report on the demonstration of real-time monitoring of the spin in a Quantum Dot using foundry-compatible Si MOS technology and a Split-Gate design with built-in charge detector. We demonstrated it on a compact object which is comparable to a classical nFET, with a wrapping Gate split in the middle of a mesa-isolated SOI NanoWire. Since single-shot readout is an indispensable step in the pursuit of Si-based fault-tolerant quantum computing, this work contributes to asserting the fabrication of Si spin qubits in a MOS technology platform as a viable and promising option.

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Phonon-induced relaxation and dephasing in a charge quadrupole qubit

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Keywords: phonon, Si/SiGe heterostructure, qubit

We study the effect of phonons on coherence of a charge quadrupole qubit in a Si/SiGe heterostructure. In general, charge qubits suffer fast relaxation due to charge noise. The recent suggestion of building the charge quadrupole qubit based on one electron in a triple quantum dot, provides the way to suppress the effects of charge noise. However phonon-induced noise still poses as a possible strong source of decoherence. We consider the dependence of relaxation rates between different states on interdot distance, the size of the dots, tunnel coupling, and quadrupolar detuning. We also study the temperature dependence of decoherence rates. We show that the larger the distance between dots, the faster the relaxation occurs. This arises from the fact that the phonons in our system are mainly long-wavelength, and a smaller device experiences their effect as an approximately constant shift in energy, which does not produce relaxation. We show that the change of quadrupolar detuning affects the relaxation rates drastically. The optimal arrangement for suppressing phonon noise is to minimize the quadrupolar detuning parameter, which could potentially cause problems for pulse sequences used to suppress the effects of charge noise. This leads to the conclusion that both these relaxation processes should be equally taken into account.

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Exchange coupling in silicon quantum dots from atomistic configuration interaction

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Keywords: Si double quantum dot, exchange coupling, Tight binding method, Full configuration interation

Two-qubit gates hosted with electron spins confined to silicon quantum dots have been experimentally demonstrated recently [doi:10.1038/nature15263]. The two-qubit gate operation relies on the exchange coupling between the electron spins, and is potentially sensitive to dot size and shape, electric and magnetic fields, and interface disorder. In this work, the exchange coupling in a silicon double quantum dot is studied as a function of these above mentioned factors using a large-scale atomistic tight-binding with full configuration interaction. The same method is also used to obtain energy levels of three-electrons in a disordered double quantum dot to understand tunnel couplings and exchange in a charge-spin hybrid qubit [10.1103/PhysRevLett.109.250503]. The simulations help to assess the range of variability in exchange coupling and its prospects for voltage control in multi-dot systems.

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Quantum dot devices with an overlapping palladium-aluminium oxide gate stack

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Keywords: quantum dots, silicon, palladium

Electron spins in gate defined quantum dots are promising candidates to operate as quantum bits. Increasing device yield, reproducibility and performance are among the key challenges. A fundamental understanding of, as well as optimization of and excellent control over the fabrication process is of considerable importance to achieve these goals. This poster presents our work on the fabrication of a quantum dot device with an overlapping gate structure consisting of palladium metal gates separated by a thin aluminium oxide layer grown by atomic layer deposition.

Lifting of Spin Blockade by Charged Impurities in Si-MOS Double Quantum Dot Devices

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Keywords: Spin qubits, Si MOS

Fabricating qubits in silicon metal-oxide-semiconductor (MOS) quantum dot devices for quantum information processing applications is attractive because of the long spin coherence times in silicon and the potential for leveraging the massive investments that have been made for scaling of the technology for classical electronics. One obstacle that has impeded the development of electrically gated MOS singlet-triplet qubits is the lack of observed spin blockade, where the tunneling of a second electron into a dot is fast when the two-electron state is a singlet and slow when the two-electron state is a triplet, even in samples with large singlet-triplet energy splittings. We present theoretical and experimental evidence that the cause of this commonly exhibited problem in MOS double quantum dots is the presence of stray positive charges in the oxide layer that induce accidental dots near the device's active
region that allow spin blockade lifting.

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Strain Mapping of Integrated Device Structures to Aid in Understanding QD Localization

Payam Amin, Nicole K. Thomas, Hubert C. George, Jessica M. Torres, James S. Clarke

Keywords: Strain mapping, QD formation, CTE induced strain

Many silicon qubit devices are affected from spurious quantum dot formation in unexpected locations. One model to explain this is strain induced by the difference in the Coefficient of Thermal Expansion between substrate and gate electrode materials that, at low temperatures, can lead to a sufficient modulation of the energy landscape to influence the location of dot formation, as shown by Zimmerman et al. [1]
A systematic approach to study the formation of QDs, and their location, is needed to allow for scaling from few- to many-dot-systems. This will facilitate energy landscape control over a larger area. Here, we focus on mapping strain in Si QD devices and linking our findings to device geometry and process conditions.
We present localized strain maps collected using nano-beam precession electron diffraction, a TEM technique, at room temperatures on a gate stack using materials typically used in an industrial semiconductor fabrication environment. We visualize tensile and compressive strain in a silicon substrate induced by metal electrodes deposited on top of the semiconductor substrate. As the first step, we compare the strain due to different gate geometries. Low temperature strain measurements capabilities exist and will be described. These will serve as a next step in our experimental plan.

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Capacitive coupling of hybrid dot-donor singlet-triplet qubits in silicon

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Keywords: singlet-triplet qubits, capacitive coupling, quantum dots, donors

Silicon provides a particularly attractive platform for realizing hybrid semiconductor qubits, as it supports both nuclear and electron spin qubits in well-isolated atomic impurities as well as highly tunable quantum dot-based spin qubits. Recent experiments [1,2] combine the favorable properties of both systems to demonstrate full coherent control of a singlet-triplet qubit in a hybrid silicon quantum dot-donor system via exchange and an intrinsic magnetic gradient provided by the hyperfine interaction with the donor nuclear spin. To investigate potential approaches for entangling these hybrid singlet-triplet qubits, we theoretically consider capacitive coupling in the presence of the hyperfine interaction. We calculate the interaction between two dot-donor systems as a function of operating point and explore the effects of both charge noise and uncertainty in the donor positions.

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Single Shot Pauli-Blockade in Lithographically Formed Few Electron MOS Double-Quantum-Dot Using a Single Layer Design

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Keywords: “MOS”, “double quantum dot”, “valley splitting”, ”Pauli Blockade”

Qubits formed with MOS leverage immediately existing silicon fabrication capability. However, it has been challenging to produce charge sensed, few electron, lithographically defined, MOS double quantum dots (QDs) tuned to the Pauli-blockade regime [1-2]. Tunable coupling between QDs is essential to reliable success for many semiconductor-based qubit schemes [3-7]. Double QD (DQD) systems in GaAs and Si-SiGe quantum well heterostructures have demonstrated control over this tunnel coupling [8-10], which has provided the tuning necessary for initialization and qubit operations. We introduce a Si-MOS DQD device that utilizes a Si-foundry compatible single poly-silicon gate layer design. We show that a well-defined few electron DQD can be achieved, for which the inter-dot tunnel coupling can be tuned over several orders of magnitude. A valley splitting of greater than 100μeV is measured for each QD. With this spitting, we demonstrate sufficient tuning of the DQD to form Pauli blockade at the (2,0)-(1,1) charge configuration. The Pauli-blockade is sensed with a remote QD charge sensor current that is amplified using a SiGe HBT cryogenic circuit allowing single shot resolution. This first demonstration of a tunable Si-MOS DQD is an important step forward for MOS QD qubits, with further advances foreseeable with isotopic enrichment of the Si substrate.

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Automated characterization of silicon photonic devices in the mid-infrared

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Keywords: Mid-Infrared Photonics, Photonic Devices

The spins of singly-ionized chalcogen donor atoms in silicon, measured and coupled via photonic cavity quantum electrodynamics, are being developed as a candidate 4K-compatible quantum platform. These deep donor systems have spin-selective valley-orbit transitions in the mid-infrared (MIR). Strongly coupling these transitions to near-resonant MIR cavities for single-spin, single-shot readout requires the development of low-loss and ideally high-yield MIR silicon photonic devices. Here we describe an automated test platform for the efficient characterization of silicon photonic devices operating in the mid-infrared.

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Coupling Si-based quantum dot qubits using microwave-frequency co-planar waveguide resonators

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Gate defined semiconductor quantum dots are a promising platform for spin based quantum computation due to their small device footprint and potential for scalability. While current designs in Si/SiGe based quantum dots can be scaled as linear chains of nearest-neighbor-coupled dots, it is important to develop methods for long range coupling between qubits. Coupling through the use of superconducting microwave resonators is a proven approach for creating two-dimensional connectivity via circuit Quantum Electrodynamics (cQED). For two qubit interactions mediated by a resonator, it is necessary for the interaction rate between the qubit and the resonator to be higher than the photon loss and qubit dephasing rates [1,2]. In this work we are interested in two qubit architectures: the charge quadrupole qubit [3] and the quantum dot hybrid qubit [4]. The charge quadrupole qubit is a triple dot qubit that incorporates resistance to quasi-static dipolar detuning noise through the symmetry of the quantum device design. The quantum dot hybrid qubit is a double dot qubit that has demonstrated long coherence times in comparison with double dot charge qubits. In this poster we present both theoretical simulations of cavity-to-quantum dot coupling and experimental measurements of resonators on Si/SiGe heterostructures. We present simulations showing achievable fidelities for coupling charge dipole and charge quadrupole qubits to co-planar waveguide resonators. In the experiments, to minimize photon loss, we have developed sample packaging and multilayer chip fabrication process aimed at minimizing radiative and dielectric loss while allowing for galvanic connection between the resonator and dot leads. Using on chip crossovers, low impedance microstrips, and quarter wave transformers, we demonstrate devices capable of DC biasing through the resonator with loaded quality factors around ~3500 in a fully integrated device.

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All-electrical control of donor-bound electron spin qubits in silicon

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We present a new design for donor based electronic spin qubits in silicon which provides a means to achieve all-electrical control of these qubits. The device consists a chain of alternating single (1P) and two donor (2P) quantum dots (QD) with ancillary 1P and 2P clusters. Alternating electric fields are to be applied from in-plane gates to control single qubit operations, while electrostatic detuning through either top or in-plane gates can be used for two-qubit operations. The device is typically suitable for fabrication by the scanning tunneling probe technique. By taking advantage of the hyperfine coupling difference between a 1P and a 2P QD, spin rotations for single qubit operations can be driven by an alternating electric field through an induced electric dipole. The detuning control of exchange coupling between the two donor-dots enables a highly tunable exchange interaction for two qubit operations, while reducing fabrication challenges of gate dimensions and densities, and also reducing the susceptibility to donor placement errors. Using a large scale atomistic tight-binding method and a time-dependent effective Hamiltonian description, we provide quantitative guidelines for the design of this device and also asses its performance.

Low-disorder gate-defined quantum dots in silicon

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Quantum dots in intrinsic silicon using a MOSFET-like architecture have attracted a lot of attention in the recent past for the formation of quantum bits. Disorder and unintentional quantum dots formed at the silicon-silicon oxide interface pose a major challenge for the reliable fabrication of such devices. We study devices following the established device layout [1] with aluminium gates and native aluminium oxide as the inter-gate dielectric by means of transmission electron microscopy. Our findings indicate that the native oxide formed all around the aluminium gates plays a role in the formation of the unintentional dots.

Therefore, we report on a novel fabrication route that replaces aluminium and its native oxide by palladium with atomic-layer-deposition-grown aluminium oxide. Using this approach, we show the formation of low-disorder gate-defined quantum dots that are reproducible across several fabrication runs. Furthermore, palladium enables us to further shrink the gate design, allowing us to perform electron transport measurements in the few-electron regime in devices comprising only two gate layers, a major technological advancement.

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