Donor Based Quantum Computing in Silicon

Lloyd C.L. Hollenberg, Centre for Quantum Computer Technology, School of Physics, University of Melbourne, Parkville 3010, Australia

While many systems have been proposed as qubits for a quantum computer, the actual physical requirements for fault-tolerant quantum information processing in a fully scaled-up architecture are only now starting to be understood. For any given implementation, these requirements for scale-up necessarily push designers well into the realms of quantum transport, control and systems engineering. This talk will concentrate on the silicon implementation and challenges for quantum computing based on donor degrees of freedom, and review the modelling hierarchy from the quantum atomic and nanoelectronic regime to the implementation and assessment of fault-tolerant quantum error correction.

Addressing the Charge and Spin of a Single Dopant Atom in a Nano MOSFET

Sven Rogge, Kavli Institute of NanoScience, Delft University of Technology

Current semiconductor devices have been scaled to such small dimensions that we need to take their atomistic nature into account to understand their operation. State of the art nano MOSFET are sufficiently small that the current below threshold can flow even through a single dopant atom [1]. This talk focusses on the physics of transport through a single n-type dopant in a semiconductor and the gate control of its wavefunction. Understanding and controlling a dopants wavefunction in a nanostructure is a key ingredient for Si quantum electronics. In our experimental system we are sensitive to a single As donor incorporated in the channel of a Si triple-gate transistor and we are able to measure the level spectrum and charging energy by means of transport spectroscopy. The measured level spectrum can be divided into levels associated with the donor potential, a triangular well at the interface, and hybridized combinations of those two [2]. The assignment is based on atomistic modeling of the dopant close to the interface in a tight binding approach. The combination of transport measurements and atomistic modeling can also be used as a nondestructive material probe for nano MOSFETs. It is possible to determine the local dopant density for an assemble of transistors with information of the individual chemical species, distance to the surface, and the local electrical field. Besides the gate control of the orbital degree of freedom of the dopant, data that link to the spin degree of freedom by the Kondo effect will be discussed.

Refs:
Progress Towards Quantum Logic using Donor Electron Spin Qubits in Silicon

Jeffery Bokor, Lawrence Berkley Laboratory

MOS architecture for control and readout of a single-atom electron spin qubit in silicon

A. Morello, C.C. Escott, K. Yen Tan, K.-W. Chan, C.D. Nugroho, N.A. Court,
L.H. Willems van Beveren, H. Huebl, F.E. Hudson, C. Yang, L.C.L. Hollenberg,
D.N. Jamieson, A.S. Dzurak and R.G. Clark

Centre for Quantum Computer Technology, Schools of Electrical Engineering & Physics,
University of New South Wales, Sydney 2052, Australia

Centre for Quantum Computer Technology, School of Physics, University of Melbourne,
Victoria 3010, Australia

Silicon is an ideal host for donor-based electron spin qubits. It can be isotopically purified to eliminate nuclear spins and obtain long electron spin coherence [1], and the negligible spin-orbit coupling ensures extremely long relaxation times. A great technological challenge is the application of standard CMOS technology to the coherent control of individual spins. Here we present a fully MOS architecture to control and readout the electron spin state of a single donor atom in silicon, to be exploited as a spin qubit for quantum information processing.

The device combines three techniques that have been recently developed: (i) single-ion implantation of individual phosphorus atoms, detected with high-fidelity by integrated P-I-N structures [2]; (ii) a radio-frequency Single Electron Transistor in silicon (Si-SET) [3], where the island of the SET is defined by tunable barrier gates that isolate a small region of electron gas that is induced by an overlying top gate [4]; and (iii) a local Electron Spin Resonance (ESR) line, consisting of a coplanar transmission line terminated by a short circuit, to supply microwave pulses and coherently control the spin state. The spin readout is obtained by spin-to-charge conversion [5], where the donor electron can tunnel into a reservoir only when it is in the excited spin state. The innovative idea here is to use the Si-SET as a fast and sensitive detector for the charge transfer, and the SET island as the electron reservoir for spin-dependent tunneling. This yields a compact and elegant ‘Atom-MOS’ structure, and very large charge transfer signals enabling one-shot spin readout with high fidelity.
For the key step of controlling the electron tunneling between individual donors and gate-induced reservoirs, we have fabricated and measured test structures for low-temperature transport experiments. Individual donors are placed underneath a barrier gate that has the function of shifting their electron levels with respect to the Fermi level of the electron reservoirs induced by the top gate. Resonant tunneling through the donor states and analysis of the capacitive coupling provides essential information on the donor spectroscopy near a Si/SiO2 interface.


Single phosphorus dopant state spectroscopy using silicon SETs

H. Huebl\(^1\), C.D. Nugroho\(^1\), A. Morello\(^1\), N. Court\(^1\), F.E. Hudson\(^1\), C. Yang\(^2\), J.V. Donkelaar\(^1\), A. Alves\(^1\), D. Jamieson\(^2\), A.S. Dzurak\(^2\) and R.G. Clark\(^2\)

\(^1\)Centre for Quantum Computer Technology, Schools of Electrical Engineering & Physics, University of New South Wales, Sydney 2052, Australia

\(^2\)Centre for Quantum Computer Technology, School of Physics, University of Melbourne, Victoria 3010, Australia

Charge centres, such as donors in semiconductors, have significant potential for quantum information processing. In silicon, which can be produced nuclear-spin free, phosphorus donors are a prime candidate for implementation of a qubit, due to their long spin coherence times. In this presentation we will discuss a hybrid structure, consisting of implanted phosphorus donors controlled by a gate potential in close vicinity to a gate-induced, MOS-based silicon single electron transistor (Si-SET). We study the dual functionality of the nearby Si-SET as a sensitive charge detector as well as a gate-induced electron reservoir. Experimentally, we observe shifts in the position of the Coulomb peaks of the Si-SET corresponding to ~20% of an electron charge. We attribute these shifts to charge transfers between the Si-SET island reservoir and the nearby phosphorus donors.

External Field Control of Donor Electrons at the Si-SiO2 Interface

Belita Koiller, Instituto de Física, Universidade Federal do Rio de Janeiro Cx.Postal 68528, 21941-972 Rio de Janeiro, Brazil

We analyze several important issues for qubit operations in the Si quantum computer architecture involving single P donors close to a SiO\(_2\) interface. We investigate the donor-
bound electron manipulation between the donor and the interface by electric and magnetic fields. We establish conditions to keep the donor-bound state at the interface in the absence of local surface gates, and estimate the maximum planar density of donors allowed to avoid the formation of a 2DEG at the interface. We also estimate the times involved in single electron shuttling between the donor and the interface.

References
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   Calderón, MJ; Koiller, B; Das Sarma, S

STM-patterned P-donor based planar Quantum Dot structures in Silicon

Martin Fuechsle, A. Fuhrer, T.C.G. Reusch and M. Y. Simmons
Centre for Quantum Computer Technology, University of New South Wales, Sydney, NSW 2052, Australia

We demonstrate a fully UHV-based fabrication scheme for STM-patterned planar, highly phosphorus doped quantum dot structures on a Si(100) surface. This technique allows for atomically precise, multi-terminal, in-plane gated donor-based quantum devices. We present electrical transport measurements on an optimized five-terminal 40 x 50 nm² quantum dot containing roughly 4000 electrons. Using an in-plane plunger gate, we observe remarkably stable Coulomb oscillations up to 4K.

By adding an EBL-defined metallic top-gate, patterned on the native oxide barrier, we are able to tune the electron number on the dot by ~350. At temperatures below 1K, we observe clear Coulomb oscillations as a function of top-gate voltage. Also, by applying a top-gate voltage, we are able to tune the gate-range of the in-plane barrier gates from 0 to more than 1V.

Our current investigations focus on the electronic properties of the tunnelling barriers as well as the impact of a metallic top-gate on device stability. Future devices will focus on going towards the few electron regime by reducing the size of the island. The intricate change of cross-capacitances within the dot structure associated with downscaling necessitates careful considerations in terms of device geometry in order to achieve full depletion.
Single Ion Implantation using Focused Ion Beam and Geiger Mode Detection

Ed Bielejec, Sandia National Laboratories, Member of Technical Staff, Radiation – Solid Interactions

Applications of electrically-detected magnetic resonance: towards spin-based quantum electronics in silicon.

Dane R. McCamey, Department of Physics, University of Utah

Spin is a fundamentally quantum mechanical property – harnessing it for electronic applications promises advances which are inaccessible with classical charge-based devices. I will discuss an approach that employs spin control of the charge observable in silicon electronic devices, namely electrically-detected magnetic resonance (EDMR).

EDMR allows us to exploit the whole range of spin manipulation techniques developed over the last 60 years for conventional electron spin resonance, and also provides electrical readout and possibly single spin sensitivity. EDMR can be used to map coherent spin states onto electrical conductivity in a wide range of systems; organic [1], amorphous [2] and crystalline [3], thus allowing important information about spin in such systems to be accessed, and possibly exploited. EDMR may also have uses in more standard silicon spintronic application, such as recently demonstrated silicon spin-FETs [4].

One important application of EDMR is in the readout of phosphorus donor spin qubits in silicon. Previously, a limiting factor of such measurements has been the inability to measure long phase coherence times, which until now have been limited to ~2μs [5]. By exploiting EDMR at high magnetic fields [6], we have developed a technique to measure long coherence times of phosphorus donor electrons in silicon (T2 > 100μs) [7]. Due to the nearly complete electron polarization, these high magnetic fields provide large signals, enabling fast readout. Additional benefits are gained by using high fields. We have recently demonstrated a non-equilibrium Overhauser-driven nuclear spin antipolarization technique which allows silicon nuclear spin antipolarization of ~70% to be obtained, simply by shining white light onto the sample [8]. Such a technique may be used to obtain initialized nuclear spin qubits in silicon.


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**Si QC Work**

Sankar Das Sarma, *University of Maryland, Professor*

**Pulsed Electron Spin Resonance Measurements of Spin Coherence in Si Structures**

Shayam Sankar, Princeton University

**Spin-Dependent Scattering in a Silicon Transistor**

Rogerio de Sousa, *University of Victoria, BC, Assistant Professor*
Quantum Workshop
Abstracts
Day Two

Error Correction for Solid-State QC

Austin Fowler, University of Waterloo, Ontario, Institute for Quantum Computing

We describe an error correction procedure well-suited to solid-state quantum computing. Given a 2-D square lattice of qubits with tunable nearest neighbor interactions and the ability to initialize and measure any qubit, we show how to tolerate gate error rates approaching 1% with modest qubit overhead. We also show that pairs of logical qubits separated by arbitrarily large distances can be interacted with linear qubit and logarithmic time overhead, thus showing that robust and rapid quantum computation is possible with only nearest neighbor interactions.

Protecting Quantum Information with Optimal Control

Matthew Grace, Sandia National Laboratories

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

Message Passing in Fault Tolerant Quantum Error Correction

Dr. Ashley Stephens, University of Melbourne
Recently we have observed spin blockade in a Si/SiGe double quantum dot. Under the same gate voltage conditions, but with the opposite direction of current flow, we observe current inside the allowed bias window, but outside the conventional bias triangles, an effect we called lifetime-enhanced transport. This effect depends equally on long spin relaxation times and on energy dependent tunneling, which causes preferential loading of states that are close to the Fermi level of the leads. Energy dependent tunneling appears to be a particularly prominent effect in our data. In this talk we discuss the role of energy dependent tunneling in lifetime enhanced transport, we extract tunneling rates from our data, and we discuss the implications of energy dependent tunneling for spin readout.

Accumulation-Mode Quantum-Dot Devices

Andrew Hunter, HRL Laboratories

M. Borselli, E. Croke, M. Gyure, R. Hayes, I. Milosavljevic, A. Schmitz, J. Moon, and A. Hunter, HRL Laboratories, 3011 Malibu Canyon Road, Malibu CA 90265

We have developed a quantum-dot device based on a double-well heterostructure in which electrons are localized in the top, mostly empty well by forward biasing a small circular gate. Charge occupancy changes in the dot are monitored by measuring current confined to a narrow channel in the bottom well. In this design, dot occupancy is primarily controlled by a single gate and interacting dots can be straightforwardly fabricated.

We have successfully fabricated and characterized single-dot devices of this design in AlGaAs/InGaAs, and are extending the design to SiGe/Si heterostructures. We have measured charging spectra of III-V versions of the device down to zero electron occupancy. Charging spectra show enhanced stability for $n=2, 6, 12, \text{and } 20$ electrons. Tunneling times for dot occupancy changes are controlled by the thickness of the barrier between the wells, and we have, so far, focused on devices with 10nm barriers and tunneling times on the order of several hundred microseconds. We have measured the tunneling times as a function of bias to map out excited states of a two-electron dot. Leakage from the gate to dot under forward biases required for dot occupancy is very low, less than one electron per second, and can be made negligibly small.

SiGe versions of these devices are more challenging due to smaller conduction band offsets and larger dopant ionization energies compared to the AlGaAs/InGaAs system. However, based on measurements of both single- and double-well SiGe devices, we have determined layer dimensions and doping levels leading to appropriate well occupancy (empty upper well and occupied lower well under the free surface). We have also fabricated more conventional depletion-gated designs using similar single-well SiGe heterostructures and have demonstrated the formation of low-electron-number dots. These results indicate material properties of SiGe heterostructures should support our accumulation-mode quantum-dot design.

Sponsored by United States Department of Defense Approved for Public Release, Distribution Unlimited

Ge/Si Nanowire-Based DQD w/ Charge Sensor

Yongjie Hu, Harvard University,
Electron-Phonon Interaction Induced Dephasing of Exchange Coupled Spin Qubits in Si Nanostructures

Xuedong Hu, University at Buffalo

We study theoretically the decoherence of exchange-coupled electron spin qubits through interaction with the lattice fluctuations. We first establish how electron-phonon interaction can affect two exchange-coupled electron spins, and show that its main effect is to cause pure dephasing between the two-electron singlet and triplet states because of their different charge distributions. We then investigate the types of electron-phonon interactions and the phonon modes involved for Si nanostructures, specifically Si/SiGe quantum dots and P2 molecules in Si:P. In particular, we show that two-spin dephasing in Si is dominated by deformation potential coupling to longitudinal acoustic phonons. An interesting aspect of electron-phonon interaction induced pure dephasing is that it does not lead to a complete loss of coherence between the singlet and triplet states. Instead, it leads to a constant loss of contrast that is dependent on wave function overlap between the two quantum dots. Since the dephasing and the exchange coupling have different dependence on the overlap, there exists a regime where dephasing due to electron-phonon interaction is still small while exchange coupling is reasonably large.

SOI Structures for Quantum Computing

Dr. David Williams, Cambridge

Two Dimensional Electron Systems with Mobility Exceeding $10^5$ cm$^2$/Vsec On Hydrogen-Terminated Silicon Surfaces

Bruce Kane, University of Maryland

Coauthors: Robert McFarland and Tomek Kott

It is likely that future semiconductor quantum information processing devices will be built from material systems with extremely low densities of defects that can either trap electrons or cause qubit decoherence. Additionally - if qubits are based on individual dopants – fabrication will require essentially atomic level precision, most readily accomplished if the dopants are positioned at or near a surface. These ideas have led us to the development and investigation of two dimensional electron systems induced by an electric field on a chemically-prepared hydrogen-terminated silicon <111> surface.

In this talk I will describe our recent magnetotransport measurements on a sample with a peak mobility of 110,000 cm$^2$/Vsec that exhibits a clear signature of the fractional quantum Hall effect developing at low temperatures. I will also discuss our preliminary work on determining if surface doping is a feasible route to creating bound states on silicon surfaces that could be used for future quantum information processing devices. Finally, since our fabrication process
remains unoptimized, it seems probable that electrons on silicon surfaces can have even higher mobilities, comparable to those heretofore obtained only using high vacuum heteroepitaxy.

**Valley Splitting in Quantum Dots**

Mark Friesen, *University of Wisconsin*

The energy levels of electrons in a silicon quantum well are split into nearly degenerate valley states. This splitting plays a crucial role for spin qubits. Recent work has shown that the valley splitting can be suppressed below its expected value when the quantum well interface is rough, or grown on a tilted substrate. On the other hand, the theoretical maximum can be recovered in quantum devices with strong lateral confinement. I will discuss recent theoretical results for valley splitting in quantum dots and quantum point contacts, taking into account rough interfaces. In particular, we determine the valley splitting as a function of device dimensions, and show that it can be large.

Work performed in collaboration with S. Coppersmith, M. Eriksson, R. Joynt and L. Reusch, with funding from ARO/LPS and NSF.

**Modeling Physical Qubits Using Tight-binding and Effective Mass Theories**

Rick Muller, *Sandia National Laboratories, Member of Technical Staff, Multiscale Dynamics Materials Modeling*
Density Functional Theory modeling of defects in silicon

Daniel W. Drumm¹, Faruque M. Hossain², Salvy P. Russo³, and Lloyd C. L. Hollenberg¹
1 Centre for Quantum Computer Technology, School of Physics, University of Melbourne, Parkville 3010, Australia
2 Quantum Communications Victoria, School of Physics, University of Melbourne, Parkville 3010, Australia
3 Applied Physics, School of Applied Sciences, RMIT, Melbourne 3001, Australia

e-mail of corresponding author: danielwd@physics.unimelb.edu.au

Atomic defects in semiconductors are responsible for both the room temperature conduction of bulk. Understanding the way these defects affect the material properties of the host is essential to the quantum computing, quantum information transport and quantum encryption fields. To further this understanding, an effort using ab initio methods to model defects such as single impurity atoms, vacant lattice sites, and structured combinations thereof will be undertaken. The defects considered will be hosted primarily in silicon.

The effects of ion implantation on Si-SiO2 interface trap densities in Si-based solid-state quantum computer device development

B. C. Johnson¹, M. L. Dunn¹, E. Gauja² and J. C. McCallum¹,
1 ARC Centre of Excellence for Quantum Computer Technology, School of Physics, The University of Melbourne, Parkville, Victoria, Australia
2 ARC Centre of Excellence for Quantum Computer Technology, School of Physics, University of New South Wales, Sydney, NSW, Australia, 2052

e-mail of corresponding author: johnsonb@unimelb.edu.au

Ion implantation doping of Si through an SiO2 overlayer is of interest for fabrication of advanced MOSFET’s and for a range of devices of interest in the development of a solid–state quantum computer (SSQC). SSQC–related devices that are currently being fabricated include structures in which spin–dependent transport is measured, or where charge transfer occurs between quantum dots or between individual donors. The implantation requirements of these devices cover ion fluences in the 10¹¹ – 10¹⁴ cm⁻² regime at energies typically in the range 10 – 20 keV and usually require implantation through a pre-existing thin device–quality thermal oxide. The subsequent thermal processing steps that are required to activate the implanted ions and repair the oxide and substrate damage should also ideally result in very limited diffusion of the implanted ions. Deep level transient spectroscopy (DLTS) in its various forms provides a convenient means of identifying and quantifying the electrically–active defects introduced within the bulk and at the SiO2–Si interface by the oxide–growth and implantation processes and it can
be used to monitor their removal via subsequent annealing steps. Of particular importance to the solid–state quantum computer fabrication program is the fact that DLTS measurements on metal–oxide semiconductor (MOS) structures allow the near–oxide interface region to be probed at sensitivities that are suitable for the ion fluence regime of interest and more importantly at defect densities that could adversely affect quantum device operation. In this presentation we will describe some of the key device structures that are currently being explored in the process of developing Si-based solid state quantum computing devices and present results from our DLTS studies of ion–implanted MOS capacitors in which interface–trap densities have been measured in as–grown and H– passivated thermal oxides and in ion implanted (P, Si or N) and rapid–thermally processed devices. For thin oxides of 5 nm or less and low ion fluences we find that implantation does not significantly increase interface trap densities and somewhat surprisingly that it can even be beneficial when the interface trap density is abnormally high (~ 1011 cm-2.eV-1) for the as-grown oxide. The implications of these studies for solid-state quantum computer development will be discussed.

**Electrical and optical measurement techniques for Si:P based devices**

Susan J. Angus, Paul Spizzirri, Nikolas Stavrias and Steven Prawer

*ARC Centre of Excellence for Quantum Computer Technology, School of Physics, The University of Melbourne, Parkville, Victoria, Australia*

A number of electrical and optical measurement techniques have been developed for the characterization of Si:P based devices. A silicon radio-frequency single electron transistor has been demonstrated at 4.2K, opening up the possibility of fast, sensitive detection at liquid helium temperature. Photoluminescence spectroscopy has been applied to low energy P+ ion implanted samples, with signals from donor clusters identified. The shift in the energy of the cluster peaks has been successfully modeled via a hydrogenic approximation of donor nearest neighbor interactions. Phosphorus donor electronic states have been mapped using Raman spectroscopy. We have a demonstrated capability to measure the temperature dependence of ground state occupation and changes in transition energies to better than 0.1meV.

**Towards Atomically Precise Single Donor Devices Patterned by STM**

Bent Weber, W.Pok, T.C.G. Reusch, M. Fuechsle, A. Fuhrer and M. Y. Simmons

*School of Physics, University of New South Wales, Sydney, NSW 2052, Australia*

In order to fabricate single phosphorus donor quantum bits in silicon using scanning tunnelling microscopy lithography we investigate the geometries and resulting electrical characteristics of the crucial components of these devices such as atomic scale dopant wires for source-drain electrodes or in-plane gate applications as well as STM fabricated tunnelling gaps.

As the size of these components shrink towards the atomic scale we observe distinct changes in the electrical transport. Dopant wires show a conductance of $2e^2/h$ consistent with a fully
transmissive single mode quantum wire as the width of the wire approaches the few donor atom regime. STM-fabricated tunnelling gaps exhibit a high zero bias resistance of $500\text{M}\Omega$ for an optimised gap geometry and a reduced electron tunnelling cross-section.

We incorporate these optimised components into the design of a STM-patterned, in-plane gated, single electron transistor (SET), we observe Coulomb blockade behaviour. Stable Coulomb diamonds have been recorded for transport measurements at $80\text{mK} - 4\text{K}$. The charge on the SET-island could be varied by up to $40e$ within the applied range of gate voltages. As we further improve our devices by employing numerical 3D capacitance modelling (FASTCAP) to optimise source-drain and in-plane gate separations we open up the pathway for the fabrication of all-in-plane fabricated single donor quantum devices.

**Broadband electrically detected magnetic resonance of phosphorus donors in a silicon field-effect transistor**


Centre for Quantum Computer Technology, Schools of Electrical Engineering & Physics, University of New South Wales, Sydney 2052, Australia

M.S. Brandt

Walter Schottky Institut, Technische Universität München, Am Coulombwall 3, D-85748 Garching, Germany

We report electrically detected magnetic resonance of phosphorus donors in a silicon field-effect transistor. An on-chip transmission line is used to generate the oscillating magnetic field allowing broadband operation. At milli-kelvin temperatures, continuous wave spectra were obtained up to 40 GHz, using both magnetic field and microwave frequency modulation. The spectra reveal the hyperfine-split electron spin resonances characteristic for Si:P and a central feature which displays the fingerprint of spin-spin scattering in the two-dimensional electron gas.

Resonant tunneling through individual implanted P donors in Si: Spectroscopy and spin splitting of a single atom

K. Yen Tan¹, K.-W. Chan¹, A. Morello¹, C. Yang², J.V. Donkelaar², A. Alves², D. Jamieson², A.S. Dzurak¹ and R.G. Clark¹

¹Centre for Quantum Computer Technology, Schools of Electrical Engineering & Physics, University of New South Wales, Sydney 2052, Australia
²Centre for Quantum Computer Technology, School of Physics, University of Melbourne, Victoria 3010, Australia

Transport spectroscopy of a single phosphorous donor is obtained by resonant tunneling between the source and drain of a MOS-compatible, double-gated silicon nano-field-effect-transistor (nanoFET). Individual phosphorous atoms, locally implanted below a barrier control gate with different selected acceleration energies (7keV and 14keV), show coupling strengths to the gate, source and drain that are consistent with the proximity of the donors to the Si/SiO₂ interface. Two possible charge states have been observed that, in a magnetic field, are successively occupied by spin-up and spin-down electrons. These two resonant states are separated by a charging energy consistent with that between the $D^0$ and $D^-$ charge states of a phosphorous donor, when electrostatic coupling to surrounding electrodes is taken into account. This experiment provides important understanding of phosphorus donor energy levels needed for the realization of Si:P spin-based qubits for quantum information processing.

Using Integer Programming for Error Correction on a Bilinear Array

Cynthia Phillips, Robert Carr, Anand Ganti, Sandia National Laboratories

In a (future) quantum computer a single logical quantum bit (qubit) will be made of multiple physical qubits. These extra physical qubits implement mandatory extensive error checking. The efficiency of error correction will fundamentally influence the performance of a future quantum computer, both in latency/speed and in error threshold (the worst error tolerated for an individual gate).

In this poster, we consider a reasonably simple architecture: the bilinear array, introduced by Hollenberg et al. Executing this quantum error correction requires scheduling the individual operations and moving qubits, or the information associated with qubits, to locations where they can interact in gates. This is a multiprocessor, precedence-constrained scheduling problem, with additional routing constraints. We describe this scheduling problem and present an initial integer programming model.

Sandia is a multipurpose laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
Coulomb Blockade in Double Top Gated Si MOS Nano-Structures

Eric Nordberg, Sandia National Laboratories

Valley Splitting in Electrostatically Confined Structures at the Si/SiO2 Interface

Lisa Tracy, Sandia National Laboratories

Fixed Charge and Interface Trap Density Dependence on Oxide Thickness Measured by Capacitance-Voltage Technique

Greg Ten Eyck, Sandia National Laboratories