Silicon Quantum Electronics Workshop

2018

13th -15th of November 2018
Sydney, Australia
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The Silicon Quantum Electronics Workshop focuses on silicon-based approaches to realizing quantum electronics circuitry such as quantum computers. The three-day workshop unites the leading researchers, students, and postdocs in the field to discuss advances in silicon quantum device fabrication, measurement, modeling, and theory.

The local organising committee consists of Professor Michelle Simmons, Professor Andrew Dzurak, Professor Sven Rogge, Professor Andrea Morello, Dr Matthew House, Dr Joris Keizer, Dr Arne Laucht, Dr Jarryd Pla, Tony Raeside and Esra Ertan.

The international organising committee includes Dr Malcolm Carroll, Professor Mark Eriksson, Dr Mark Gyure, Professor Kohei Itoh, Professor Steve Lyon, Dr Marc Sanquer, Dr Thomas Tarman and Professor Lieven Vandersypen.

Venue:

Jones Bay Wharf
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T +61 2 8571 0622

Contact:

Esra Ertan (UNSW)
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M: +61 432 147 463
# Program

**Day 1 – Tuesday 13th November 2018**

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<td>Sam Gorman</td>
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<td>Alessandro Crippa</td>
<td>Dispersive readout of a spin qubit by gate reflectometry</td>
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<td>Miguel Gonzalez</td>
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<td>2.10-2.30pm</td>
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<tr>
<td>2.45-5pm</td>
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<td>9.10-9.30am</td>
<td>James Owen</td>
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<td>9.30-9.50am</td>
<td>Simon Cooil</td>
<td>In-situ patterning of ultra-sharp dopant profiles in silicon</td>
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<tr>
<td>9.50-10.10am</td>
<td>Justin Wells</td>
<td>The electronic band structure of delta doped silicon</td>
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<td><strong>10.10-10.40am</strong></td>
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<td><strong>10.40am-12.20pm</strong></td>
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<td>10.40-11am</td>
<td>Simon Schaal</td>
<td>A CMOS dynamic random access architecture for radio-frequency readout of quantum devices</td>
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<td>11.00-11.20am</td>
<td>Gertjan Eenink</td>
<td>Hot silicon MOS spin qubits</td>
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<td>11.20-11.40am</td>
<td>Stephen Lyon</td>
<td>Low disorder Metal-Oxide-Silicon double quantum dots</td>
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<td>11.40-12pm</td>
<td>Sophie Rochette</td>
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<td>12-12.20pm</td>
<td>Alejandro Márquez Seco</td>
<td>Single-atom nanoMOSFETs in silicon</td>
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<td><strong>Lunch</strong></td>
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<td><strong>1.30-2.50pm</strong></td>
<td>Session 6: Theory</td>
<td>Chair - Brandur Thorgrimsson</td>
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<td>1.30-1.50pm</td>
<td>Xuedong Hu</td>
<td>Decoherence of a donor-dot flip-flop qubit in Si</td>
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<td>1.50-2.10pm</td>
<td>Maximilian Russ</td>
<td>Quadrupolar exchange-only (QUEX) spin qubit</td>
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<td>2.10-2.30pm</td>
<td>Charles Hill</td>
<td>Architecture for a 2D surface code quantum computer based on exchange-coupled donor qubits in silicon</td>
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<td>2.30-2.50pm</td>
<td>Garnett Bryant</td>
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<td>MengKe Feng</td>
<td>Coherent transfer of singlet-triplet qubit states in an architecture of triple quantum dots</td>
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<td>4-4.20pm</td>
<td>Aaron Jones</td>
<td>Spin-Blockade Spectroscopy of Si/SiGe Quantum Dots</td>
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<td>4.20-4.40pm</td>
<td>Toby Jacobson</td>
<td>For better or for worse: spin-orbit coupling and its physical manifestations in Si quantum dot qubits</td>
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<tr>
<td>4.45pm</td>
<td>Close</td>
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<tr>
<td>6pm</td>
<td>Workshop dinner</td>
<td>Cruise departs at 6.15pm sharp from Star Casino Wharf</td>
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<tr>
<td>9pm</td>
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<td>Cruise returns to Star Casino Wharf</td>
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<td>10.10-10.40am</td>
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<td>10.40am-12.20pm</td>
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<td>10.40-11am</td>
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<tr>
<td>11-11.20am</td>
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<td>12-12.20pm</td>
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<td>1.50-2.10pm</td>
<td>Nicole Thomas</td>
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<td>Andy Mounce</td>
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<td>Harald Homulle</td>
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<td>2.50-3.10pm</td>
<td>Justyna Zwolak</td>
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<td>Lars Schreiber</td>
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<td>4-4.20pm</td>
<td>Yuanxing Xu</td>
<td>A Si/SiGe based quantum dot with floating gates for scalability</td>
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<tr>
<td>4.20-4.40pm</td>
<td>Brandur Thorgrimsson</td>
<td>Silicon, Superconductivity, Stability, and the Search for Gateability</td>
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### Afternoon Tea

3.40-4.40pm

### Close

4.40-4.50pm

Announcement of 2019 Silicon Workshop – Dr María José Calderón

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The Sydney organising committee thanks you for your attendance and wishes you all safe travel home.
Gate fidelities and noise correlations in a two-qubit Si/SiGe quantum dot device

X. Xue$^{1,2}$, J. M. Boter$^{1,2}$, T. F. Watson$^{1,2}$, J. Helsen$^1$, D. R. Ward$^3$, D. E. Savage$^3$, M. G. Lagally$^3$, V. N. Premakumar$^3$, M. Friesen$^3$, R. Joynt$^3$, S. N. Coppersmith$^3$, M. A. Eriksson$^3$, S. Wehner$^1$ and L. M. K. Vandersypen$^{1,2}$

$^1$QuTech, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands
$^2$Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands
$^3$University of Wisconsin-Madison, Madison, WI 53706, USA

Various candidate implementations for future quantum computers have been investigated over the past twenty years. Silicon spin qubits show great promise for quantum computing, because of their relative insensitivity to noise leading to long coherence times, as well as the potential integration with conventional CMOS technology. However, gate fidelities and noise properties in two-qubit devices have been studied only to a limited extent. In this work we use a two-qubit device in a Si/SiGe heterostructure [1] to study both the fidelities of single-/two-qubit operations and the correlations of noise from the environment.

We employ randomized benchmarking to quantify the fidelities for both single- and two-qubit gates. Single-qubit gates are benchmarked on both qubits individually as well as simultaneously, to probe cross-talk effects. For the two-qubit controlled-phase gate, we characterize its behaviour by interleaving it with single-qubit Clifford operations on the target qubit [2]. In addition, we develop and experimentally verify a new method which we call character randomized benchmarking. It allows us to extract the fidelity of the controlled-phase gate by interleaving it only with single-qubit Cliffords on both qubits in parallel. This is more resource efficient and moreover provides tighter bounds on the controlled-phase gate fidelity than the traditional methods [2, 3].

Furthermore, noise correlations are investigated by studying the dephasing in two subspaces formed by either anti-parallel or parallel Bell states. These Bell states are insensitive to either correlated or anti-correlated noise, resembling the concept of decoherence-free subspaces, which allows us to extract the uncorrelated, correlated and anti-correlated contributions to the noise affecting the qubits from the dephasing times in different subspaces [4]. Knowledge about the noise properties makes it possible to design operations that are less sensitive to this noise, and yields information on the noise source, which potentially makes it possible to reduce the noise.

A two-qubit gate between phosphorus donor electrons in silicon

Y. He*, S. K. Gorman*1, D. Keith1, L. Kranz1, J. G. Keizer1 and M. Y. Simmons1

1Centre of Excellence for Quantum Computation & Communication Technology,
UNSW Sydney, Sydney, Australia.

Electron spin qubits formed by atoms in silicon have large (tens of meV) orbital energies and weak spin-orbit coupling giving rise to isolated electron spin ground states with seconds long coherence times [1]. Exquisite high fidelity (>99.9 %) coherent control of these qubits has also been demonstrated promising an attractive platform for quantum computing [2]. However inter-qubit coupling, an essential ingredient for reaching large-scale circuits in atom-based qubits, has yet to be demonstrated. Exchange interactions between spins [3] promise fast (GHz) gate operations and two-qubit gates have recently been demonstrated in silicon quantum dots [4-6]. Yet until now, creating a tunable exchange interaction between two electrons bound to phosphorus atom qubits has not been possible. This reflects the challenges in knowing how far apart to place the atoms to turn on and off the exchange interaction, whilst aligning atomic circuitry for high fidelity independent read out of the spins. Here we report a fast (~800 ps) \( \sqrt{SWAP} \) two-qubit exchange gate between phosphorus donor electron spin qubits in silicon with independent ~94 % fidelity single shot spin read-out on a complete set of basis states. By engineering qubit placement on the atomic scale, we provide a route to the realisation and efficient characterisation of multi-qubit quantum circuits based on donor qubits in silicon.

References


* These authors contributed equally to this work.
Fidelity benchmarks for two-qubit gates in silicon

W. Huang\textsuperscript{1}, C. H. Yang\textsuperscript{1}, K. W. Chan\textsuperscript{1}, T. Tanttu\textsuperscript{1}, B. Hensen\textsuperscript{1}, R. C. C. Leon\textsuperscript{1}, M. A. Fogarty\textsuperscript{1,2}, J. C. C. Hwang\textsuperscript{1}, F. E. Hudson\textsuperscript{1}, K. M. Itoh\textsuperscript{3}, A. Morello\textsuperscript{1}, A. Laucht\textsuperscript{1} and A. S. Dzurak\textsuperscript{1}

\textsuperscript{1} Center for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, NSW 2052, Australia
\textsuperscript{2} London Centre for Nanotechnology, UCL, 17-19 Gordon St, London WC1H 0AH, United Kingdom
\textsuperscript{3} School of Fundamental Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan

Universal quantum computation will require qubit technology based on a scalable platform, together with quantum error correction protocols that place strict limits on the maximum infidelities for one- and two-qubit gate operations. Silicon-based quantum dot qubits are amenable to large-scale manufacture and can achieve high single-qubit gate fidelities [1-2] (exceeding 99.9 \%) using isotopically enriched silicon. However, while two-qubit gates have been demonstrated in silicon [3-5], it has not yet been possible to rigorously assess their fidelities using randomized benchmarking, since this requires sequences of significant numbers of qubit operations (\(> 20\)) to be completed with non-vanishing fidelity. Here, for qubits encoded on the electron spin states of gate-defined quantum dots, we demonstrate Bell state tomography with fidelities ranging from 80 \% to 89 \% and two-qubit randomized benchmarking with an average Clifford gate fidelity of 94.7 \% and average Controlled-ROT (CROT) fidelity of 98 \%. These fidelities are found to be limited by the relatively slow gate times employed here compared with the decoherence times \(T_2^*\) of the qubits. Silicon qubit designs employing fast gate operations based on high Rabi frequencies [2,6], together with advanced pulsing techniques, should therefore enable significantly higher fidelities in the near future.

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

Mateusz Madzik\textsuperscript{1}, Arne Laucht\textsuperscript{1}, Vincent Mourik\textsuperscript{1}, Vivien Schmitt\textsuperscript{1}, Fay E. Hudson\textsuperscript{1}, Kohei M. Itoh\textsuperscript{2}, David N. Jamieson\textsuperscript{3}, Andrew S. Dzurak\textsuperscript{1}, and Andrea Morello\textsuperscript{1}

\textsuperscript{1}CQC2T, School of Electrical Engineering \& Telecommunications, UNSW Australia, Sydney NSW 2052, Australia
\textsuperscript{2}School of Fundamental Science and Technology, Keio University, 3-14-1 Hiyoshi, Kanagawa 223-8522, Japan
\textsuperscript{3}CQC2T, School of Physics, University of Melbourne, Melbourne, Victoria 3010, Australia

Ion-implanted 31P donor spin qubit devices is enriched 28Si have achieved coherence times as long as 30 seconds and gate fidelities beyond 99.9\%, with electron spin resonance linewidths of order 2 kHz [1]. This suggests a strategy to implement 2-qubit logic gates mediated by exchange interaction, where a native CNOT gate is obtained by a microwave pulse at a resonance frequency that depends on the state of the other qubit. [2]. Newly fabricated devices with an increased implantation dose revealed a high number of donors in the vicinity of a single-electron transistor. Electron spin resonance (ESR) spectra show spectroscopic evidence of exchange-coupled donor pairs. We present a preliminary demonstration of CNOT 2-qubit logic gate using state-conditional ESR pulses.

References


Towards high-fidelity CNOT gate based on phosphorous qubits in silicon

M. Usman\(^1\), C.D. Hill\(^1\), B. Voisin\(^2\), J. Salff\(^2\), M.Y. Simmons\(^2\), S. Rogge\(^2\), and L.C.L. Hollenberg\(^1\)

\(^1\)Center for Quantum Computation and Communication Technology, School of Physics, The University of Melbourne, Parkville, VIC 3010 Australia
\(^2\)Center for Quantum Computation and Communication Technology, School of Physics, The University of New South Wales, Sydney, NSW 2052 Australia

Phosphorus donors in silicon are one of the leading qubit candidates for the design of spin-based devices and quantum computing architectures \([1,2]\) due to the associated long coherence times \([3]\). In the recent years, there has been remarkable progress including fabrication of P atoms in silicon with single atom precision \([4]\), post-fabrication metrology of exact P spatial locations \([5]\), controllable coupling between two P donors \([6]\), and a theoretical proposal for a scalable quantum computing architecture \([2]\). Current state-of-the-art atomic precision fabrication of P atoms in silicon has demonstrated an accuracy of donor placement within one lattice-site variation \([4]\). However, even such small donor position uncertainties could result in variations in electron-electron exchange interactions, leading to a reduction in quantum gate fidelities. This work theoretically discusses pathways based on system characterisation and robust control to mitigate exchange variations arising from small donor position variations in STM fabrication and achieve two-qubit CNOT gates with fidelities commensurate with the error-correction threshold limit. We also investigate how the application of a small strain field offers additional flexibility in the design of high-fidelity CNOT gates.

Time-resolved single-shot single-gate RF spin readout


Australian Research Council Centre of Excellence for Quantum Computation and Communication Technology, School of Physics, UNSW, Sydney, New South Wales, 2052, Australia

For solid-state spin qubits, single-gate RF readout can minimise the number of gates required for scale-up since the readout sensor can integrate into the existing gates used to manipulate the qubits [2,3]. However, state of the art topological error correction codes benefit from the ability to resolve the qubit state within single-shot, that is, without repeated measurements [4,5]. Here we demonstrate single-gate, single-shot readout of a singlet-triplet spin state in silicon, with an average readout fidelity of 82.9% at 3.3 kHz measurement bandwidth. We use this technique to measure a triplet $T_-$ to singlet $S_0$ relaxation time of 0.62 ms in precision donor quantum dots in silicon. We also show that the use of RF readout does not impact the spin lifetimes ($S_0$ to $T_-$ decay remained approximately 2 ms at zero detuning). Thus, the use of single-gate RF readout now presents a viable option in a scalable quantum computer as also seen by other groups in recent submissions [6,7].

Gate-based single-shot readout of spins in silicon

A. West\(^1\)*, B. Hensen\(^1\)*, A. Jouan,\(^2\) T. Tanttu\(^1\), C.H. Yang\(^1\), A. Rossi\(^3\), M.F. Gonzalez-Zalba\(^4\), F.E. Hudson\(^1\), A. Morello\(^1\), D.J. Reilly\(^2,5\) and A.S. Dzurak\(^1\)

\(^1\)Centre for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, NSW 2052, Australia

\(^2\)ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, NSW 2006, Australia

\(^3\)Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom

\(^4\)Hitachi Cambridge Laboratory, J.J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom

\(^5\)Microsoft Corporation, Station Q Sydney, The University of Sydney, Sydney, NSW 2006, Australia

* These authors contributed equally

A scalable error-corrected quantum processor will require repeated error detection across its constituent qubits. At present, the requisite single-shot spin qubit measurements are performed using on-chip electrometers[1,2], capacitively coupled to the quantum dots. However, as the number of qubits is increased, this approach becomes impractical due to the complexity of the electrometers, combined with the required proximity to the quantum dots[3]. Gate-based dispersive sensing allows detection of single electron tunnelling in semiconductor quantum dots without the need for an external charge sensor[4]. Moreover, dispersive sensing of inter-dot charge transitions in tunnel coupled quantum dots combined with Pauli spin-blockade can be used to readout the electronic spin state without the need for a nearby electron reservoir[5-7]. These properties can significantly reduce gate count and architectural complexity of extended one- or two-dimensional arrays of quantum dots[8-10]. At present, it has not been possible to achieve single-shot spin readout using a gate-based technique. Here[11], we detect single electron tunnelling in a double quantum dot and demonstrate that gate-based sensing can be used to readout the electronic spin state in a single shot, with an average readout fidelity of 73%. The result demonstrates a key step towards the readout of many spin qubits in parallel, using a compact gate design that will be needed for a large-scale semiconductor quantum processor.

Dispersive readout of a spin qubit by gate reflectometry

A. Crippa1, R. Maurand1, R. Ezzouch1, A. Aprá1, A. Amisse1, X. Jehl1, M. Sanquer1, M. Urdampilleta2, T. Meunier2, B. Bertrand3, L. Hutin3, M. Vinet1 and S. De Franceschi1

1Université Grenoble Alpes & CEA INAC-PHELIQS, F-38000 Grenoble, France
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In contrast to local charge sensors routinely implemented for readout of spin qubits, gate-coupled RF reflectometry makes use of a gate of the quantum device as a charge transfer detector [1, 2]. This may partially mitigate the proliferation of electrodes for on-chip charge sensing and in perspective ease the qubit layer structure of a quantum processor [3, 4].

Here, we demonstrate gate-reflectometry readout of a spin qubit in silicon. A lossy lumped-element resonator ($Q \approx 20, L = 220 \text{nH}$) embeds a prototypical qubit device fabricated with a standard CMOS process flow. The sample is a p-type silicon etched-nanowire Field Effect Transistor [5]; at $T_{\text{base}} = 15 \text{mK}$ the qubit functionality is achieved by operating just two gates in series wrapping the nanowire. The DC biases of these gates tune an isolated hole double quantum dot (DQD) in the wire, while two distinct RF tones (one per gate) allow spin manipulation and accomplish dispersive readout. At finite magnetic field ($B \sim 0.5 \text{T}$) a microwave excitation drives electric dipole spin resonance (EDSR) transitions between two spin states thanks to spin-orbit interaction [6]; the EDSR dispersive signal relies on the different quantum capacitances associated to singlet and triplet states of the DQD, which result in a spin-dependent phase response of the resonator.

Coherent single-spin control is achieved by varying the duration of the microwave burst, which reveals Rabi oscillations with a minimum period of 85 ns.

Such a readout scheme could allow dispersive spin detection in few-qubit, gate-dense structures like quantum dot arrays.

Gate-based readout: Rules for optimal performance

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In the quest for scaling up silicon-based quantum computing, readout by already existing
gate electrodes has gained prominence due to its reduced impact in the qubit layout and
comparable sensitivities to conventional charge sensors. Gate-based sensing enables readout of
spins by projective measurements using the state-dependent differential capacitance of the
system [1,2]. Recently, single-shot readout has been achieved with this technique [3-5] but
further improvements are necessary to set gate-based readout well above quantum error-
correction thresholds.

We present results that highlight the steps to maximize the sensitivity of capacitive gate-
based readout. At the device level, the dispersive signal can be enhanced by increasing the gate-
coupling to the quantum system. Here, high-k dielectrics are the key [6]. At the resonator level,
a high loaded quality factor and good matching to the line are essential. These can be achieved
by using superconducting elements and optimal circuit topologies [7, 8]. Finally, at the
electronics readout level, the sensitivity can be further improved by reducing the noise floor
using quantum-limited Josephson parametric amplification.

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Over the last fifty years, the CMOS (Complementary-Metal-Oxide-Semiconductor) electronics industry has been continuously scaling down transistors in size, to increase performance and reduce power consumption. Nowadays, the smallest transistors in industry achieve 5nm features. As a result, those silicon structures tend to exhibit undesirable quantum effects for a classical transistor which appear to be new research opportunities for quantum information processing.

In particular, it is nowadays possible to trap single electron spins in silicon quantum dots and perform high fidelity quantum gates\textsuperscript{i}. These demonstrations combined with the intrinsic properties of the silicon lattice\textsuperscript{ii} (low spin orbit and hyperfine interaction) make CMOS device an excellent candidate for scalable quantum architectures.

In this presentation, we will show how we can detect a single spin in a CMOS device thanks to an original approach which combines gate-based dispersive charge sensing and a latched Pauli spin blockade mechanism\textsuperscript{iii}. For this purpose, we use a double quantum dot coupled to a single reservoir where one of the dot carries the spin information while the second dot is used as an ancillary dot to perform the readout.

This scalable method allows us to read out a single spin with a fidelity above 99% for 1 ms integration time\textsuperscript{iv}. Moreover, we show that the demonstrated high read-out fidelity is fully preserved up to 0.5 K. This results holds particular relevance for the future co-integration of spin qubits and classical control electronics.

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Spin Dynamics in Strongly Coupled Spin-Photon Hybrids

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Solid-state based quantum systems (e.g. single spin systems like NV centers in diamond or phosphor donors in silicon, superconducting qubits, nanomagnets, and nanomechanical elements) are building blocks for devices exploiting quantum phenomena. With different quantum systems available, coupling schemes have moved into focus. In particular, sufficient coupling enables information transfer between the individual sub-systems.

Here, we focus on spin-photon hybrids based on paramagnetic spin ensembles and superconducting microwave resonators. We will quantitatively analyze various planar superconducting resonator geometries regarding their performance in electron spin resonance experiments. This includes the homogeneity of the microwave magnetic field and the numerical analysis of the collective coupling strength between the spin ensemble and the resonator modes. At temperatures in the 30-300 mK regime, we expect and observe strong coupling between microwave resonator and the spin system. Using pulsed, Hahn-echo type experiments, we explore the temporal dynamics of the coupled system and observe a more complex behavior compared to conventional pulse sequences. We present a model describing the observations.
Towards coupling a superconducting circuit with a single spin

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Superconducting qubits are often considered as a leading potential candidate for the physical realization of a quantum computer. These qubits can be easily fabricated, manipulated and coupled together using simple linear electrical elements like capacitors, inductors and transmission lines. However, they suffer from rather poor coherence times due to their macroscopic size.

A promising research direction is to combine these qubits with spins in semiconductors and construct a hybrid quantum system. Indeed, spins may have extremely long coherence times and could therefore be a perfect system to reliably store the quantum information while superconducting qubits with their strong coupling with external fields are perfect systems to easily process fast quantum gates.

Efficient transfer of quantum information between these systems requires reaching the so-called “strong coupling regime” where the coupling between the different systems is much larger than their decoherence rates. In this talk, I will present our progress and current experimental efforts in the quest for reaching the strong coupling regime between a superconducting circuit and a single spin [1-3].

Exploring the sweet spot regime of singlet-triplet qubits coupled to a microwave resonator

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Coupling semiconducting quantum dot qubits to microwave resonators is one of the most promising strategies for performing two-qubit gates beyond nearest-neighbor interactions. However, for spin qubits, the coupling is typically weak, so it may be necessary to hybridize the spin and charge degrees of freedom to enhance the interaction [1, 2, 3]. In this regime, the qubit-photon system is unfortunately more sensitive to charge noise. The optimal working point therefore represents a trade-off between strong coupling and strong decoherence, making it desirable to identify sweet spots to improve the gate fidelity.

Singlet-triplet $S-T_0$ qubits are robust against global magnetic noise and, at the symmetric operating point, charge fluctuations [4]. However, strong coupling to a resonator requires hybridizing the $(1,1)$ and $(0,2)$ singlet states, making the qubit more sensitive to charge noise. We find that, in the operating regime where the tunnel coupling is comparable to the magnetic field gradient, sweet spots emerge, that are distinct from the symmetric operating point, but offer interesting opportunities for high-fidelity gate operations.

In this work we explore this sweet-spot regime, which provides both resilience to charge noise and strong dipolar coupling to the resonator. We analyze the trade-offs between strong coupling, relaxation, dephasing, and leakage to the $(0,2)$ singlet state, and we maximize the resulting gate fidelities. We identify a wide window in parameter space over which the qubit-resonator system can achieve strong coupling.

References


Robust Fabrication and Measurement of Atomically Precise, Single Electron Transistors

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NIST is developing atomically precise, atom-based electronic devices for use in quantum information processing (QIP) and quantum materials research. We are using hydrogen-based scanning probe lithography to enable deterministic placement of individual dopant atoms1 with atomically aligned contacts and gates to fabricate single electron transistors for use in spin-to-charge conversion, initialization, and readout in qubit operation.

We have developed robust lithography, device relocation, and contact processes that enable routine electrical measurement of atomically precise devices with an emphasis on minimizing process-induced dopant movement.2 Our low temperature palladium silicide contact process provides low-resistance ohmic contacts with yield better than 98% while maintaining process temperatures below 250°C.3

In addition to our fabrication technology, this presentation will cover measurements of STM patterned test structures and few-nanometer scale wire devices to investigate low dimensional transport and materials properties. We will present the characterization of reproducible atomic-scale tunnel junctions and single electron transistors that demonstrate stable coulomb blockade oscillations. We will demonstrate controlled variation in electronic and quantum properties as a function of atomic scale changes in device geometry. Our low temperature measurements demonstrate superb charge stability with minimal switching events.

In summary, our research is focused on the design and fabrication of QIP devices and emerging 2D quantum metamaterials with specific attention to atomically precise dopant placement and robust processes that yield reproducible atom-scale geometrical configurations.

References
STM chlorine resist lithography on Si(100)-2×1 surface
for the fabrication of donor-based atomic scale devices

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We propose a method for the incorporation of phosphorus atoms into the upper Si(100) layer with high precision instead of the selected Si atom. The mask on the Si(100) surface is formed in the chlorine monolayer with the scanning tunneling microscope (STM) tip patterning to create Si vacancies. The difference between the chlorine and hydrogen monolayers is most pronounced in thermal desorption experiments: SiCl₂ compound removes from the Si(001)-2×1-Cl surface [1], while hydrogen desorbs from Si(001)-2×1-H as H₂ molecule [2]. Therefore, one can expect that as a result of electron-stimulated desorption, atomic defects containing a silicon vacancy will be created by STM tip.

To predict the possibility to utilize chlorine resist for phosphorus incorporation into silicon lattice we have studied PH₃ interaction with Si(001)-2×1-Cl surface. Phosphine adsorption on Si(001)-2×1-Cl surface with mono- and bivacancies in the adsorbate (Cl, Cl₂) layer and combined vacancies with removal of silicon atoms (SiCl and SiCl₂), was investigated by density functional theory (DFT) calculations [3]. In the case of the SiCl vacancy, phosphorus was found to occupy the vacant place in the silicon lattice in the form of compound PH, while in the case of the SiCl₂ vacancy — in the form of PH₂. Calculated activation barriers for phosphine dissociation in SiCl and SiCl₂ vacancies are about 0.1–0.5 eV. Therefore, PH or PH₂ incorporate in the surface layer selectively within local defects (SiCl or SiCl₂) at room temperatures.

After phosphine adsorption, the surface should be covered with epitaxial silicon layers. To study the possibility of silicon epitaxy on chlorinated Si(100)-2×1 surface, we investigated the adsorption of a single silicon atom on Si(100)-2×1-Cl as the starting process of Si epitaxy [4]. According to DFT calculations, the incorporation of a silicon atom under Cl monolayer proved to be the most energetically favorable process. In addition, we found that at Si adsorption, SiCl₂, SiCl₃, and SiCl₄ clusters can be formed above a Si(100)-2×1-Cl surface. SiCl₂ clusters are bound weakly to the substrate, and their desorption leaves the silicon surface free of chlorine. Our results show that chlorine segregates to the surface during Si deposition and does not incorporate into homoepitaxial layers.

As a starting point of our method realization, we prepared Si(100)-2×1-Cl surface with a low defect density (< 0.4%). The possibility of creation pits in Si(100)-2×1-Cl by STM tip has been demonstrated and the mechanism of pits creation has been discussed.

This work was supported by Grant No. 16-12-00050 from the Russian Science Foundation.

Improving HDL Dopant Placement Precision


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Hydrogen Depassivation Lithography (HDL) using an STM tip has become established as a method for atomic-precision patterning for P-dopant-based devices. For devices such as the ‘single atom transistor’[1], single dopant atoms need to be placed precisely relative to other device elements, such as electrodes, gates, other single dopant atoms. Furthermore, for 2D Quantum Metamaterials[2], arrays of single dopants are required, with extreme precision and high yield. As the scope of buried-dopant devices expands, other dopant elements are also being considered, each of which will require its own placement and incorporation strategy.

As the demands upon STM lithography expand, the limitations of current STM technology are being exposed. Piezoelectric elements suffer from both time-dependent position errors, creep, and position-history-dependent errors, hysteresis, which make precise open-loop tip positioning with atomic precision difficult. Secondly, the feedback control loop, while in principle sensitive to motions of a fraction of an atomic dimension, can easily become unstable, particularly under lithography conditions, causing failure of the tip, contamination of the pattern, patterning errors, and other problems.

As we continue to develop the ZyVector™ automated STM lithography control system, we aim to address all of these technological issues. As we reported previously, real-time creep and hysteresis correction reduce tip position errors significantly. Over a 100 nm area, creep correction can reduce errors to less than one dimer row allowing for effectively perfect patterning, while on the larger scale, position errors are reduced by 80-90%. Hysteresis correction reduces the position errors caused by large motions when making the bigger parts of device patterns, saving time on relocating and repositioning the tip for each step. Correction in the z direction greatly reduces the settling time of the tip after landing, so that processes requiring that the z feedback loop be switched off, such as atom manipulation, can be performed more quickly after landing.

Recently, we have implemented a real-time measurement of the local barrier height[4], so that the PI loop can be made more responsive, while not becoming unstable, thereby reducing the frequency and severity of tip events, and allowing for faster scanning and lithography. With better control over the tip height during lithography, the line edge roughness of narrow patterns is improved. We are now developing an automated Feedback Controlled Lithography process for single-dopant pattern creation. By moving away from lithography conditions as soon as a H removal is detected, single-atom and single-dimer patterns can be created. This process can be automated to make arrays of single-dimer patterns.

By making these separate, but complementary, improvements to the STM control system, we hope to achieve significant improvements in the precision, speed and efficiency of STM as a lithography tool. Furthermore, we believe that these improvements will also feed back into the performance of STM as a microscope.

References

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In-situ patterning of ultra sharp dopant profiles in silicon

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We demonstrate a new method for patterning a buried two-dimensional electron gas (2DEG) in silicon using low kinetic energy electron stimulated desorption (LEESD) of a monohydride resist mask. A buried 2DEG forms as a result of placing a dense and narrow profile of phosphorus dopants beneath the silicon surface; a so-called δ-layer. Such 2-dimensional dopant profiles have previously been studied theoretically, and by angle-resolved photoemission spectroscopy, and have been shown to host a 2DEG with properties desirable for atomic scale devices and quantum computation applications. Here we outline a new patterning method based on low kinetic-energy electron beam lithography, combined with in-situ characterisation, and demonstrate the formation of patterned features with dopant concentrations sufficient to create localized 2DEG states.
The electronic band structure of delta doped silicon

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The electronic bandstructure contains complete information about the occupied electronic states which exist in a material. For example, intrinsically including information on doping, Fermi velocities, confinement, the orbital nature of the bands, spin-coupling and all possible interactions. Measuring the electronic bandstructure is possible using using techniques derived from photoelectron emission spectroscopy; but for non-surface-localised phenomena, there are particular challenges involved. As a result of this, studies of δ-doped silicon are scarce [1-3].

I will present our recent developments in developing photoelectron spectroscopies for studying δ-layers (and derived structures). More specifically; the simultaneous quantisation of both the conduction and valence bands in Si:P δ-layers [4], understanding the observed sub-band structure (see figure) [5], the response of the the 1Δ and Γ states to confinement, the role of spin-orbit coupling in Si:P δ-layers, and the electronic properties of in situ patterned dopant structures [6].

Figure 1: The band structure of an Si:P δ-layer: The most occupied band (a.k.a. 1Γ) splits into two branches in the axial directions. In fact, although only 2 bands are expected, 3 bands are clearly visible in the measurement.

A CMOS dynamic random access architecture for radio-frequency readout of quantum devices

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Quantum computing technology is maturing at a relentless pace, yet individual quantum bits are wired one by one. As quantum processors become increasingly more complex, they will require efficient interfaces to deliver signals for control and readout while keeping the number of inputs manageable. Digital electronics may offer solutions to the scaling challenge by leveraging established industrial infrastructure and applying it to integrate silicon-based quantum devices with conventional CMOS circuits. Here, we demonstrate the building blocks of a dynamic-random access architecture for efficient readout of complex quantum circuits. The architecture integrates quantum devices and digital electronics operating at millikelvin temperatures. The circuit is divided into two cells, each containing a field-effect transistor that enables selective readout of a CMOS quantum dot (QD) device. Charge can be stored on the QD gate similar to 1T-1C DRAM technology. We show dynamic readout of the charge state of two QDs by interfacing them dispersively with a single radio-frequency resonator. We measure the charge retention time and give guidelines for optimal operation. Finally, we propose a scaled-up architecture that reduces the number of input lines per qubit and could enable addressing large-scale device arrays.

References


Hot silicon MOS spin qubits

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Quantum superposition and entanglement, the most fundamental principles of quantum mechanics, may be exploited to construct powerful quantum computers that can radically change the way we process and think about information. Decoherence is a central challenge in these systems and leading solid-state approaches focus on decreasing the operation temperature to almost zero Kelvin to combat thermal noise. However, a crucial question is if the available cooling power will be sufficient for operation of thousands or millions of qubits required for practical quantum computing. If qubits could be operated at elevated temperatures, this would create a pathway to quantum integrated circuits hosting the qubits, interconnects and control electronics all on the same chip [1,2,3].

Here, we explore the prospects of operating silicon quantum dot qubits at elevated temperatures and even above 1 K. We show silicon MOS qubit devices fabricated on isotopically purified \textsuperscript{28}Si wafers with overlapping gates, using a novel integration scheme. We study both experimentally and theoretically the temperature and magnetic field dependence of the spin lifetime. We find spin lifetimes above 1 ms at 1 K and propose strategies for further improvement [4,5]. We demonstrate ‘hot’ qubit operation and discuss the promises for scalable and practical quantum processors.

References

Low disorder Metal-Oxide-Silicon double quantum dots

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Metal-oxide-silicon (MOS) structures are the mainstay of silicon device technology, but many groups have opted to use Si/SiGe heterostructures for quantum devices, instead, in part due to concern about the quality and performance of the Si/SiO$_2$ interface at the single electron level. Si/SiGe heterostructures can exhibit low-temperature mobilities which are as much as two orders of magnitude larger than typical MOS structures.[1] However, if the disorder in MOS structures can be controlled, they have advantages in terms of the ease of integrating donor impurities with quantum dots, and relatively large quantum-dot valley splitting. While a number of MOS quantum-dot and donor-based devices have been demonstrated, scaling MOS quantum dots to multi-qubit systems has lagged behind Si/SiGe systems, where an array of nine uniform quantum dots has been shown.[2]

We will present data from a double quantum dot where a reconfigurable “dual rail” architecture[3] has been adapted to MOS technology. These devices have been made using an MOS process designed to reduce the density of very shallow electron traps[4] and allow reproducible quantum dot devices to be fabricated. The underlying process has been shown to produce very low critical and shallow trap densities (8.3 - 9.5×10$^{10}$ cm$^{-2}$), and simultaneously very high mobilities (1.4 - 2.3×10$^4$ cm$^2$/Vs) despite exposure to high-energy processes like electron-beam lithography.[5] These densities are within a factor of two of Si/SiGe heterostructures. Low frequency bias spectroscopy measurements through the individual dots in the upper channel show regular Coulomb blockade diamonds, demonstrating low levels of disorder with uniform charging energies consistent with the lithographic size of the dots. Defining a charge sensor dot in the center of the lower conduction channel allows measurements of each upper channel quantum dot down to the single-electron regime. The controllable formation of a quantum double-dot is also demonstrated.

The presence of defects is always a concern in MOS structures, and a total of 3 distinct defect states capable of localizing an electron can be seen in the charge stability diagrams when scanned over a wide range of voltages. That number is approximately consistent with the density expected from this process. Charge-noise spectroscopy measurements yield a 1/f power spectral density with a value of 3.4 μeV/Hz$^{1/2}$ at 1 Hz and 300mK, consistent with other reported values of charge noise in MOS and Si/SiGe devices. Monitoring the N=0→1 and N=1→2 transition as a function of a perpendicular magnetic field, we find a valley-splitting of 110±26 μeV. Overall, these results provide evidence that reproducible MOS spin qubits are feasible, and that this process represents a promising platform for their development.

References

Quantum dots in ultra-thin body and buried oxide 28 nm FD-SOI

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Leveraging the capabilities of the semiconductor industry for the fabrication of quantum devices through standard manufacturing processes offers one of the most promising avenues for reliable fabrication of multi-qubit devices \cite{1-2} and co-integration \cite{3-5}. Here we present a quantum dot device fabricated with STMicroelectronics’ ultra-thin body and buried oxide (UTBB) 28 nm fully-depleted silicon-on-insulator (FD-SOI) technology. The device is entirely fabricated inside a standard process line \cite{6} and relies on a split enhancement gate design for electrostatic formation of quantum dots and reservoirs \cite{7}. We explore various regimes in gate voltage space and demonstrate reproducible operation of multiple devices at 1.5 K and 10 mK. With transport measurements we identify conditions for the formation of quantum dots in various regimes, including electrostatic single and double quantum dots. These results help establish pathways toward improved FD-SOI devices with fully tunable lithographic quantum dots manufactured in a modern transistor processing line.

![Figure 1: (a) 3D schematic of the split enhancement gate UTBB FD-SOI device. (b) Stability diagram for G1 and G3 side gates showing a single quantum dot, at a temperature of 1.5 K. Inset: top-view of the estimated location of the quantum dot (QD) and reservoirs in the regime of (b).](image)

References


Single-atom nanoMOSFETs in silicon

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Single-atom devices in silicon are very promising for the implementation of spin qubits: the nuclear spin of an atom can store quantum information, while its electrons can mediate interactions with nearby atoms [1]. Furthermore, the electron and nuclear spin states can be read out [2].

At the University of Twente, we study transport through atoms in silicon nano-MOSFETs. We implant arsenic ions with low doses in the conduction channel. To measure single-electron transport, we fabricate MOSFET devices similar to [3] with extra gates to modify the electrochemical potential in the implantation area.

At 4.2 K, electron transport measurements of 4 different devices showed signatures of a single-atom transistor: only two Coulomb diamonds with charging energies between 25 and 50 meV for the first transition. In non-implanted devices, several transitions are often measured with charging energies below 20 meV. In contrast, much disorder appears in devices implanted with high doses, indicating charge transport through many atoms.

(a) Schematic cross section and (b) top view of the device. The green square defines the region with implanted atoms. (c) Charge transport through a non-implanted device, (d) through devices implanted with $5 \times 10^{11} \text{ at/cm}^2$ and (e) with $5 \times 10^{12} \text{ at/cm}^2$.

Decoherence of a donor-dot flip-flop qubit in Si

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A recent proposal for a scalable donor-based quantum computer architecture promises excellent coherence properties, fast qubit couplings and insensitivity to donor placement [1]. The suggested system consists of two different types of qubits per donor: a flip-flop qubit of the electron and nuclear spins at the donor site, and a charge qubit of the electron tunneling between the donor and an interface quantum dot. The proposal identifies a parameter regime where qubit dephasing due to electrical noise is strongly suppressed, even though charge motion is a crucial component of the qubit.

Here we study in detail the decoherence properties of the qubit when positioned at and near this sweet spot. In particular, we study the effect of charge noise on the flip-flop qubit. The flip-flop qubit is indirectly coupled to the noise via the dependence of the hyperfine interaction and the electron gyromagnetic ratio on whether the electron is located at the donor or the interface dot. We find that while zero and low-frequency contributions to the dephasing rate are indeed suppressed at the sweet spot, finite-frequency contributions come into play via coupling to the charge excited states. We explore various dependences of this decoherence channel, and determine how it can be modified by external controls such as the applied magnetic field and tunnel coupling between the donor and the dot.

We thank support by US ARO.

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We propose a quadrupolar exchange-only spin (QUEX) qubit [1] that is highly robust against charge noise and nuclear spin dephasing, the dominant decoherence mechanisms in semiconductor quantum dots. The qubit consists of four electrons trapped in three quantum dots [see Fig. 1 (a)], and operates in a decoherence-free subspace to mitigate dephasing due to nuclear spins [2]. To reduce sensitivity to charge noise, the qubit can be completely operated at an extended charge noise sweet spot that is first-order insensitive to electrical fluctuations. The QUEX qubit has several desirable features: Firstly, the QUEX qubit offers a significant improvement in protection against charge noise due to the flatter qubit dispersion originating from screening effects [see Fig. 1 (b) (c)]. Additionally, there are no internal matrix elements in the qubit subspace states from local magnetic fields, thus making it superior in terms of noise protection without addition in operational complexity. Finally, the qubit energy splitting is given by valley splitting and on-site exchange mediated by the Coulomb interaction, which makes the energy splitting electrically tunable to an amount as large as several GHz even in the “off”-configuration and at the sweet spot. This strongly tunable qubit splitting paves the way for novel cavity coupling mechanisms [3] and makes it compatible to conventional superconducting transmission line resonators with the aim of producing long-distance entanglement. All these properties render the QUEX qubit suitable for implementation in a large-scale quantum information processing architecture.

Figure 1: (a) Illustration of the proposed four-spin qubit residing in a triple quantum dot. The four spins are coupled via inter-dot and onsite exchange interaction. There are two electrons in the center dot giving rise to a large and electrostatically tunable energy splitting. (b) Estimated dephasing time $T_{\phi}$ of the QUEX qubit due to low-frequency charge noise. (c) Estimated dephasing time $T_{\phi}$ of the exchange-only (AEON) qubit due to low-frequency charge noise for comparison.

Architecture for a 2D surface code quantum computer based on exchange-coupled donor qubits in silicon

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Spin qubits in silicon based on quantum dots and/or donor confinement are promising candidates for quantum computing [1]. The development of topological quantum error correction (TQEC) codes such as the surface code has provided a scheme for error correction with a relatively high threshold that is commensurate with experiments [2-5]. While the physical requirements of the surface code are relatively straightforward to contemplate – a two dimensional array of nearest-neighbour coupled qubits. However, for all physical qubit platforms, even with assumptions about quantum interconnects [6], the challenges inherent in the spatial arrangement of gates, and temporal characterisation and control complexity for \(N\) independent qubits to carry out TQEC are formidable. The introduction of shared control [7] in this architecture design space reduces the spatial complexity and dovetails naturally with the repetitive spatio-temporal control requirements of surface code TQEC, and is one of the few architecture proposals that attempts to address the full challenge of scale-up. In demanding a high level of uniformity and a fundamental qubit pitch of \(\sim 35\) nm, CNOT gates are based on the donor electron spin dipole interaction with a phase-matched electron loading protocol to rectify timing variations associated with the hyperfine interaction. Ideally, one would use the exchange interaction, however, the severe spacing requirements (<20nm) and inherent variations in the exchange coupling work against the design of a 2D array for TQEC. Here we propose a new donor spin architecture based on shared control in a 35nm pitch control-line array, which incorporates fast exchange coupled spin qubits without the need for phase matched loading at the qubit site. Atomic level simulations, with typical placement variations expected in STM fabrication, indicate CNOT gate times at us and below are possible and the overall scheme has potential to meet the stringent control requirements of the surface code.

Quantum simulations with dopant-based arrays: extracting quantum and many-body information

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Atomically precise placement of dopants in Si provides exciting opportunities for quantum computing with dopant qubits. At the same time, the creation of dopant arrays provides new approaches to perform quantum simulations in the limit where temperature is much less than hopping and interaction energies [1, 2]. Significant challenges exist for realizing atom-based solid-state simulations. Hopping between dopants can be sensitive to the dopant separation, making disorder in dopant separation a critical effect [3]. Valley physics complicates any models that might be built for simulations. At the same time, very closely spaced dopants are needed to realize quantum simulations with hopping comparable to or greater than the interaction. Nevertheless, it is important to understand what can be learned about many-body physics, generation and transfer of quantum information and resources like entanglement from small, finite-size, atom-based solid-state quantum simulations. Moreover, it is also important to understand how to extract this information from experimental simulations.

Here we describe simulations done for one-dimensional arrays of atoms used to implement an extended range Fermi-Hubbard model. For small systems with up to 20 atoms we find not just the ground state, but all of the excited states of the interacting system. For systems with 20-30 atoms we can still find a large number of the low-energy excitations. We show that multiple regimes exist depending on the relative strength of hopping and interaction. For strongly interacting systems the dominant low excitations are quantum plasmons. More strongly interacting systems are strongly correlated. For even stronger interaction, hopping becomes the weak effect. We show how to characterize the full spectrum of excitations using measures such as the single-particle excitation content to reveal the crossovers between regimes. We add qubits to each end of the chain and show how interacting states on the chain can mediate qubit-qubit coupling. We discuss ways to simulate colliding and interfering many-body excitation. Finally, we discuss ways that one might get this information out of experimental simulations [4,5]. As one example, we discuss the possibility of developing the scanning tunneling microscope as an analog to the quantum gas microscope used for simulations with ultracold atoms to interrogate entanglement and interaction between different many-body excitations [6].

References


Analyzing the fidelity of a singlet-triplet spin-orbit qubit in silicon using gate set tomography

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It has been recently demonstrated that spin-orbit effects observed in silicon quantum dots are much larger than what is expected for bulk silicon [1-3]. These spin-orbit effects can be used to achieve all-electrical universal control of a double quantum dot singlet-triplet qubit without the need for any external components, such as micromagnets or microwave resonators, to produce a magnetic field gradient [4]. In this work, we use gate set tomography to analyze the fidelity of these gates. We also explore the possibility of using AC control, both in the weak and strong driving regimes, to improve the fidelity of qubit operations.

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-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the DOE’s National Nuclear Security Administration under contract DE-NA0003525

References

Coherent transfer of singlet-triplet qubit states in an architecture of triple quantum dots

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We propose two schemes to coherently transfer arbitrary quantum states of the two-electron singlet-triplet qubit across a chain of 3 quantum dots. The schemes are based on electrical control over the detuning energy of the quantum dots. The first is a pulse-gated scheme, requiring dc pulses and engineering of inter- and intra-dot Coulomb energies. The second scheme is based on the adiabatic theorem, requiring time-dependent control of the detuning energy through avoided crossings at a rate that the system remains in the ground state. We simulate the transfer fidelity using typical experimental parameters for silicon quantum dots [1,2]. Our results give state transfer fidelities between 94.3% < $\mathcal{F}$ < 99.5% at sub-ns gate times for the pulse-gated scheme and between 75.4% < $\mathcal{F}$ < 99.0% at tens of ns for the adiabatic scheme. Taking into account dephasing from charge noise [3-6], we obtain state transfer fidelities between 94.9% < $\mathcal{F}$ < 99.2% for the pulse-gated scheme and between 64.9% < $\mathcal{F}$ < 93.6% for the adiabatic scheme.

Spin-Blockade Spectroscopy of Si/SiGe Quantum Dots
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This talk presents an in situ technique for measuring the singlet-triplet energy splitting responsible for spin-to-charge conversion in semiconductor quantum dots. By monitoring fast, single-shot charge measurements as a function of double-dot detuning, this method reliably extracts an energy in the limits of both large and small splittings. We perform this technique on an undoped, accumulation-mode Si/SiGe triple-quantum dot and find that the measured splitting varies smoothly as a function of confinement gate biases. This demonstrates the value of having an in situ measurement technique as part of a standard tune-up procedure and also suggests that in typical Si/SiGe quantum dot devices, spin-blockade can be limited by in-plane orbital excitation energy rather than valley splitting.
For better or for worse: spin-orbit coupling and its physical manifestations in Si quantum dot qubits

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If you’ve performed an experiment on an electron spin qubit in a Si quantum dot and observed an unexpectedly complex response to applied magnetic field, chances are that spin-orbit coupling (SOC) is the culprit. Indeed, in recent years our community has compiled a significant body of experimental and theoretical evidence pointing to stronger-than-expected SOC for electrons in Si confined near interfaces. It turns out that SOC is potent enough to drive singlet/triplet qubits with no engineered magnetic field gradient [1-3] and is sufficiently variable to permit good individual addressability of single electron spins [4-6]. In this talk, I will summarize the current state of our understanding of SOC effects in Si quantum dots and provide a unifying taxonomy of relevant SOC mechanisms and their physical consequences for qubit operation, in light of our latest experiments [3].


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

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the DOE’s National Nuclear Security Administration under contract DE-NA0003525.
Controllable growth of Ge/Si(001) wires for hole qubits

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Low-dimensional Ge/Si(001) system has the unique combination of low hyperfine and strong spin-orbit interactions, which offers a long spin coherence time and a fast electrical manipulation for qubits. Very recently, Ge hole spin qubits [1] and coupling between hole spin and superconducting microwave resonator in Ge/Si(001) hut wires [2] have been demonstrated. However, it’s the prerequisite to controllably grow such Ge wires with precise positions for the addressability and scalability of qubits. Here, we show that the site-controlled Ge(Si) hut wires can be obtained on patterned Si(001) substrate after the growth of SiGe mound followed by subsequent Ge deposition using molecular beam epitaxy (MBE). Wires with lengths up to 10 um and parallel wires with spaces of tens of nanometers can be achieved easily. Other structures such as L- and square-shaped wires can also obtained. Thermodynamic model shows that the enhanced strain relaxation drives the Ge nanowire to grow on pre-grown SiGe mound, rather than on flat surface. Together with recent progress of Ge qubits, the site-controlled growth of Ge/Si(001) hut wires indicates that it is a promising system for integrated qubits. In addition, we will also discuss the epitaxial growth of isotopically purified Si and Ge materials.

References:
Single hole spins hosted in quantum dots in Ge/Si core/shell nano wires form a promising platform for the implementation of quantum bits by combining several advantageous properties [1-3]. The potentially nuclear spin-free host material allows for long spin relaxation and coherence times due to the reduced hyperfine coupling of holes. Furthermore, a strong and electrically tunable spin-orbit interaction in the valence band is predicted, which arises from the strong confinement to one dimension in the nano wire [2].

Here, we report highly tunable switchable single, double, and triple tunnel-coupled quantum dot arrays, with indications of single-hole occupancy. We study Pauli blockade (PSB) in the double-dot configuration. We study the lifting of PSB as a function of the amplitude and direction of an externally applied magnetic field. Shifting all through investigating mixing mechanism and we find indications of a sizable spin-orbit interaction.

When combined with the anisotropic and electric field tunable g-factor [5,6], this saves the way for single-spin submicron electric dipole resonant and controlling via microwave cavity.
Electrically driven spin rotations, Pauli spin blockade and supercurrent discretization in germanium quantum devices

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Superconductors and semiconductors are important players in the field of quantum computing. They can be combined into hybrid devices that bring together unique properties giving rise to emergent phenomena and providing novel means for quantum control. This drives intensive research, but most studied materials are degraded by disorder, strong hyperfine coupling or the lack of a planar technology.

Here, we present strained germanium quantum well structures with hole mobilities that are state-of-the-art for undoped systems [1,2]. Like silicon, germanium possesses abundant isotopes without nuclear spin. In addition, holes in germanium do not suffer from valley degeneracy, while they do allow for fast electrical driving mediated by strong spin-orbit coupling. We show the operation of a double quantum dot with independently tunable source, drain, and interdot tunnel couplings. We observe Pauli spin blockade and use it to demonstrate electrically driven spin rotations. Furthermore, we show Josephson field effect transistors demonstrating supercurrents that are carried by holes and extend over record values of several micrometers. We demonstrate the Josephson nature of the supercurrent by the observation of a Fraunhofer magnetic field dependence and the presence of Shapiro steps under microwave irradiation. In superconducting quantum point contacts we observe discretization of the critical current, demonstrating ballistic transport [3].

These demonstrations are essential building blocks for the development of hybrid technologies and show that germanium is a strong candidate for novel quantum electronic devices.

References


A hole spin qubit in a Ge hut-wire double quantum dot

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The possibility for a high density qubit packing and interfacing with standard control electronics makes spin qubits, hosted in semiconductor quantum dots [1], a promising platform towards logical qubits. In the past few years the interest in hole spins has been continuously raising due to their intrinsically large spin-orbit coupling, which can lead to fast and fully electrically controlled spin qubits. Indeed in 2016, the first fully electrically controlled hole spin qubit was demonstrated in natural Si [2].

Here we will present a hole spin qubit created in a Ge hut wire [3] double quantum dot [4]. Rabi-frequencies of 140 MHz were reached and dephasing times $T_2^*$ exceeding 130 ns were measured. More complex measurement protocols were, however, not possible due to the limitations imposed by the current readout. A solution to this problem can come from dispersive readout [5-7]. First results from gate reflectometry measurements of Ge hut-wire double dots will be presented.

References

Spin and orbital structure of holes in a silicon metal-oxide-semiconductor quantum dot

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Valence band holes confined in silicon quantum dots are attracting significant attention for use as fast, highly coherent spin qubits [1]. However, experimental studies of single-hole spins have been hindered by challenges in the fabrication of stable devices that are capable of confining a single hole. This means that fundamental questions, such as the sequence of orbital shell filling of holes in silicon planar quantum dots have not been studied. In this work [2], we show a planar silicon metal-oxide-semiconductor-based quantum dot device and demonstrate operation down to the last hole. Magneto-spectroscopy studies show magic number shell filling consistent with the Fock–Darwin states of a circular two-dimensional quantum dot, with the spin filling sequence of the first six holes consistent with Hund’s rule. Next, we use pulse-bias spectroscopy to determine that the orbital spectrum is heavily influenced by the strong hole–hole interactions. These results are a promising step towards hole-based spin qubits, since they demonstrate a stable single-hole quantum dot operating in the same planar geometry that has already proven highly successful for electron spin qubits [3].

References


Visualizing valley interference to engineer robust donor qubit coupling in silicon

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Donor-bound spins in silicon promise compact and high-speed quantum devices with their long coherence times. Recent achievements of devices fabricated by scanning tunneling microscope (STM) where donors can be placed with atomic accuracy [1] notably comprise high fidelity addressing [2] and spin resonance of single electrons [3]. Future developments now rely on the ability to engineer and control interactions between qubits. The exchange interaction is a key element to couple donors, either directly in view of two-qubit gates, or to create hybrid multi-spin qubits that can couple to electric fields. However the presence of the valley degree of freedom in silicon has often been deemed detrimental to scaled applications, as valley interference are predicted to result in the exchange interaction varying locally by 5 orders of magnitude [4].

Here we probe pairs of exchange-coupled donors using low temperature STM, leading to a fabrication strategy to resolve this issue. Valley interference are revealed from wavefunction imaging, enabling determination of the donors absolute crystal lattice positions [5] and the resulting valley phase difference between them. Supported by atomistic calculations, these phase differences are then linked to the exchange behavior. Our analysis notably shows that the exchange is insensitive to in-plane valley interference around the [110] crystallographic direction, setting an engineering requirement compatible with STM device fabrication for the donors to remain in a single atomic plane. Variations can be minimised to a factor of 8, opening an avenue towards uniform exchange interaction between exceptionally coherent donors for quantum technologies in silicon.

References

Experimental Determination of the Radius of Ground State in Isotopically Pure Silicon

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We have performed high field magnetoabsorption spectroscopy of Si:P at the High Field Magnet Laboratory. The absorption spectrum was obtained with FTIR. We used fields up to 30T in order to observe the quadratic Zeeman effect (QZE), which produces an energy shift proportional to the square of the product of radius and field [1], and therefore allows extraction of the state radius.

We have recently shown that the radius of the excited states of Si:P agree very well with effective mass theory [2]. It has been possible to verify the applicability of effective mass theory to determining their Rydberg radii (and shown that there are small, but noticeable effects of non-parabolicity). However, the QZE has not been used to extract the ground state. The ground state wavefunction extent is not well characterized even after decades of spectroscopy research, due to the uncertainty over the degree of electron penetration into ion core, whose potential, called the Central Cell Correction (CCC), is unknown.

Using isotopically pure 28Si the sharper transition lines give much greater precision for extraction of the experimental QZE, and have allowed us to determine the ground state QZE and radius of well isolated single donors (as opposed to donors near interfaces and surfaces) for the first time.

References

Donor clusters: ground state, exchange and future prospects

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We propose a simple and general semi-analytical method, based on the effective mass approximation, for determining the ground state of a cluster of two donors. The method can be employed for an arbitrary orientation of the cluster axis and is especially useful for revealing the valley composition of the ground state. It can be generalised to calculate (i) the exchange between two sets of donor clusters where the axis of each cluster and their relative orientation may differ (ii) the strength of the hyperfine interaction and its interplay with an external electric field. Numerical results can be benchmarked against more advanced tight-binding techniques. I will discuss the ground state of donor clusters along the (100), (110) and (111) directions as well as preliminary results for inter-cluster exchange, with a particular focus on suppressing valley oscillations in the latter [1].

References

Recent progress towards fabricating and measuring novel device structures based on donors in silicon will be described, in particular the optical response of a 2D isolated donor system and the first demonstration of two donor species device fabrication where each species is patterned using STM hydrogen resist lithography.

Firstly, we fabricated a dilute disordered phosphorus delta-layer ~15 nm below the surface of bulk silicon and measured the optical response of the donors to THz radiation at different temperatures and bias voltages. We found two main differences between the delta-layer and equivalently-doped bulk silicon: firstly, the Rydberg states of the phosphorus donors shifted to higher energies (whereas the Rydberg states of the arsenic donors in the bulk remained unchanged); secondly, we measured a strong signal at low temperatures, down to 200 mK, that could not be explained by photothermal ionization (PTI). We show, with a three-layer potential model, that the energy shift originates from the proximity to the surface, and the extent of the shift scales with the proximity. Then we show that this proximity to the interface also leads to a new low-temperature conduction mechanism, which is absent in the bulk, and is different to the high-temperature PTI: current flow through a quasi-continuum of excited surface states at the Si/SiO₂ interface. These findings open the way to selective optical manipulation of even closely-spaced (relative to the diffraction limit) donors/qubits. By patterning the silicon overlayer we can control the transition energies of individual donors. Additionally, a direct electronic readout is available even at a temperature that is considered too low for PTI. Additionally, we show we can use the line shape of the transitions to nondestructively determine the depth and thickness of our delta-layers.

In device structures consisting of dopant atoms in silicon, fabricated using the technique of STM hydrogen desorption lithography, the patterned dopant of choice has traditionally been phosphorus. However, expanding this technique to include a second species of donor impurity atom will provide new possibilities for device structure and function. Here we describe the STM patterning of arsenic (As) atoms in silicon. This is achieved by replacing the P precursor gas (PH₃) with the As analogue, AsH₃. We find that AsH₃ is compatible with the multiple process steps involved in the STM fabrication, but also report a number of important differences in the surface chemistry, solid state diffusion, and electrical transport of the 2D As delta-layers in Si. We also demonstrate the fabrication of a device structure consisting of phosphorus and arsenic, both defined by STM resist lithography.
High Precision Deterministic Ion Implantation for Large-Scale Arrays of Single Donor Qubits in Silicon

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The remarkable success in addressing and manipulating single P-donor spins (“qubits”) in $^{28}\text{Si}$ [1,2] represents a milestone for the realisation of quantum-computing and information transport applications. Inspired by these results, innovative quantum architectures such as the highly scalable flip-flop qubit configuration were recently proposed [3]. A robust qubit entanglement over long distances up to several hundreds of nanometres loosens the generally tight constraints on the donor-qubit placement precision. This in turn makes ion implantation – the standard doping tool of semiconductor industry – highly suitable, considering the significant results from implanted single donor qubit devices.

Regarding the establishment of donor qubit architectures via deterministic single ion implantation, a number of key milestones have been recently made for the three most promising implant technologies.

Regarding the Ion Beam Induced Charge (IBIC) technique, being developed in Melbourne, we present single ion detection performance at room temperature, which constitutes a major step towards upscale-compatible donor qubit placement with sub-10nm spatial precision. We furthermore address the employment of heavy molecule-ions for improved single ion detection fidelity and ultra-shallow donor placement.

In this ion implantation progress report, we additionally highlight the promising Paul-Ion-Trap [5] and Image Charge Detection [6] approaches, being developed in the CQC²T collaborators network. Our technologies and their combined usage are being presented within the context of near- and long-term demands on scalable top-down fabrication of donor-based silicon quantum devices.

References

SQuBiC1: An Integrated Control Chip for Semiconductor Spin Qubits

Dennis Nielinger\textsuperscript{1}, Anton Artanov\textsuperscript{1}, Volker Christ\textsuperscript{1}, Carsten Degenhardt\textsuperscript{1}, Lotte Geck\textsuperscript{1}, Andre Kruth\textsuperscript{1}, Daniel Liebau\textsuperscript{1}, Pavithra Muralidharan\textsuperscript{1}, Petra Schubert\textsuperscript{1}, Patrick Vliex\textsuperscript{1}, André Zambanini\textsuperscript{1} and Stefan van Waasen\textsuperscript{1,2}

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In most quantum experiments nowadays the control and readout electronics is placed at room temperature. The number of qubits which can be operated with this approach is severely limited by the number of interconnects and the wiring between the qubit operating temperature level and the room temperature level. At the Central Institute for Electronic Systems at the Forschungszentrum Jülich we develop and design scalable solutions for readout and control of qubits for future use in quantum computers \cite{1}. Our approach leverages the advances of state-of-the-art commercial CMOS technologies while operating at deep-cryogenic temperatures close to the actual qubit. We designed and layouted a first chip for concept proof (see figure 1) in a commercial 65 nm CMOS process. This chip contains a DC-digital-to-analog converter (DC-DAC), a pulse digital-to-analog converter, a 500 MHz digitally controlled current starved ring oscillator and a 20 GHz LC-oscillator. The DC-DAC is operating in a voltage range between 0 V and 1 V. The pulse DAC operates at a sample rate of 250 MHz and generates pulses in a range of 8 mV. As an example, Figure 2 shows simulation results for the DC-DAC. The output voltage for 20 different output channels can be observed. A discharge of the sampling circuit due to leakage occurs and the output has to be refreshed periodically to stay within the required voltage stability level. In this presentation the chip architecture will be discussed in detail and corresponding simulation results will be shown.

Figure 1: High level block diagram (left) and chip layout (right) of the SQuBiC1 chip

Figure 2: Simulated performance of the DC-DAC

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Bringing advanced semiconductor process technology to Si spin qubit research

N. Thomas¹, R. Pillarisetty¹, H.C. George¹, J. Roberts¹, L. Lampert¹, P. Amin¹, T.F. Watson¹, G. Zheng¹,², J. Torres¹, M. Metz¹, R. Kotlyar¹, P. Keys¹, J.M. Boter², J.P. Dehollain², G. Droulers², G. Eenink², R. Li², L. Massa², D. Sabbagh², N. Samkharadze², C. Volk², B. P. Wuetz³, A.-M. Zwerver³, M. Veldhorst³, G. Scappucci³, L.M.K. Vandersypen², J.S. Clarke¹

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Today, limited process control in academic fabrication environments appears to inhibit improvements in spin qubit performance. However, semiconductor qubits based on spins of electrons, confined through an arrangement of gate electrodes, have many similarities to classical silicon transistors. Hence, the process capabilities provided by a high volume, state-of-the-art CMOS manufacturing line are considered essential to drive improvements in qubit device yield and variability.

Here, we present progress toward the realization of 300mm based spin qubit devices in a production environment. This includes (i) isotopically purified ²⁸Si epi substrates with a compelling LT Hall mobility of ~10,000 cm²/Ns (²⁸SiMOS), (ii) design of a custom qubit layout, (iii) integration of fin-based spin qubit devices using immersion lithography, moving from classical transistor structures to full spin qubits, and (iv) the realization of quantum dots in a nested gate design novel to a 300mm process line.

We further discuss our approach to process and material engineering based on physical analysis of devices and electrical testing. These include, for example, engineering of our SiGe stacks currently showing LT Hall mobility of ~ 400,000 cm²/Ns, strain imaging of nested gate structures at room and cryogenic temperatures, respectively, as well as electrical test data of transistor and quantum dot device structures.

With a single wafer producing more than 10,000 individual test structures, spin qubit R&D is expected to be significantly accelerated by the potential volume of statistical data provided. While automated testing of a wafer can be completed in less than an hour at room temperature, data collection at cryogenic temperatures is currently limited to a small number of devices with data turn-around times in the range of days. We present our vision for automated full-wafer testing at cryogenic temperatures, enabling efficient volume screening of test structures for future spin qubit research.
Image Analysis, Automation, and Machine Learning Techniques Applied to MOS Quantum Dot Tune-Up

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Tune-up and analysis of quantum dots (QD) is an arduous manual task consisting of a sequence of steps that builds upon one another. The tuning and analysis complexity is increasing as designs extend from QDs to multi-objects (e.g., donor-QD coupling [1] and multi-QDs [2]). The process can be simplified by utilizing image recognition techniques and automation. In this talk, I will present image analysis techniques which extract information from transport and charge sensing stability plots. These analysis modules can determine parameters such as tunnel rates and charge configurations in the QD systems. We identify the necessary combination of tune-up steps and feedback from analysis modules (i.e., output parameters for the next scan) that can automate tuning to few-electron charge sensing. This talk presents some of the proof-of-concepts, details and key future challenges.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

QuRO: a compact read-out interface for spin qubits operating at deep-cryogenic temperatures
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Quantum processors represent the next step towards the future of computing, thanks to the expected exponential speed-up over classical processors. However, the core elements of these processors, i.e. qubits, rely on extremely low temperatures ($10^{-100}$ mK) to exhibit the underlying quantum mechanical properties (superposition and entanglement) that are key to quantum computations. This requires a complex supporting system comprising electronics and cooling equipment. Currently, the so-called quantum—classical electronic interface is mostly placed at room temperature, which is far away from qubits, requiring long interconnects to the cryogenic environment. Being limited by space and heat constraints, a future quantum processor may be restricted by the number of these interconnects.

We propose to bridge the temperature gap by placing the majority of the required electronics inside the cryogenic environment, close to the qubits, which would require less room temperature interconnects. A read-out platform for spin qubits was constructed that can properly operate at 4 K, consisting of low-noise amplifiers, a directional coupler, an analog-to-digital converter and a digital controller. An FPGA (Artix 7 from Xilinx) is the main embodiment for the digital processing of the quantum data, and can be reconfigured, even during operation of the quantum system. The system houses voltage regulators and a clock generator, making the system both compact and reliable, and further limiting RF interconnects towards room temperature. This platform is the first demonstration of a complete cryogenic read-out chain for qubits, paving the way towards the large-scale integration of the quantum—classical electronics at deep-cryogenic temperatures.
Vector-supported learning and auto-tuning of devices in quantum dot experiments

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Over the past decade, machine learning techniques have revolutionized how scientific research is done, from designing new materials to finding significant events in particle physics to assisting drug discovery. Recently, we added to this list by showing how a machine learning algorithm, combined with optimization routines, can assist experimental efforts in tuning semiconductor quantum dot devices. In particular, we demonstrated that deep convolutional neural networks can be used to characterize the state and charge configuration of single and double quantum dots devices based on measurements of a current-gate voltage transport characteristics or via the conductance of a nearby charge sensor \cite{1,2}. Our approach provides a paradigm for fully-automated experimental initialization through a closed-loop system that does not rely on human intuition and experience.

Given the recent progress in the physical construction of systems with $N \gg 3$ gates to create a large number of dots, in both one and two dimensions \cite{3,4}, it is imperative to have a reliable method to find a stable, desirable electron configuration in the dot array. Given the high-dimensional (where $N$ sets the parameter space dimension) control challenges posed by these larger systems, which may be intractable with non-automated heuristic approaches, it is essential to automate the search through the voltage space that yields the right number of confinement regions (dots) with the right number of electrons on each.

Working with experimental devices characterized by high-dimensional parameter spaces poses many challenges: from performing reliable measurements to identifying the device state to tuning to a desirable configuration.

Here we expand upon our prior work to show how a machine learning-based approach can be applied for pattern recognition to these higher-dimensional systems. In particular, we will present a preliminary approach that differs from the conventional machine learning literature, in which we consider the benefit of using a “fingerprint” of state space. Rather than working with full-sized sweeps of the gate voltage space, we train a machine-learning algorithm using use 1D traces (“ray”) of fixed length in multiple directions to recognize relative position of the features characterizing given state (i.e., to “fingerprint”) in order to differentiate between various state configurations. We use a double dot device as a toy model to compare with our existing, CNN approach, and then show how this fingerprinting can extend to higher-dimensional systems. Our approach not only allows to automate the recognition of states, but also to reduce the number of measurements required for tuning.

Spin relaxation and dephasing in a $^{28}\text{SiGe}$ QD with nanomagnet

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Coherent control of a single electron spin in gate-defined semiconductor quantum dots has been drastically enhanced by reducing the hyperfine interaction, as demonstrated in isotopically purified $^{28}\text{Si}$ devices and recently in $^{28}\text{Si}/\text{SiGe}$ quantum dots [1]. In the $^{28}\text{Si}/\text{SiGe}$ device, the stray-field of a micro-magnet was used for spin manipulation. An open question is to what extent the stray-field itself limits the spin coherence. Investigation of the magnetic field dependence of the spin relaxation time provides insight into the decoherence channels. Several relaxation mechanisms were suggested, including electrical noise from different sources [2], interplay with valley-states [2,3] and purely magnetic noise from the micro-magnet [4].

$\frac{1}{T_1} (1/\text{s})$
\begin{align*}
B (\text{T}) &\quad \text{SO Johnson} \\
&\quad \text{SO Phonon} \\
&\quad \text{SV Johnson} \\
&\quad \text{SV Phonon}
\end{align*}

Figure 1: Electron spin relaxation rate $1/T_1$ as a function of the external magnetic field $B$. Relevant relaxation mechanisms are considered and add up to the fit (solid coloured lines). The nanomagnet gradient field contributes to spin-orbit (SO) type coupling.

Here, we investigate the single spin relaxation time $T_1$ as a function of the externally applied magnetic field in an MBE-grown $^{28}\text{Si}/\text{SiGe}$ device [5], for which one electrostatic gate was replaced by a cobalt nano-magnet. The nano-magnet is single domain and generates smaller gradient magnetic fields in the quantum dot compared to a typical micro-magnet approach [1]. By energy-dependent tunneling to the reservoir for single-shot spin readout, we measure the $T_1$ time and discuss the dominant spin relaxation mechanism in various magnetic field regimes (see Fig. 1) and for different quantum dot tunings. We observe a spin relaxation hot-spot, if the Zeeman energy matches the valley splitting. By gate tuning, we can set the valley splitting to $\sim 200 \, \mu\text{eV}$. We further analyse the magnetic field gradient of the nanomagnet via the spin Rabi frequency when applying microwaves to different gates and study the spin dephasing.

A Si/SiGe based quantum dot with floating gates for scalability

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For silicon spin qubits based on gate-defined quantum dot, DC lines are required to confine individual electrons in a quantum dot [1]. When considering multiple dot, the voltage applied on the gates typically vary due to the non-uniformity of the substrate, layout design or fabrication process. The standard operating mode is to connect each DC line to a DAC operating at room temperature through the bond wires from the chip to the sample carrier and the refrigerator wiring. However, when scaling towards a fault-tolerant quantum computer, which needs hundreds of thousands of quantum dot, simply adding more wires and electronics would cause problems, due to space constraints in the connection between the sample and the sample board and excessive heat load through the wires. Thus an integration strategy is required to provide specific voltages for each gate efficiently [2].

In this study, we explore a DRAM-based floating gate circuit to bias all the quantum dot gates. A single DAC line can provide different voltages to several DRAM cells sequentially, while the transistor in series with the capacitor is used as a switch to float the gates of the dot from the voltage supply line. In this way the required voltages can be stored locally on the capacitors. All elements are integrated on Si/SiGe based substrate and should be functional at the same cryogenic temperature as the dots. By combining a de-multiplexer to address each DRAM cell, the number of wires needed from the chip to the sample carrier and dilution refrigerator is vastly reduced.

As a proof of concept, we first made a device with a floating plunger gate of a single quantum dot. Most of the device fabrication process follows the normal CMOS fabrication standard. There are some minor differences. Firstly, e-beam lithography is used for all patterns instead of photo lithography since the pitch of a quantum dot is a few tens of nanometers. Secondly, since the process is based on a Si/SiGe hetero-layer substrate, the process temperature is limited to 700°C to prevent strain releasing of the strained-Si layer. Therefore a rapid thermal annealing method is used to activate the implanted phosphorus dopants at 700 °C for 15s and the gate oxide is made by ALD Al₂O₃ at 350 °C.

The device is measured at 20 mK. We observed that the DRAM-like circuit doesn’t affect the Coulomb peaks of the quantum dot dramatically. A parallel RC circuit is used to model the discharging behavior of the floating node. The discharging time constant is extracted to be 485 s, which results in a re-charging frequency of approximately 200 Hz if a voltage accuracy of 1 μV is required for the gate voltages.

This work shows that implementing a DRAM-like floating gate structure with qudots has potential for scalability. In the next step, we will measure the performance of a single quantum dot with all gates floating. Furthermore, we will implement a de-multiplexing strategy to address each gate using reduced number of wires as shown in other works [3].

References

Silicon, Superconductivity, Stability, and the Search for Gateability


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While silicon is widely known for its ubiquitous roles in classical computing as well as its promising potential for scalable spin qubits for quantum computing, it is less widely appreciated that silicon can host superconductivity [1,2]. If this superconductivity can be controlled with gate voltages, new opportunities arise to apply superconducting effects not as a hybrid with a semiconductor, but rather as an integral and voltage controllable resource. In combination with spin orbit coupling, which is now routinely introduced into silicon through the use of micromagnets [3], such a resource could open the prospect of topologically-protected qubits — through the phenomenon of Majorana fermions — in a semiconductor platform that can host both classical and non-topological quantum circuitry.

Here we discuss both experimental and theoretical studies that seek to evaluate the potential of superconductivity in silicon for quantum computing. Experimentally, our goal is to achieve gateable superconductivity. We have implanted silicon with gallium at high doses which, after annealing at temperatures of order 550 °C, is known to lead to gallium inclusions and superconductivity [2]. We confirm superconductivity in a variety of device geometries, finding critical temperatures well above 4 K. We find that this superconductivity has non-trivial time dependence, including a reduction in critical current as a function of shelf life at room temperature—behavior that needs to be understood and controlled if superconductivity in silicon is to be useful for quantum computing.

We also present theoretical work describing how Majorana fermions can be produced inside superconducting silicon with its very low intrinsic spin-orbit coupling. We discuss practical ways to make helical magnetic fields, which are known to support Majorana fermions in nanowire-superconductor hybrid structures [4]. Further, we show that magnetic field configurations very different from such ideal helical shapes can also support topological states, and we present theoretical phase diagrams for a wide range of experimental parameters.

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3. **Serwan Asaad** (*CQC2T, UNSW*)
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4. **Andrew Baczewski** (*Sandia National Laboratories*)
   Towards a disorder model for the Si/SiO2 interface

5. **Ian Berkman** (*CQC2T, UNSW*)
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