3rd Conference and Workshop on

Spin-Based Quantum Information Processing

6th -10th of November, 2017

Sydney, Australia



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Spin Qubit3

The 3rd Conference and Workshop on Spin-Based Quantum Information Processing (Spin Qubit 3) brings together world-leading researchers from the field of solid-state, spin-based quantum information processing to participate in a 5-day conference and workshop.

The topics will cover different spin-based quantum bit implementations like colour centres in diamond and SiC, donors in silicon, gate-defined quantum dots in GaAs, SiGe and MOS-Si, and self-assembled InGaAs quantum dots, but there will also be some focus on fabrication, algorithms and cryogenic control electronics.

This conference is chaired by Prof Andrew Dzurak, Prof Andrea Morello and Prof David Reilly. The local organizing committee consists of Dr Arne Laucht, Karen Jury and Mateusz Mądzik.

Art Gallery - Domain Theatre
Art Gallery - Centenary Auditorium
Art Gallery - Function Space
Art Gallery - Chiswick
Sheraton on the Park
Messel Lecture Theatre (SNH)

MONDAY (6.11.)

12:20 - 13:40	REGISTRATION and WELCOME LUNCH	
13:40 - 14:00	WELCOME & OPENING	
14:00 - 14:40	**David Awschalom** (The University of Chicago)	Chair: **Dzurak**
14:40 - 15:20	**Tim Taminiau** (TU Delft)	
15:20 - 15:30	**Raith** (Sponsor)	
15:30 - 16:00	BREAK	
16:00 - 16:10	**BlueFors** (Sponsor)	
16:10 - 16:50	**Thaddeus Ladd** (HRL Laboratories, LLC)	Chair: **Laucht**
16:50 - 17:30	**Silvano De Franceschi** (CEA-INAC/UJF-Grenoble)	

TUESDAY (7.11.)

8:30 - 9:00	ARRIVAL	
9:00 - 9:40	**Jörg Wrachtrup** (University of Stuttgart)	Chair: **Finley**
9:40 - 10:20	**Mihir Bhaskar** (Harvard University)	
10:20 - 10:50	BREAK	
10:50 - 11:30	**Andrew Dzurak** (University of New South Wales)	Chair: **Erikson**
11:30 - 12:10	**Seigo Tarucha** (The University of Tokyo)	
12:10 - 13:10	LUNCH	
13:10 - 13:50	**Daniel Loss** (University of Basel)	Chair: **Ladd**
13:50 - 14:30	**Susan Coppersmith** (University of Wisconsin - Madison)	
14:30 - 15:40	BREAK (3pm Melbourne Cup Race)	
15:40 - 16:20	**Dominik Zumbühl** (University of Basel)	Chair: **De Franceschi**
16:20 - 17:00	**Ferdinand Kümmeth** (University of Copenhagen)	
17:00 - 17:10	**Stahl Electronics** (Sponsor)	
18:00 - 22:00	CONFERENCE DINNER	

WEDNESDAY (8.11.)

8:30 - 9:00	ARRIVAL	
9:00 - 9:40	**Lieven Vandersypen** (Intel & TU Delft)	Chair: **Yacoby**
9:40 - 10:20	**Mark Eriksson** (University of Wisconsin - Madison)	
10:20 - 10:40	BREAK	
10:40 - 11:20	**Jonathan Finley** (TU Munich)	Chair: **Taminiau**
11:20 - 12:00	**Alexander Hamilton** (University of New South Wales)	
12:00 - 13:00	LUNCH	
13:00 - 14:00	NSW Art Gallery Gallery Highlights Tour	
13:00 - 13:45	ChooChoo (13:15)	
13:30 - 14:15	ChooChoo (13:45)	
13:45 - 14:45	Opera House	
14:15 - 15:15	Opera House	
14:30 - 15:20	NSW Art Gallery Indigenous Collection Tour	
14:45 - 15:30	ChooChoo (15:00)	
15:15 - 16:00	ChooChoo (15:30)	
16:00 - 16:30	Bus	
16:00 - 16:30	Bus	
16:30 - 18:00	Lab Tour The University of Sydney	
16:30 - 18:00	Lab Tour University of New South Wales Sydney	
18:00 - 18:30	Bus	
18:00 - 18:30	Bus	

THURSDAY (9.11.)

9:00 - 9:40	ARRIVAL	
9:40 - 10:20	**Amir Yacoby** (Harvard University)	Chair: **Morello**
10:20 - 11:00	**Malcolm Carroll** (Sandia National Laboratories)	
11:00 - 13:20	POSTER SESSION and LUNCH The recommended poster format is DIN A0 portrait.	
13:20 - 14:10	**Standards & Metrics Discussion**	Chair: **Vandersypen**
14:20 - 15:00	**Michelle Simmons** (University of New South Wales)	
15:00 - 15:10	**Scienta Omicron** (Sponsor)	
15:10 - 15:40	BREAK	
15:40 - 16:20	**David Zajac** (Princeton University)	Chair: **Coppersmith**
16:20 - 17:00	**Guido Burkard** (University of Konstanz)	
19:30 - 21:00	PUBLIC LECTURE **Andrea Morello** (University of New South Wales) Schrödinger's cat is alive and means business Directions and opportunities in the quantum technology revolution	Chair: **David Reilly**

FRIDAY (10.11.)

8:30 - 9:00	ARRIVAL	
9:00 - 9:40	**David Reilly** (Microsoft)	Chair: **Dzurak**
9:40 - 10:20	**Hendrik Bluhm** (RWTH Aachen)	
10:20 - 10:30	**Keysight** (Sponsor)	
10:30 - 11:00	BREAK	
11:00 - 11:40	**Mark Hodson** (QxBranch)	Chair: **Reilly**
11:40 - 12:20	**Stephen Bartlett** (The University of Sydney)	
12:20 - 13:40	LUNCH	
13:40 - 14:20	**Maud Vinet** (CEA-Leti)	Chair: **Bluhm**
14:20 - 15:00	**Marissa Giustina** (Google)	
15:00 - 15:30	BREAK	
15:30 - 16:10	**Matthias Troyer** (Microsoft)	Chair: **Giustina**
16:10 - 16:50	**Michael Bremner** (University of Technology Sydney)	
16:50 - 17:00	CLOSING	

Invited Talks

Controlling and connecting spin qubits in semiconductor defects

David D. Awschalom

University of Chicago, Chicago, IL 60637 USA

There is a growing interest in exploiting the quantum properties of electronic and nuclear spins for the manipulation and storage of information in the solid state. Recent efforts embrace materials with incorporated defects whose special electronic and nuclear spin states allow the processing of information because of their explicitly quantum nature. Here we focus on recent developments that utilize precise quantum control techniques to explore coherent spin dynamics and interactions at the level of single spins. In particular, we present recent results of manipulating and connecting spins in both silicon carbide and diamond. We find that defect-based electronic states in silicon carbide can be isolated at the single spin level [1, 2] with surprisingly long spin coherence times and high-fidelity control. The revealed spin-photon interface offers an opportunity to implement all-optical holonomic spin gates [3] for quantum information processing within a wafer-scale material operating at near-telecom wavelengths. We also discuss pathways for connecting spins using hybrid spin-ferromagnetic systems that may relax the requirement of direct dipolar coupling. Using ferromagnetic spin-wave modes, we demonstrate long-range coherent control of spins in diamond using YIG thin-films [4]. The magnetic modes amplify the oscillating field of the microwave source by more than two orders of magnitude, thereby efficiently driving remote spin states.

[1] D. J. Christle, P. V. Klimov, C. F. de las Casas, K. Szász, V. Ivády, V. Jokubavicius, J. Hassan, M. Syväjärvi, W. F. Koehl, T. Ohshima, N. T. Son, E. Janzén, Á. Gali, and D. D. Awschalom, Phys. Rev. X **7**, 021046 (2017)
[2] A. L. Falk, Science **357**, 649 (2017)
[3] B. B. Zhou, P. C. Jerger, V. O. Shkolnikov, F. J. Heremans, G. Burkard, D. D. Awschalom, Phys. Rev. Lett. **119**, 140503 (2017)
[4] P. Andrich, C. F. de las Casas, X. Liu, H. L. Bretscher, J. R. Berman, F. J. Heremans, P. F. Nealey, and D. D. Awschalom, npj Quantum Information **3**, 28 (2017)

Diamond quantum networks for distributed quantum computation

Tim H. Taminiau[1,2]

[1] *QuTech, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands*

[2] *Kavli Institute of Nanoscience, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands*

Quantum networks provide a promising way to realize large-scale quantum computations and simulations. Such networks consist of nodes that contain multiple qubits to store and process quantum states, and that are connected together by distributing entangled states through optical links using photons. Crucially, imperfections and errors can be overcome by distributing logical qubits, computations and error correction over the network [1]. This approach is scalable to large sizes by connecting many independent modules, thus avoiding the challenges of a single large structure of ever increasing complexity.

The nitrogen vacancy (NV) center in diamond is a promising candidate to realize such quantum networks, as it combines optical entanglement links [2] with long-lived multi-qubit nodes that can store and process quantum information [3-5]. In this talk I will discuss the recent progress of my group towards quantum networks for distributed quantum computations and argue that we are getting close to the point where imperfections can be overcome using quantum error correction so that the quantum network becomes increasingly stable as it is made larger and larger.

[1] N. H. Nickerson, Y. Li, S. C. Benjamin, Nature Commun. **4**, 1756 (2013)
[2] B. Hensen et al., Nature **526**, 682 (2015)
[2] J. Cramer et al., Nature Commun. **7**:11526 (2016)
[3] N. Kalb et al., Nature Commun. **7**:13111 (2016)
[4] A. Reiserer et al., Phys. Rev. X **6**, 021040 (2016)

Magnetic Noise in SiGe Isotopically Enhanced Triple-Dot Qubits

Thaddeus D. Ladd

HRL Laboratories, LLC, 3011 Malibu Canyon Road, Malibu, California, USA

Triple-dot qubits offer promise of exchange-only spin-qubit control, but employ an encoding that depends on homogeneous magnetic fields [1]. Inhomogeneous magnetic fields lead to leakage errors [2]. In this talk, I will discuss the sources of inhomogeneous magnetic fields in isotopically purified triple quantum dots in Si/SiGe heterostructures as probed by singlet-triplet oscillation experiments and noise spectroscopy via multiple exchange echoes [3,4]. We find that magnetic noise sources remain dominated by nuclear effects. but there are some notable surprises, including Meissner screening from superconducting gates, interface spin-orbit effects. $1/f$ noise due to spin-glass-like ^{29}Si dynamics, and structure in the high-frequency noise spectrum due to ^{73}Ge quadrupole dynamics. Unravelling the noise spectrum from these effects may provide insight into more complex triple-dot characterization experiments such as randomized benchmarking.

[1] D. P. DiVincenzo *et al.*, Nature **408**, 339 (2000).
[2] T. D. Ladd, Phys. Rev. B **86**, 125408 (2012).
[3] K. Eng *et al.*, Sci. Adv. **1**, e1500214 (2015).
[4] M. D. Reed *et al.*, Phys. Rev. Lett. **116**, 110402 (2016).

Spin-orbit qubits seen through holes

Alessandro Crippa[1,5], **Romain Maurand**[1,5], **Léo Bourdet**[2,5], **Dharmraj Kotekar-Patil**[1,5], **Heorhii Bohuslavskyi**[1,2,5], **Andrea Corna**[1,5], **Romain Lavieville**[1,2,4], **Louis Hutin**[3,4], **Benoit Bertrand**[3,4], **Sylvain Barraud**[3,4], **Tristan Meunier**[4,5], **Christopher Bauerle**[4,5], **Xavier Jehl**[1,5], **Yann-Michel Niquet**[2,5], **Marc Sanquer**[1,5], **Maud Vinet**[3,5], **Silvano De Franceschi**[1,5]

[1] *CEA, INAC-PHELIQS, Grenoble, France*
[2] *CEA, INAC-MEM, Grenoble, France*
[3] *CEA, LETI-MINATEC, Grenoble, France*
[4] *CNRS, Institut Néel, Grenoble, France*
[5] *University Grenoble Alpes, Grenoble, France*
http://www.quantumsilicon-grenoble.eu

The spin-orbit interaction couples an electronic spin degree of freedom to a gate-tunable electric-field enabling spin control via electric dipole spin resonance. This possibility was exploited in a recent publication [Maurand *et al.*, Nature Communications **7**, 13575 (2016)] where we reported the experimental demonstration of a hole spin qubit in a silicon device where coherent spin rotations are electrically driven by a resonant gate-voltage modulation. Here we take a step further and present an experimental and theoretical work revealing the physical origin of the observed hole spin resonance. Our work builds upon measurements of the full angular dependence of the Rabi frequency, the gate-voltage dependence and the anisotropy of the hole g-factors. We show that a formalism based on the Landé g-matrix can simultaneously capture and discriminate the contributions of two mechanisms so-far independently discussed in the literature: one relying on a modulation of the g tensor components, the other not. The validity of this approach to other types of spin-orbit qubits is discussed.

Quantum algorithms for improved sensing

J. Wrachtrup
Institute for Quantum Science and Technology, University of Stuttgart, Germany
wrachtrup@physik.uni-stuttgart.de

The accuracy of measurements is limited by quantum mechanics. Ingenious demonstrations, like measuring gravitational fields or time have explored accuracy limits and reached fundamental obstructions. Yet, precision measurements so far are restricted to macroscale and dedicated environments. In the talk I will discuss spin quantum sensors comprising a single electron spin plus a nuclear spin quantum register. With such a system we measure a variety of quantities including electric and magnetic fields, temperature, and force. We use nuclear spins to enhance the measurement accuracy of the electron spin e.g. via quantum error correction or as ancillary quantum bits as memory or for quantum Fourier transformation [1-3]. I will present a variety of applications ranging from quantum simulations to imaging of cellular structures.

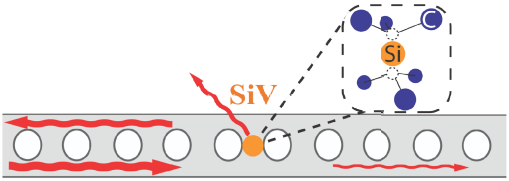
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[3] F. F. de Oliveira, et al. Nat. Commun. 8, 15409 doi: 10.1038/ncomms15409 (2017)

An integrated diamond nanophotonics platform for quantum optical networks

Mihir Bhaskar[1]

[1] *Department of Physics, Harvard University, 17 Oxford Street, Cambridge, Massachusetts 02138, USA*



Solid-state quantum-emitters with long spin coherence times and strong interactions with single optical photons could form the building blocks of a quantum network. To date, no solid-state quantum-emitter has yet been able to satisfy both of these requirements simultaneously. In this talk, I will discuss experiments [1,2,3,4] which demonstrate that silicon-vacancy (SiV) color centers in diamond can address both of these challenges. First, we integrate SiV centers into diamond nanophotonic devices to obtain strong interactions between a single SiV center and an optical photon. Using this platform, we demonstrate a quantum optical switch controlled by a single SiV center and entanglement generation between two SiVs in a single nanophotonic device [2]. By cooling SiVs down to 100mK, we improve the SiV spin coherence time by five orders of magnitude and achieve a coherence time of 13-milliseconds [3,4]. These results make SiV centers in nanophotonic devices a leading solid-state platform for the realization of quantum networks.

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Spin-based quantum computing using silicon-MOS quantum dots

Andrew S. Dzurak
UNSW, School of Electrical Engineering, Sydney, Australia

Spin qubits in silicon are excellent candidates for scalable quantum information processing [1] due to their long coherence times and the enormous investment in silicon CMOS technology. In particular, gate-defined quantum dots formed using standard silicon metal-oxide-semiconductor (SiMOS) technology [2] can be conveniently configured to realise multi-qubit devices. Such qubits can have long spin lifetimes T1 = 2 s, while electric field tuning of the conduction-band valley splitting removes problems due to spin-valley mixing [3]. In isotopically enriched Si-28 these SiMOS qubits have demonstrated control fidelities exceeding 99% using simple pulsed electron spin resonance (ESR) [4], while more sophisticated optimized ESR pulses enable fidelities exceeding 99.9%, consistent with that required for fault-tolerant QC. By gate-voltage tuning the electron g-factor, the ESR operation frequency can be Stark shifted by > 10 MHz [4], allowing individual addressability of many qubits. Neighbouring SiMOS quantum dot qubits can also be directly exchange coupled, and a CNOT gate can be realised by a combination of single qubit rotations and a two-qubit CZ operation [5]. Now that both one- and two-qubit logic are available in silicon, one of the next challenges on the path to large-scale quantum computing will be the demonstration of quantum error correction protocols, to realize a logical qubit which can have a coherence time much longer than its constituent physical qubits. A recent paper [6] has proposed a detailed design and protocol for a logical qubit based on a linear array of silicon quantum dots, comprising between 14 and 20 spins. I will conclude my talk by discussing the prospects of scalability of this technology using traditional CMOS manufacturing, in order to realise large-scale 2D arrays of potentially millions of qubits [7].

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[2] S.J. Angus et al., “Gate-defined quantum dots in intrinsic silicon”, *Nano Lett.* 7, 2051 (2007).

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[5] M. Veldhorst et al., “A two-qubit logic gate in silicon”, *Nature* 526, 410 (2015).

[6] Cody Jones et al., “A logical qubit in a linear array of semiconductor quantum dots”, arXiv:1608.06335.

[7] M. Veldhorst et al., “Silicon CMOS architecture for a spin-based quantum computer”, arXiv:1609.09700, to appear in *Nature Communications*.

Acknowledgments. We acknowledge support from the US Army Research Office (W911NF-13-1-0024 and W911NF-17-1-0198), the Australian Research Council (CE11E0001017), and the NSW Node of the Australian National Fabrication Facility. The views and conclusions contained in this document are those of the author and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Office or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein.

Dephasing and gate fidelity of spin qubits with GaAs and Si quantum dots

Seigo Tarucha

The University of Tokyo, Bunkyo-ku, Tokyo, Japan
RIKEN, Wako-shi, Saitama, Japan

Qubit number and error rate are both key parameters to characterize the power of quantum computing, but they are still challenging problems. The underlying physics for the error rate is dephasing due to coupling to the environment noise, magnetic or electrical for the case of spin qubits with quantum dots (QDs). Here I will discuss the spin dephasing measured for QDs made out of GaAs and Si/SiGe and how to suppress the dephasing to raise the gate fidelity in manipulating single spins and two spins. In GaAs QDs the dephasing arises predominantly from the fluctuating nuclear spin bath. This noise is time-correlated and the variance increases with increasing correlation time from msec to 100 sec in the non-ergodic regime. We employ a micro-magnet technique for making the spin-1/2 single qubit and the phase control of the two spin qubits. We show that fast gating with the micro-magnet, fast measurement, and feedback control are all useful to reduce the influence from the magnetic noise and raise the fidelity exceeding 99 %. On the other hand, in Si QDs the magnetic noise is significantly reduced but electrical noise can be crucial instead. We apply the micro-magnet technique for isotopically purified Si/SiGe QDs and obtain the fidelity exceeding 99.9 %, and in addition find that the fidelity is predominantly limited by charge noise. I will discuss influences from charge fluctuations on the gate fidelity in the presence of a micro-magnet induced stray field.

Hole Spin Qubits in Ge and Si Nanowires

Daniel Loss
Department of Physics, University of Basel, Switzerland

I will present recent results on hole spin qubits in Ge and Si nanowires connected to superconducting striplines. The recent discovery [1] of an electrically induced spin-orbit interaction of Rashba type in the low-energy hole states of Ge/Si (core/shell) nanowires provides an attractive alternative to realize a tunable-coupling qubit. Similar results apply to pure Si nanowires. The qubit is encoded in two orthogonal dressed spin states of a hole confined in a nanowire quantum dot. Hole spins are particularly attractive since their p-wave orbitals have minimal overlap with the nuclei resulting in long coherence times and have recently been demonstrated to be compatible with industrial CMOS technology. Crucially the strong direct Rashba spin-orbit interaction (DRSOI) is controlled by an electric field applied perpendicular to the wire [1,2]. This enables the electrostatic control of the coupling between the spin degree of freedom and the electromagnetic field along the wire. Exploiting this feature we have proposed a scalable surface code architecture obtained by combining nanowire hole-spin qubits with a novel coplanar waveguide resonator grid structure [3]. The latter can be viewed as a generalization of the celebrated 1D quantum bus architecture to two dimensions. Furthermore, owing to the small size of the hole-spin qubits, a few tens of nanometers in length, they can be entirely embedded within the microwave resonators allowing for more compact resonator geometries with enhanced vacuum field strengths. The electrostatic fields required to tune the microwave-qubit coupling, are provided in situ by voltage biasing the resonator center conductor thus reducing the number of required leads.

References

[1] C. Kloeffel, M. Trif, and D. Loss, Phys. Rev. B 84, 195314 (2011).
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Achieving fast, high fidelity gates of novel quantum dot qubits

Susan N. Coppersmith

Department of Physics, University of Wisconsin-Madison, Madison, WI 53706 USA

This talk will present theoretical work at the University of Wisconsin-Madison on optimizing the gate fidelity of novel quantum dot qubits. First, we will discuss our recent work on optimizing gates of the quantum dot hybrid qubit, which consists of three electrons in a double quantum dot and which can be viewed as a hybrid of a spin and charge qubit. This qubit has been implemented experimentally [1,2,3], and coherence times and gate speeds consistent with fidelities ∼99% have been demonstrated. Our recent work shows that fidelities of 99.9% with gate times of ∼1 ns are achievable by appropriate tuning and simultaneous driving of the detuning and the tunnel couplings [4].

Second, we will discuss the charge quadrupole qubit, a highly symmetric charge qubit formed in a triple quantum dot [5]. The unique design of the quadrupole qubit enables a particularly simple pulse sequence for suppressing the effects of noise during gate operations. Simulations yield gate fidelities 10-1,000 times better than traditional charge qubits, depending on the magnitude of the environmental noise [5,6]. Our results suggest that any qubit scheme employing Coulomb interactions (for example, encoded spin qubits or two-qubit gates) could benefit from such a quadrupolar design.

This work was supported in part by ARO (W911NF-17-1-0274) and the Vannevar Bush Faculty Fellowship program sponsored by the Basic Research Office of the Assistant Secretary of Defense for Research and Engineering and funded by the Office of Naval Research through Grant No. N00014-15-1-0029. The views and conclusions contained here are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Office (ARO), or the U.S. Government.

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[2] Dohun Kim, D. R. Ward, C. B. Simmons, John King Gamble, Robin Blume-Kohout, Erik Nielsen, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson, "Microwave-driven coherent operation of a semiconductor quantum dot charge qubit," preprint arXiv:1407.7607, Nature Nanotechnology **10**, 243-247 (2015).
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Hyperfine-phonon spin relaxation in a single-electron GaAs quantum dot

Leon C. Camenzind[1,*], Liuqi Yu[1,*], Peter Stano[2,3,4], Jeramy D. Zimmerman[5,6], Arthur C. Gossard[5], Daniel Loss[1,2], and Dominik M. Zumbühl[1]

[1]*Department of Physics, University of Basel, Basel 4056, Switzerland*
[2]*Center for Emergent Matter Science, RIKEN, Saitama 351-0198, Japan*
[3]*Department of Applied Physics, School of Engineering, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[4]*Institute of Physics, Slovak Academy of Sciences, 845 11 Bratislava, Slovakia*
[5]*Materials Department, University of California, Santa Barbara 93106, USA*
[6]*Physics Department, Colorado School of Mines, Golden CO 80401, USA*

presenting author: Dominik M. Zumbühl

Understanding and controlling the spin relaxation time T_1 is central importance for spin qubits, since T_1 is setting an upper limit to the coherence time. A longer T_1 is generally better for the qubit, though for particular tasks, a short T_1 can also be useful. The spin relaxation occurs via phonon emission and spin-orbit coupling in GaAs quantum dots at low temperatures and high in-plane magnetic fields $\mathbf{B}$. The characteristic dependence $T_1 \propto \mathbf{B^{-5}}$ and B-field anisotropy were already confirmed experimentally. However, it has also been predicted 15 years ago that at low enough fields, the spin-orbit interaction is replaced by the coupling to the nuclear spins, where the relaxation becomes isotropic, and the scaling changes to $T_1 \propto \mathbf{B^{-3}}$. We establish these predictions experimentally, by measuring T_1 over an unprecedented range of magnetic fields – made possible by lower temperature, control over the B-field direction up to 14 T, and an extremely stable dot – and report a maximum $T_1 = \mathbf{57 \pm 15}$ s at the lowest fields, setting a new record for the spin lifetime in a nanostructure.

Using a novel type of orbital excited state spectroscopy with an in-plane magnetic field, we extract unparalleled information about the 3D shape. size and orientation of the quantum dot wave function by fitting to a 3D numerical model. With this model at hand, we can extract the Rashba and linear Dresselhaus parameters from the B-field anisotropy of the spin relaxation, in good agreement with spin-orbit parameters from other experiments. Further, we simulate the hyperfine induced spin relaxation rate, in very good agreement with the experiment, all with a single consistent set of parameters. While ramping the magnetic field from 0.6 T to about 10 T. the spin relaxation rate changes by a striking 6 orders of magnitude. Yet this is very well captured by the theory throughout the entire range – putting the model to a very stringent test. With spin-orbit parameters at hand, it also becomes easy to maximize the electric dipole spin resonance Rabi frequencies in future experiments by selecting the strongest spin-orbit direction, thus potentially facilitating a large improvement over previous experiments.

*These authors contributed equally to this work

Spin exchange processes in gated arrays of quantum dots

Ferdinand Kuemmeth

Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen, Denmark

I will present our recent work on controlling spin exchange dynamics between neighboring quantum dots, in order to implement coherent operations in multidot devices.

Using a linear array of quantum dots in a GaAs heterostructure, defined and controlled by top gates, we explore different configurations and choices of inducing coherent spin exchange processes. I will explain the use of pulsed barriers to implement symmetric exchange pulses, resulting in an enhancement of two-electron coherence at electrical sweet spots [1]. I will then show the symmetric tuning of triple-dot qubits, yielding multidimensional electrical sweet spots in the three-electron spin spectrum, and demonstrate coherent control using an IQ-modulated resonant control tone [2]. As an application of high-quality exchange pulses (employing more than a a thousand control pulses), I will demonstrate notch filtering of the nuclear spin noise present in these samples [3,4]. In fact, at high magnetic fields we find that qubit depasing originates from nuclear Larmor precessions, occurring at well-defined discrete frequencies associated with ^{69}Ga, ^{71}Ga, and ^{75}As nuclear spins. By applying pulse sequences that implement notch filters at exactly these discrete frequencies we extend qubit coherence times to 0.87 ms, i.e. more than five orders of magnitude longer than the duration of a exchange gate in the same device. Finally, I will show coherent spin exchange processes that involve a large multielectron dot (occupied by approximately 100 electrons). We find that the resulting spin-exchange coupling can have opposite sign compared to exchange between singly-occupied dots, indicating the presence of non-trivial electron correlations [5]. By coupling two singlet-triplet qubit to a multielectron dot, we map out different configurations useful for long-distance spin exchange, including superexchange, direct spin exchange, and on-site exchange mediated by the multielectron dot.

Our results show a pathway to implementing fast, non-nearest neighbor two-qubit gates in semiconducting spin qubits.

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Quantum computation and simulation – Spins Inside

Lieven M.K. Vandersypen[1]

[1] *QuTech and Kavli Institute of Nanoscience, TU Delft, Lorentzweg 1, 2628 CJ Delft, Netherlands*

Quantum computation has captivated the minds of many for almost two decades. For much of that time, it was seen mostly as an extremely interesting scientific problem. In the last few years, we have entered a new phase as the belief has grown that a large-scale quantum computer can actually be built. Quantum bits encoded in the spin state of individual electrons in silicon quantum dot arrays, have emerged as a highly promising direction [1]. In this talk, I will present progress in our group along three fronts. First, we created and operated a programmable two-qubit device based on silicon spin qubits [2]. Through universal all-electrical control of two spin qubits in a double quantum dot combined with individual single-shot read-out of each qubit, we have successfully programmed the four instances of the Deutsch-Jozsa and the Grover algorithms on two qubits, and created high-fidelity entangled states. This work builds on our earlier work on all-electrical single-spin manipulation [3]. Second, we have explored coherent coupling of spin qubits at a distance via two routes. In the first approach, the electron spins remain in place and our coupled via an intermediary degree of freedom [4]. In the second approach, spins are shuttled along a quantum dot array, preserving both the spin projection [5] and spin phase [6]. Third, we have developed new concepts and techniques that make quantum dot arrays a credible platform for quantum simulation of the Mott-Hubbard model. As a first demonstration, we map out the transition from Coulomb blockade to collective Coulomb blockade, the finite-size analogue of the Mott insulator transition [7]. When combined, the progress along these various fronts can lead the way to scalable networks of high-fidelity spin qubit registers for computation and simulation.

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The Quantum Dot Hybrid Qubit in Silicon

Mark A. Eriksson

Department of Physics, University of Wisconsin-Madison, Madison, WI 53706 USA
maeriksson@wisc.edu

This talk focuses on experimental measurement, manipulation, and readout the quantum dot hybrid qubit (QDHQ) [1] in silicon. The QDHQ consists of three electrons in a tunnel-coupled double quantum dot, operates at zero magnetic field, and can be manipulated on time scales as short as a few nanoseconds [2,3]. Ramsey-like experiments enable measurement of the Hamiltonian parameters that describe the qubit, and can be used to aid in tuning those parameters to enhance the qubit coherence times [4]. An essential ingredient in manipulation of the QDHQ is achieving an energy splitting between the qubit states 0 and 1 that simultaneously is greater than kT (~2 GHz in typical experiments) and low enough to be in a convenient microwave frequency range (less than 20 GHz is ideal). The valley splitting in silicon quantum dots provides one way to set the qubit energy splitting in this range, and this talk will discuss the tunability of this splitting as well as new Si/SiGe growth techniques aimed at increasing the predictability of this important energy scale.

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Microsecond dynamics of electron and hole spin qubits in self-assembled quantum dots.

A. Bechtold[1], T. Simmet[1], F. Li[2], N. Sinitsyn[2], K. Müeller[1], and J. J. Finley[1]

[1] *Walter Schottky Institut, TU-Munich, Am Coulombwall 4, 85748 Garching, Germany.*
[2] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA.*

It is by now well established that the hyperfine coupling with nuclear spin bath governs spin dynamics and loss of coherence in III-V quantum dots (QDs) [1-4]. However, the mechanisms by which coherence is ultimately lost, for *both* electron and holes, remain subject to active investigation. We present optical studies of the dynamics of electron and hole spins in individual dots over time-scales up to $\geq 100\mu s$ [5]. For *electron* spin qubits at zero magnetic field, our results show that relaxation proceeds over several distinct regimes; a first stage over the first few nanoseconds arising from coherent spin dynamics in the randomly orientated quasi-static Overhauser field. a second stage occurring over several hundred nanoseconds reflecting the quadrupolar evolution of the nuclear spin bath and third stage in which the spin decays very towards to the longest timescales investigated ($\sim 100\mu s$). Traditional approaches to probe spin-coherence involve coherent control using e.g. spin-echo pulse sequences. At $B = 4$ T we observe an exponential decay of the spin-echo signal corresponding to $T_2^{echo} \sim 1.4\mu$s that gives way to a pronounced oscillatory dependence at lower field, a signature of hyperfine dynamics of the nuclear spin bath. Measurement of higher order spin temporal correlators such as $g^3{}_{(1,2)}$, is shown to facilitate the direct determination of $T_2 \sim 1.5\mu$s and $T_2^* \sim 2$ ns for the electron, without coherent spin control [6,7]. Hole spin qubits in III-V QDs have a fundamentally different hyperfine interaction than electrons. The valence states have p-like character with vanishing amplitude at the position of the nuclei. The Fermi *contact* hyperfine interaction is, therefore, strongly suppressed [8-10], while the dipolar part of the hyperfine interaction remains [11,12]. This is expected to lead to much *slower* hole-spin dynamics in an anisotropic effective nuclear field. an expectation supported by recent CPT experiments [10]. We have probed the dynamics of single hole at $B = 0$T over timescales extending up to ~ 0.1 ms. After preparing the hole $\langle S_z \rangle = 1$, we observe no dynamics up to $\sim 50ns$, followed by an exponential decay before saturating at $\langle S_z \rangle \sim 0.3$ for timescales $\geq 50\mu s$. We will discuss the implications of this result for hole spin qubits in optically active quantum dots.

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Pauli spin blockade and spin-dependent shell filling in heavy hole quantum dots: going down to the last hole

Alexander Hamilton
School of Physics, UNSW Sydney

The spin states of heavy holes in semiconductor quantum dots are attracting significant attention for quantum information applications, with rapid progress being made by a number of groups over the past few years. The interest arises because the weak hyperfine coupling to nuclear spins allows long coherence times, while the strong spin-orbit interaction enables fast spin manipulation. In this talk I will discuss our recent progress studying spin properties of holes in silicon and gallium arsenide quantum dots [1,2,3]. In silicon single quantum dots we are able to study the spin shell filling sequence for the first 8 holes, which is consistent with the Fock-Darwin states of a circular 2D quantum dot. However while the spin filling obeys Hund's first rule, the hole-hole interaction energy is 90% of the orbital energy, so that the two-hole system to be on the verge of having a ferromagnetic ground state. In few hole GaAs and Si double quantum dots we observe Pauli spin blockade, and find that the lifting of the spin blockade by an external magnetic field is highly anisotropic. These results highlight the promise, and challenges, of using holes for spin qubits.

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Single Triplet Spin Qubits in the Rotating Frame

Amir Yacoby

Department of Physics, Harvard University. 17 Oxford St. Cambridge, MA 02138.

Electron spins in semiconductors holds promise for encoding and manipulating quantum information. The weak coupling of the spin degree of freedom to its environment provides spin qubits exceedingly long storage times. However, while storage is in the spin degrees of freedom, controlling spin qubits often involves manipulating the charge degree of freedom of the participating electrons which is far more susceptible to decoherence due to charge noise. In this talk I will discuss the advantages of operating a two electron singlet-triplet qubit in the rotating frame as a way to mitigate some of the unwanted effects of charge noise. We will demonstrate a new readout scheme for these qubits which is needed for operating in the rotating frame as well as full single and two qubit process tomography demonstrating two qubit gate fidelity in excess of 0.9.

The MOS Interface for Singlet-Triplet Quantum Bits

M. Carroll,[1] R. Jock,[1] M. Rudolph,[1] N. Tobias Jacobson,[1] P. Harvey-Collard,[1,2] J. Gamble,[1] D. Ward[1], S. Carr,[1] A. Mounce,[1] A. Shirkhorshidian[1,3] and M. P. Lilly[1]

[1]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA
[2]University of Sherbrooke, Sherbrooke, Quebec, J1K 2R1, Canada
[3]University of New Mexico, Albuquerque, New Mexico 87131, USA

Electron spins in silicon metal-oxide-semiconductor (MOS) offer a potential path to implement quantum information science. Despite silicon's opportunity to provide a near magnetic "vacuum", fundamental doubts have been raised about the MOS interface (e.g., trap disorder and noise). In this talk, I will present characterization of the MOS interface using singlet-triplet (ST) quantum bits (qubit). The ST qubit is an excellent characterization platform. The two coupled spins can be tuned to directly probe most central properties including: valley splitting (VS), g-factor non-uniformity, charge and "magnetic" noise. Disorder is still present although an increasing number of instances from this lab and others show that design and tuning can lead regularly to single electron QDs. We will present highly tunable QDs that are fabricated without metals in the nanostructure region, minimizing potential complications of metal electrodes related to charge noise [1], stress [2], and modifications of the local magnetic field [3]. We find that the MOS interface in these QDs provides a tunable VS [4] with charge noise properties comparable to other semiconductor ST qubits [5]. We also examine the effect of introducing impurities (i.e., donors). These shallow states can be tuned in to resonance to form a useful qubit [6] or alternatively tuned out of resonance where they are undetected by other qubit's performance. For magnetic noise, we find the effective Overhauser field variation consistent with the anticipated magnitudes from the ^{29}Si concentration. We also observe a strong and tunable g-factor non-uniformity between QD locations. This particular effect is advantageously used to control a ST qubit and raises interesting future prospects.

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Precision donor qubits in silicon

Michelle Y. Simmons[1]

[1] *Centre for Quantum Computation and Communications Technology, Australian Research Council Centre of Excellence, School of Physics, University of New South Wales, Sydney, 2052, Australia*

Extremely long electron and nuclear spin coherence times have recently been demonstrated in isotopically pure Si-28 [1,2] making silicon one of the most promising semiconductor materials for spin based quantum information. The two level spin state of single electrons bound to shallow phosphorus donors in silicon in particular provide well defined, reproducible qubits [3] and represent a promising system for a scalable quantum computer in silicon. An important challenge in these systems is the realisation of an architecture, where we can position donors within a crystalline environment with approx. 20–50 nm separation, individually address each donor, manipulate the electron spins using ESR techniques and read-out their spin states.

We have developed a unique fabrication strategy for a scalable quantum computer in silicon using scanning tunneling microscope lithography to precisely position individual P donors in Si [4] aligned with nanoscale precision to local control gates [5] necessary to initialize, manipulate, and read-out the spin states [6]. During this talk I will focus on demonstrating single-shot spin read-out [8] and ESR control of precisely-positioned P donors in Si. I will also describe our approaches to scale up using rf reflectometry [9] and the investigation of 3D architectures for implementation of the surface code [10] and highlight that the device produced have the lowest noise characteristics of any silicon device to date [11].

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Quantum CNOT Gate for Spins in Silicon

D. M. Zajac[1], A. J. Sigillito[1], M. Russ[2], F. Borjans[1], J. M. Taylor[3], G. Burkard[2] and J. R. Petta[1]

[1]*Princeton University, Princeton, NJ 08544, USA*
[2]*University of Konstanz, D-78457 Konstanz, Germany*
[3]*Joint Quantum Institute and Joint Center for Quantum Information and Computer Science, NIST and University of Maryland, College Park, MD 20742, USA*

Realizing robust two qubit gates has been one of the major hurdles for semiconductor spin qubits. Extremely long coherence times and high fidelity single qubit gates have been realized in spin qubits, but conventional exchange based two qubit couplings have suffered from a high sensitivity to charge noise. We demonstrate a resonantly driven single-step CNOT gate in a regime where exchange is a small perturbation to a large magnetic field gradient [1]. By placing a double quantum dot (DQD) in the fringing field of a Co micromagnet, we are able to electrically drive single spin resonance with Rabi frequencies greater than 10 MHz. We achieve single qubit fidelities of 99.3 $\pm$ 0.2 % and 99.7 $\pm$ 0.1 % for each qubit, as determined by Clifford randomized benchmarking. By turning on an exchange coupling between the two spins we split the single qubit frequencies by 19.7 MHz and use a frequency selective drive to realize a CNOT gate in 200 ns. In addition to nearest neighbor coupling of spin qubits, long distance coupling using microwave frequency photons may relax design constraints imposed by nearest-neighbor exchange coupling. I will also present our group's recent progress in coupling single electrons to microwave photons [2]. We achieve the strong coupling regime for both charge and spin, and achieve spin-photon coupling rates above 10 MHz [3,4].

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Electric-dipole control and coupling of spin qubits

Guido Burkard[1]

[1] *Department of Physics, University of Konstanz, Germany*

Electron spin qubits in dilute nuclear-spin materials now rank among the most coherent systems for quantum information processing. However, a number of challenges remain on the way to a scalable spin-based qubit architecture. Here, we address the need for fast and robust quantum gates between spin qubits, both local and non-local, from a theoretical point of view. Recent progress in realizing electrically driven two-qubit gates for electron spins in adjacent silicon quantum dots in a magnetic-field gradient [1] has motivated several further conceptual advances, such as the synchronized controlled-NOT gate [2].

The placement of a double quantum dot filled with a single electron into a field gradient endows the electron spin with a large and controllable electric dipole. Our theoretical analysis shows that in combination with a superconducting microwave resonator, the induced spin-photon coupling makes the strong-coupling regime of cavity quantum electrodynamics attainable [3], in agreement with a recent experiment demonstrating spin-cavity strong coupling [4].

While electrical control and cavity coupling for spin-1/2 qubits can be achieved using magnetic field gradients [1–4]. multi-spin qubits allow for all-electric control purely on the basis of the Pauli exclusion principle, in the form of both local gates and non-local coupling to a superconducting microwave resonator [5,6]. However, the electric controllability of spin qubits is typically accompanied by an increased sensitivity of the spin qubit to electric noise. We have analyzed this effect and have identified suitable points in parameter space, so-called sweet spots, where qubits are optimally shielded from electrical noise [5,6].

We finally highlight the extraordinarily long coherence time of defect spins in diamond and present a method for their electric-dipole control using optical fields [7]. Recently, we have found that the use of geometric phases allows for the implementation of robust all-optical holonomic single-qubit gates [8]. Looking further ahead, we describe a mechanism for electrically controlled non-local quantum gates between defect spins coupled to an optical cavity [9].

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Scaling-up Spin Qubits

David J Reilly[1,2]

[1]*School of Physics, University of Sydney, Sydney, NSW 2006, Australia*
[2]*Microsoft Corporation, Station Q Sydney, University of Sydney, Sydney, NSW 2006, Australia*

Useful quantum computers likely require 1000s of physical qubits, controlled, read out, and error corrected with platforms that push the limits of classical technology available today. This talk will describe work towards devising new approaches to scale up spin qubits and their classical interfaces. As a side-bar, recent results on extending spin coherence using nuclear polarization of ^{13}C in diamond will be presented.

High fidelity gates for GaAs based singlet-triplet qubits by feedback tuning

P. Cerfontaine[1], T. Botzem[1,2], S. Humpohl[1,2], D. Schuh[3], D. Bougeard[3], A. Ludwig[4], A. Wieck[4], and H. Bluhm[1,2]

[1] *RWTH Aachen University, Aachen, Germany*
[2] *Forschungszentrum Jülich, Jülich, Germany*
[3] *Ruhr-University Bochum, Bochum , Germany*
[4] *Regensburg University, Regensburg, Germany*

Singlet-triplet qubits in double quantum dots allow fast, fully electric control with baseband pulses. However, these pulses are subject to systematic errors due to, e.g., finite rise times and a nonlinear relation between the qubit detuning and the exchange coupling used for control. Furthermore, the dephasing rate arising from electrical noise depends on the operating point. Standard Rabi control does not yield optimal performance, and leakage out of the computational subspace has to be avoided. For GaAs based qubits, an additional challenge is the hyperfine-mediated dephasing due to nuclear spins. We address these difficulties and experimentally demonstrate high fildelity single qubit gates for GaAs based singlet-triplet qubits.

The starting point of our approach is a numerial optimization of the control pulses taking hardware capabilities as well as experimentally measured noise characteristics into account [1]. To eliminate systematic errors due to imperfect knowledge of the device and setup, we employ a self-consistent tuning protocol that iteratively modifies the pulses based on error syndromes obtained from short sequences of gates. By tuning two $\pi/2$ pulses around orthogonal axis simultaneously, effects of state preaparation and measurement errors can largely be avoided. Convergence is typically obtained after a few iterations, while up to 40 free parameters can be adjusted.

Randomized benchmarking of the optimized gates yields an average gate fidelity of up to 99.5 %. A modified randomized benchmarkig protocol allows us to extract a leakage rate of 0.05 %. Further insight on systematic errors is obtained by repeated execution of the gates.

Simulations indicate that the same approach can be extended to exchange-based two-qubit gates for single-triplet qubits while increasing the error rate by only a factor of two.

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The role of quantum computing simulation

Mark Hodson[1]

[1] *QxBranch LLC, 1200 18th Street NW, Washington DC, 20036, USA*

The final state for quantum computing is one where established hardware technologies, architectures, and programming are made available through standard interfaces to a rich software ecosystem codifying new quantum algorithms and delivering benefits to the enterprise through hybrid classical-quantum applications. A *Quantum Computing System Model* (Figure 1) defines a hardware-software stack designed to bring the benefits of quantum computing technologies through to each enterprise vertical. Standards for implementation of each layer in this model enable industry collaboration and technology interchange to achieve desired end-user outcomes.

A simulation-based approach is key to maturing the form and interfaces within the Quantum Computing System Model when hardware is not readily accessible. This enables us to begin to answer questions such as:

1. What programming languages will be used to build quantum applications?

2. What domain specific languages will be needed to codify hardware control?

3. Can these concepts be merged to create an *embedded language* for quantum programming?

4. Can a quantum computer simulator be used as a hardware surrogate to commence early application development?

5. Are there additional benefits that quantum computer simulation can provide?

Through development of the Quantum Computer Simulation System, QxBranch has gained insights into these and other questions regarding the best software development approach to quantum computing systems.

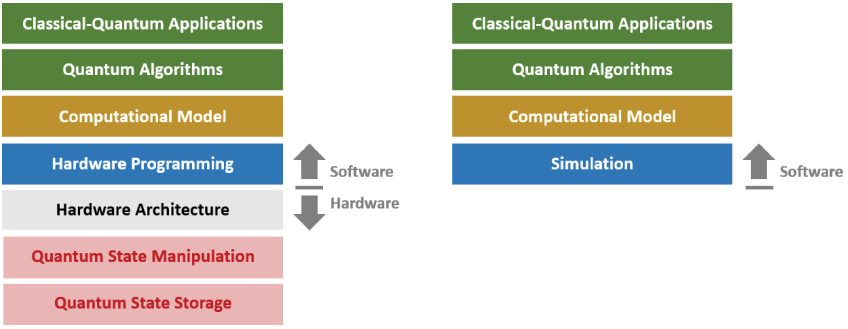


Figure 1: Quantum Computing System Model (left); Simulation-based solution (right).

Recent developments in quantum error correction with few qubits

Stephen D. Bartlett

Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney NSW Australia

Quantum error correction and the theory of fault-tolerance are the principal tools that we imagine using to perform quantum computations with noisy devices. Recent experiments have demonstrated simple error correcting codes to reduce the effects of noise, and theoretical results show that in principle large quantum computers can function very accurately if operations have sufficiently low noise and are implemented *fault tolerantly*.

Unfortunately, current approaches such as those based on the surface code have a prohibitively large overhead; they are very costly to build as the required level of redundancy is astronomical. Motivated by this practical limitation, theorists have been working to characterise the range of approaches to fault tolerant quantum computation and to use this understanding to substantially reduce this overhead. One aspect of this approach is to use more realistic and structured descriptions of the noise environment, and to take advantage of the structure of the noise.

I'll present some recent results from the theory literature that suggest ways to execute quantum error correction without an astronomical overhead. I'll focus on results that have implications for spin qubit quantum computing in the near future.

[1] "Ultra-high error threshold for surface codes with biased noise," David K. Tuckett, Stephen D. Bartlett, Steven T. Flammia, arXiv:1708.08474.
[2] "Tailored codes for small quantum memories," Alan Robertson, Christopher Granade, Stephen D. Bartlett, Steven T. Flammia, arXiv:1703.08179.

Hardware challenges to a large-scale quantum computer based on superconducting qubits

Marissa Giustina[1]

[1] *Google LLC*

A paramount goal across the quantum information field is to build a quantum computer with a large number of high-fidelity qubits. Superconducting qubits, which are operated in a cryogenic environment ($\approx$ 20 mK) and controlled with microwave electronics, are an interesting platform for this research. We briefly review a few candidate architectures for building a quantum computer with superconducting qubits, and discuss similarities between the physical implementations of each in the Google Quantum-AI lab. We consider what hardware is currently used to build these systems and examine the limits of brute-force scaling. The road to a large-scale quantum computer will include the development of a number of new technologies.

Elucidating Reaction Mechanisms on Quantum Computers

M. Troyer[1,2], M. Reiher[3], N. Wiebe, K.M. Svore, D. Wecker[1]

[1] *Microsoft Research, Redmond, WA 98052, USA*
[2] *Theoretische Physik and Station Q Zurich, ETH Zurich, 8093 Zurich, Switzerland*
[3] *Laboratorium für Physikalische Chemie, ETH Zurich, 8093 Zurich, Switzerland*

We show how a quantum computer can be employed to elucidate reaction mechanisms in complex chemical systems, using the open problem of biological nitrogen fixation in nitrogenase as an example. We discuss how quantum computers can augment classical-computer simulations for such problems, to significantly increase their accuracy and enable hitherto intractable simulations. Detailed resource estimates show that, even when taking into account the substantial overhead of quantum error correction, and the need to compile into discrete gate sets, the necessary computations can be performed in reasonable time on small quantum computers. This demonstrates that quantum computers will realistically be able to tackle important problems in chemistry that are both scientifically and economically significant.

[1] M. Reiher *et al.* PNAS **114** 7555-7560 (2017).

Beyond classical computing with near-term quantum computers

Michael J. Bremner[1]

[1] *Centre for Quantum Software and Information and Centre for Quantum Computation and Communication Technology, Faculty of Engineering Information Technology, University of Technology Sydney, NSW 2007, Australia*

Over the last few years significant attention has been devoted to devising experimental demonstrations of quantum computational supremacy: namely using a quantum computer to solve a computational task in a regime that goes beyond what is possible on a classical, digital, machine. This is, in part, driven by the hope that a clear demonstration of post-classical computation can be performed with a device that is intermediate between the small quantum circuits that can currently be built and a full-scale, fault-tolerant, quantum computer. The theoretical challenge that this poses is twofold: firstly we must identify the physically least expensive quantum computations that are classically unachievable; and we must also determine if this advantage can be maintained in the presence of physical noise. In this talk I will review the IQP, Boson Sampling, and chaotic circuit approaches to quantum computational supremacy, how they can be generalized to other intermediate quantum computing models, and to what extent the experimental resource requirements of these problems can be reduced.

[1] M. J. Bremner, A. Montanaro, and D. J. Shepherd, *Achieving quantum supremacy with sparse and noisy commuting quantum computations*, Quantum **1**, 8 (2017). arXiv:1610.01808
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[3] S. Boixo, et al, *Characterizing quantum supremacy in near-term devices*, arXiv:1608.00263
[4] A. Lund, M. J. Bremner, T. C. Ralph *Quantum sampling problems, BosonSampling and quantum supremacy* npj Quantum Information **3**, Article number: 15 (2017). arXiv:1702.03061

Public Lecture

Schrödinger's cat is alive and means business - Directions and opportunities in the quantum technology revolution

Quantum science has often been portrayed as a spooky, counterintuitive topic of interest only for a few weirdos. This popular depiction was never accurate – no electronic device would work if it weren't for the quantum behaviour of electrons in a crystal, for example – but it is now becoming completely untenable. Today, we are witnessing a not-so-silent revolution in the way quantum phenomena can impact our lives. We are also witnessing unprecedented progress in the way we can "see", and thus understand, the quantum world.

In this public lecture, I will illustrate the working principles and the applications of some of the pillars of the quantum technology revolution: quantum computing, quantum communication, and quantum sensing. Forget about spookiness and weirdness: this stuff is here and it's working. Many large businesses are already ramping up investment to partake of the opportunities offered by the one of the most transformative technologies of this century. Don't miss out!

Speaker: Prof Andrea Morello *(University of New South Wales, Sydney)*

Time: Thursday, 9th of November 2017, 19:30 - 21:00

Location: Messel Lecture Theatre at the Sydney Nanoscience Hub (SNH) at the University of Sydney

List of Posters

1. **Shankar Bhattarai** *(Tribhuvan University)*
   Interpretation of Double Langmuir Probe I-V Characteristics at Different Ionospheric Plasma Temperatures
2. **Julien Camirand** *(Institut quantique, Université de Sherbrooke)*
   Silicon platforms for quantum dot spin qubits
3. **Xanthe Croot** *(University of Sydney)*
   Device Architecture for Coupling Spin Qubits Via an Intermediate Quantum State
4. **Michael Fogarty** *(CQC2T, UNSW Sydney)*
   High-fidelity single-shot readout and exchange control of spin qubits in silicon-MOS quantum dots
5. **Samuel Gorman** *(CQC2T, UNSW Sydney)*
   Tunneling statistics for analysis of spin readout fidelity
6. **Robin Harper** *(University of Sydney)*
   Recent developments in the theory of randomised benchmarking
7. **Toivo Hensgens** *(Qutech and Kavli Institute of Nanoscience, TU Delft)*
   Quantum simulation of a Fermi-Hubbard model using a semiconductor quantum dot array
8. **Charles Hill** *(CQC2T, University of Melbourne)*
   A Phosphorus in Silicon Adiabatic Quantum Computer
9. **Danielle Holmes** *(CQC2T, University of Melbourne)*
   Implantation of Bi and 28Si for Donor Electron Spin Resonance in Enriched Si
10. **Wister Huang** *(CQC2T, UNSW Sydney)*
    Noise spectroscopy and randomized benchmarking of a silicon quantum dot qubit
11. **Benjamin Joecker** *(CQC2T, UNSW Sydney)*
    Effective mass theory simulations of exchange coupled donors in silicon

12. **Daniel Keith** *(CQC2T, UNSW Sydney)*
    High Bandwidth Electron Spin Readout with the Radio Frequency Single Electron Transistor
13. **Mizuki Kobayashi** *(Tokyo Institute of Technology)*
    Physically-defined p-channel silicon double quantum dots with a charge sensor
14. **Ludwik Kranz** *(CQC2T, UNSW Sydney)*
    Coherent electron spin control in atomically precise donor systems
15. **Jan Krzywda** *(Institute of Physics, Polish Academy of Sciences)*
    Localization of a magnetic moment using a two-qubit probe
16. **Damian Kwiatkowski** *(Institute of Physics, Polish Academy of Sciences)*
    Entanglement dynamics of NV centers coupled to a bath of C-13 nuclear spins
17. **Benedikt Lechtenberg** *(Kyoto University)*
    Parity Symmetry Protected Spin Entanglement in the Two Impurity Model
18. **Ross Leon** *(CQC2T, UNSW Sydney)*
    Designs for electrically driven spin qubits based on silicon-MOS quantum dots
19. **Scott Liles** *(UNSW Sydney)*
    Spin filling of holes in a silicon quantum dot
20. **Mateusz Madzik** *(CQC2T, UNSW Sydney)*
    Ion-implanted 31P donor devices for 2-qubit logic gates
21. **Vincent Mourik** *(UNSW Sydney)*
    Exploring quantum chaos within a single 123-Sb donor in silicon
22. **Usman Muhammad** *(CQC2T, The University of Melbourne)*
    Atomic-precision spatial metrology of phosphorous donors in silicon by STM imaging of wave functions
23. **Akito Noiri** *(RIKEN)*
    A controlled-phase gate between spin qubits of different kinds
24. **Prasanna Pakkiam** *(CQC2T, UNSW Sydney)*
    Design and characterization of a device for hosting singlet-triplet qubits with atomic precision donors in silicon
25. **Sarath Raman** *(Department of Physics and Astronomy, Macquarie University)*
    A Fibre-cavity platform

26. **Simon Robson** *(CQC2T, University of Melbourne)*
    Single Ion Detectors for Deterministic Top-Down Fabrication of Donor-Qubit-Based Silicon Quantum Electronics

27. **Lachlan Rogers** *(Macquarie University)*
    Bayesian inference of switching rates for blinking silicon-vacancy emitters in nanodiamonds

28. **Lachlan Rogers** *(Macquarie University)*
    Germanium-vacancy centres and the quest for "perfect" diamond qubits

29. **Maximilian Russ** *(University of Konstanz)*
    Synchronized high-fidelity quantum gates in Si/SiGe double quantum dots

30. **Vivien Schmitt** *(CQC2T, UNSW Sydney)*
    Donor spin qubit with robust long-distance coupling

31. **Thomas Smith** *(University of Sydney)*
    Spin-exchange via a multielectron quantum mediator

32. **Sergei Studenikin** *(National Research Council of Canada)*
    Single and two hole spin qubits formed in a gated GaAs/AlGaAs double quantum dot

33. **Kuan Tan** *(Visiting Research Fellow - CQC2T, UNSW Sydney)*
    Tunable Electromagnetic Environment of a Superconducting Resonator Realized Through a Quantum-Circuit Refrigerator

34. **Tuomo Tanttu** *(CQC2T, UNSW Sydney)*
    Angular dependence of electron g-factor and Stark shift in a silicon quantum dot

35. **Gustav Teleberg** *(Oxford Instruments NanoScience)*
    A compact, fast turn-around, cryogen-free platform operating at 1 K or 50 mK

36. **Henry Yang** *(UNSW Sydney)*
    High-fidelity gate control of silicon quantum dot qubits using shape-optimized microwave pulses

37. **Jun Yoneda** *(Riken)*
    An isotopically-enriched silicon spin qubit with >99.9% fidelity and charge-noise-limited coherence

Interpretation of Double Langmuir Probe I-V Characteristics at Different Ionospheric Plasma Temperatures

Shankar Bhattarai
MSc Physics, Department of Physics, Patan Multiple Campus, Tribhuvan University, Lalitpur, Nepal
oshobhattarai2@gmail.com

ABSTRACT

A Single Langmuir probe is always connected to an electrode as fixed potential. In cases where such an electrode does not exist or the plasma potential is fluctuating significantly, this method is not relevant. This weakness was overcome by the development of the floating double probe by Johnson and Malter [1]. A distortion of the probe characteristics due to varying potential is eliminated, while the whole probe system is floating. This supports probe operation also in discharges with strongly varying potential.

Double Langmuir probe (DLP) is a usually used diagnostics for instantaneous measurement of electron temperature and density in low temperature laboratory plasmas as well as in edge region of fusion plasma chambers. This research paper focuses on the study of Spherical Double Langmuir Probe I-V characteristics in Maxwellian interstellar plasma. To generate the exact plasma conditions of the experimental testing environments computational procedures is adopted. The investigations address the development of a technique to model Maxwellian plasma. Three different ionospharic plasma temperatures are theoretically taken and its effects on floating potential are studied in this research. The variation of floating potential and ion saturation current due to temperature is clearly depicted. A manifest trail in the I-V curves is the bump that occurs right after the floating potential. This feature in the transition region affects ability to determine the electron temperature, ion saturation current and plasma potential. Symmetric characteristic when both tips are of equal geometry is an important advantage of the double probe. Generally, all surfaces adjacent to the plasma become contaminated with deposits, so also does any probe. Here I have also deliver some sense of how one might proceed to use these results in the analysis of experimental I-V curves obtained in space.

Keywords: *Double Langmuir probe, I-V Characteristic, Maxwellian plasma, Ionosphere*

Silicon platforms for quantum dot spin qubits

Julien Camirand Lemyre[1], Ph. Galy[2], P. Lemieux[1], F. Arnaud[2], D. Drouin[1,3] and M. Pioro-Ladrière[1,4]

[1] *Institut quantique, Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada*
[2] *STMicroelectronics, 38926 Crolles, France.*
[3] *Département de génie électrique et génie informatique, Université de Sherbrooke, Sherbrooke, J1K 2R1, Canada.*
[4] *Quantum Information Science Program, Canadian Institute for Advanced Research, Toronto, Ontario M5G 1M1, Canada.*

Silicon offers compelling properties for high-performance spin qubits in quantum dots. On one hand, isotopically purified silicon qubits [1] with integrated micromagnets have demonstrated fast and reliable single-qubit gates [2]. On the other hand, the compatibility of silicon qubits with microelectronics offers a unique opportunity for co-integration with dedicated classical controls [3]. Hence, finding suitable structures to bridge the gap between high performances qubits and large-scale integration is crucial for long-term development of spin qubits [4]. Toward this objective, we investigate foundry compatible structures for minimalist qubit designs, integrated micro-magnets and co-integration. In this work, bulk MOS and FDSOI structures are studied.

First, cobalt micromagnets, characterized with our electrostatic hall-bar platform [5], have been successfully integrated on single-stack MOS poly-silicon quantum dots [6] based on the split gate design [7]. The fabrication process of micromagnets is found to be compatible with our MOS specific materials. Transport measurements show electrostatic stability of quantum dots with signature of shell-filling. Also, magneto-spectroscopy reveals the influence of the micromagnet on the energy levels of the quantum dot.

Then, a first step towards co-integration of spin qubits with classical electronics has been taken on an N-MOS structure fabricated entirely inside STMicroelectronics foundry using 28 nm ultra-thin body and buried oxide fully depleted silicon on insulator (UTBB FD-SOI) technology [8]. The MOS structure is functional cryogenic temperature with both front and back gate controls.

Acknowledgements : We thank our colleagues from STMicroelectronics for their support, especially Sotiris Athanasious. This work was carried in close collaboration with N.T. Jacobson, J. Anderson, R. P. Manginell, T. Pluym, D. Ward and Malcolm S. Carroll from Sandia National Laboratories. 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 multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.

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Device Architecture for Coupling Spin Qubits Via an Intermediate Quantum State

X. G. Croot[1], S. J. Pauka[1], J. D. Watson[2,3], G. C. Gardner[3,4], S. Fallahi[2,3], M. J. Manfra[2,3,4,5] and D. J. Reilly[1,6]

[1] *ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, NSW, Australia*
[2] *Department of Physics and Astronomy, Purdue University, West Lafayette, IN, USA*
[3] *Birck Nanotechnology Center, Purdue University, West Lafayette, IN, USA*
[4] *Station Q Purdue, Purdue University, West Lafayette, IN, USA*
[5] *School of Materials Engineering and School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA*
[6] *Microsoft Corporation, Station Q Sydney, The University of Sydney, Sydney, NSW, Australia*

We demonstrate a scalable device architecture that facilitates indirect exchange between singlet-triplet spin qubits, mediated by an intermediate quantum state. The device comprises five quantum dots, which can be independently loaded and unloaded via tunnelling to adjacent reservoirs, avoiding charge latch-up common in linear dot arrays. In a step towards realizing two-qubit entanglement based on indirect exchange, the architecture permits precise control over tunnel rates between the singlet-triplet qubits and the intermediate state, demonstrably tunable between 1.5 and 5.4 GHz. We show that by separating qubits by ~ 1 μm, the residual capacitive coupling between them is reduced to ~ 7 μeV.

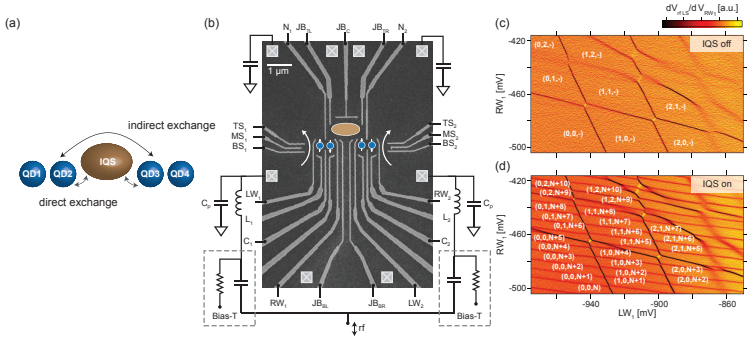


Figure 1: (**a**) Cartoon of our device architecture for coupling singlet-triplet qubits via an intermediate quantum state. (**b**) Electron micrograph and circuit schematic of the double quantum dots (blue circles) coupled by an intermediate quantum state (brown 'jellybean' ellipsoid). (**c**) Charge stability diagram measured with the left sensor as a function of the gates on the left double dot, without the presence of the dot associated with the IQS, and (**d**) with the IQS.

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High-fidelity single-shot readout and exchange control of spin qubits in silicon-MOS quantum dots

M. A. Fogarty[1], K. W. Chan[1], B. Hensen[1], W. Huang[1], T. Tanttu[1], C. H. Yang[1], A. Laucht[1], M. Veldhorst[2], F. E. Hudson[1], K. M. Itoh[3], D. Culcer[4], A. Morello[1] 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, New South Wales 2052, Australia.*

[2] *QuTech, and Kavli Institute of Nanoscience, TU Delft, Lorentzweg 1, 2628CJ Delft, the Netherlands.*

[3] *School of Fundamental Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan.*

[4] *School of Physics, The University of New South Wales, Sydney 2052, Australia.*

A fully error-corrected quantum processor will require parallel stabilizer measurements of its physical qubits. A natural implementation of this would employ spin-parity readout at targeted locations in one- and two-dimensional qubit arrays[1,2]. Here we demonstrate single-shot spin-blockade readout for a pair of spin qubits in a Si-MOS[3] quantum double-dot. A high readout visibility of 98% is achieved using a reservoir-charge state-latching protocol[4,5]. Using this, we characterize the two-spin system by coherently controlling oscillations between the S/T- states via Landau-Zener-Stückelberg Interferometry[6] and S/T0 states through control over the Heisenberg exchange coupling[7]. Furthermore, our preliminary measurements show that spin-blockade readout is compatible with single spin control via electron spin resonance (ESR) in these devices[8]. By removing the need for the large Zeeman splitting that is required for reservoir-based spin readout, we achieve improved flexibility in control and spectroscopy, field-dependent studies of spin-orbit and hyperfine effects, and enable the use of ESR frequencies reduced by an order of magnitude ($\simeq$4 GHz), allowing more flexible engineering of future quantum processors.

We acknowledge support from the US Army Research Office (W911NF-13-1-0024 and W911NF-17-1-0198), the Australian Research Council (CE11E0001017), and the NSW Node of the Australian National Fabrication Facility. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Office or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein. B.H. acknowledges support from the Netherlands Organization for Scientific Research (NWO) through a Rubicon Grant. K.M.I. acknowledges support from a Grant-in-Aid for Scientific Research by MEXT, NanoQuine, FIRST, and the JSPS Core-to-Core Program.

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Tunneling statistics for analysis of spin readout fidelity

Samuel K. Gorman[1], Yu He[1], Daniel Keith[1], Matthew G. House[1], L. Kranz[1], Joris G. Keizer[1], L. Fricke[1], Samuel J. Hile[1], Matthew A. Broome[1], and Michelle Y. Simmons[1]

[1] *Centre of Excellence for Quantum Computation and Communication Technology, School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia*

We investigate spin and charge dynamics of a quantum dot of phosphorus atoms coupled to a radio-frequency single-electron transistor (rf-SET) using full counting statistics. We show how the magnetic field plays a role in determining the bunching or anti-bunching tunnelling statistics of the donor dot and SET system. Using the counting statistics we show how to determine the lowest magnetic field where spin-readout is possible. We then show how such a measurement can be used to investigate and optimise single electron spin-readout fidelity. To analyse the spin readout fidelity we present a full theoretical analysis of single-shot readout to help standardise readout fidelity methodologies while describing the critical parameters to achieve high fidelity readout. In particular, we derive a model for energy selective state readout based on a charge detector response and examine how to optimise the fidelity by choosing correct experimental parameters. Although we focus on single electron spin readout, the theory presented can be applied to any single-shot readout technique.

Recent developments in the theory of randomised benchmarking

Robin Harper[1], Steve Flammia[1], and Stephen Bartlett[1]

[1] *Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, Australia*

Randomized benchmarking is an important protocol for robustly characterizing the error rates of quantum gates. This poster will cover some of the more recent developments relating to the randomized benchmarking protocol, such as the ability to characterize the coherence of the noise [1] and the ability to use this parameter, known as the *unitarity* of the noise, to provide bounds on the diamond norm of the noise that are tighter than bounds that can be achieved using average gate fidelity alone [2, 3]. Other developments that will be highlighted will include:

- proposed changes to the randomized benchmarking protocol that allows better estimates to be made of the average gate fidelity, such as dicussed in [4];
- analysis of the impact of gate dependent noise [5] and [6];
- alterations to the protocol that allow it to be used to to characterize T-gates [7] as well as arbitrary gates [8, 9].

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Quantum simulation of a Fermi-Hubbard model using a semiconductor quantum dot array

T. Hensgens[1], T. Fujita[1], L. Janssen[1], Xiao Li[2], C. J. Van Diepen[3], C. Reichl[4], W. Wegscheider[4], S. Das Sarma[2] & L. M. K. Vandersypen[1]

[1] *QuTech and Kavli Institute of Nanoscience, TU Delft, 2600 GA Delft, The Netherlands*
[2] *Condensed Matter Theory Center and Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, USA*
[3] *QuTech and Netherlands Organization for Applied Scientific Research (TNO), 2600 AD Delft, The Netherlands*
[4] *Solid State Physics Laboratory, ETH Zürich, 8093 Zürich, Switzerland*

Seminal efforts are underway to study novel emergent magnetic and electronic properties of strongly-correlated electronic phases of low-dimensional condensed matter physics using dedicated quantum simulators. Experimentally realized correlations, however, are typically limited by the residual entropy of the initialized systems, and scaling to similarly homogeneous but larger system sizes is not always straightforward.

We show that quantum dot arrays in semiconductors constitute a promising platform in these regards. Not only do tunnel-coupled dots readily adhere to the Fermi-Hubbard model in the effective low temperature limit necessary for seeing strong correlations, but one can also directly leverage developments for using quantum dots as spin qubits. By describing an experimental toolbox for Hamiltonian engineering, validated by direct numerical simulations, we negate the combination of disorder inherent to the solid state and the inefficiency of calibration routines which has previously limited the scaling of quantum dot experiments in scope and size. As we map out the experimental phase space of a triple quantum dot device [1], we show the onset of collective Coulomb blockade [2], the finite-size analogue of the interaction-driven Mott transition.

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A Phosphorus in Silicon Adiabatic Quantum Computer

Charles D. Hill[1], M. Usman[1], S. Rogge[2], M. Y. Simmons[2], and L. C. L. Hollenberg[1]

[1] *Center for Quantum Computation and Communication Technology, School of Physics, The University of Melbourne, Parkville, Victoria, 3010, Australia*
[2] *Center for Quantum Computation and Communication Technology, School of Physics, The University of New South Wales, Sydney, NSW, 2052, Australia*

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

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Implantation of Bi and ^{28}Si for Donor Electron Spin Resonance in Enriched Si

Danielle Holmes
Centre for Quantum Computer Technology, School of Physics,
University of Melbourne, Parkville, VIC 3010, Australia

Donors in silicon are promising qubit candidates as they exhibit long electron and nuclear spin coherence times (T_2) allowing for high fidelity quantum operations. Bismuth donors, the heaviest of the group V donors, were the focus of this work as they offer fabrication advantages including reduced straggling, allowing for increased spatial precision preferable in deterministic ion implantation. They also offer technological advantages including an increased quantum memory resulting from a larger nuclear spin ($I = 9/2$) and magnetically stable qubit manipulation due to so-called 'Clock Transitions'.

We use Electrically Detected Magnetic Resonance (EDMR) and Electron Spin Resonance (ESR) to probe shallow Bi-implanted n-type natural silicon Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs). EDMR and ESR were performed on background P dopants to show that the lattice was repaired and the P donors electrically activated after the Bi implant and subsequent annealing step. Bulk ESR was then performed on the shallow implanted Bi donors and the first ($I = 1/2$) ESR transition was observed.

Further, depletion of the ^{29}Si isotope ($I = 1/2$) in natural silicon increases donor electron T_2 times by reducing the background noise attributed to these nuclear spin flips. Isotopic enrichment of silicon was achieved by implanting a high fluence of ^{28}Si ions and verified using Secondary Ion Mass Spectrometry (SIMS). This enriched silicon will be used for future ESR measurements of donor electron T_2 times.

Noise spectroscopy and randomized benchmarking of a silicon quantum dot qubit

Kok Wai Chan[1], Wister Huang[1], Henry Yang[1], Jason Hwang[1], Bas Hensen[1], Tuomo Tantt[1], Fay Hudson[1], Kohei Itoh[2], Arne Laucht[1], Andrea Morello[1], and Andrew Dzurak[1]

[1] *Center for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, New South Wales 2052, Australia*

[2] *School of Fundamental Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan*

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

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Effective mass theory simulations of exchange coupled donors in silicon

Benjamin Joecker,[1] John King Gamble,[2] Andrew D. Baczewski,[2] Jarryd Pla,[1] and Andrea Morello[1]

[1] *Centre for Quantum Computation and Communication Technology, University of New South Wales, Sydney, New South Wales 2052, Australia*

[2] *Center for Computing Research, Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*

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

Keywords: ^{31}P donors in Si; exchange interaction; effective mass theory; Hartree-Fock method

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

D. Keith[1], M. G. House[1], M. B. Donnelly[1], T. F. Watson[1,2], B. Weber[1,3], and M. Y. Simmons[1]

[1] *CQC2T, UNSW, Sydney, Australia*
[2] *QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, Netherlands*
[3] *Division of Physics and Applied Physics, Nanyang Technological University, Singapore*

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

Here, we demonstrate using a radio frequency SET (rf-SET) and characterize its bandwidth, shot-noise and readout fidelity. At the full bandwidth of the rf-SET circuit, 9.5 MHz, we demonstrate single-shot electron spin readout at $B = 1.5$ T with an effective signal-to-noise ratio of 7.2. For electron charge state detection the power broadening is no longer limited by the electron spin state splitting, allowing us to achieve an effective signal-to-noise ratio of 12.7 by increasing the driving power before being limited by heating of the rf-SET. Optimized single-shot readout of electrons, with 50 kHz tunnel rates, achieved measurement fidelities above 98% limited by the base electron temperature (200 mK).

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

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Physically-defined p-channel silicon double quantum dots with a charge sensor

Mizuki Kobayashi[1], Egle Tylaite[1], Naoki Shimatani[1], Yu Yamaoka[1], and Tetsuo Kodera[1]

[1] *Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Japan*

Spins in silicon quantum dots (QDs) are promising candidates for integrated qubits because of the long coherence time and compatibility with conventional silicon device fabrication technologies[1]. Especially, p-channel silicon QDs are studied well recently [2] because hole spins in silicon QDs can be controlled with spin-orbit coupling. It means that micro magnets for creating slanting fields are not necessary, which is advantageous for future integration.

In this work, we fabricated and characterized the physically-defined p-channel silicon double QDs with a charge sensor. The QD structures were fabricated by using electron beam lithography and SF_6 dry etching. The scanning electron microscope (SEM) image is shown in Fig. 1 (a). In DC measurements, we observed charge stability diagrams, Pauli spin blockade (PSB) in a charge triple point as shown in Fig.1 (b), and charge sensing signals, at a temperature of 1.5 K.

For future high-speed charge sensing, we also applied radio frequency (RF) reflectometry [3] to the device as shown in Fig. 1 (a). Chip inductor and parasitic capacitance C_p work as a resonance circuit and it can eliminate large impedance mismatch between a coaxial line (50 Ω) and QDs (>100 kΩ). 470 nH chip inductor of right-hand side, 1 kΩ resistor, and 2.2 nF chip capacitor work as a bias tee, enabling simultaneous RF and DC measurement. We observed a resonance at 292 MHz as shown in Fig.1 (c) and the capacitance is estimated as 0.6 pF. Note that this is preliminary data of reflection measurements since the resonance is obtained without inducing two dimensional hole gas.

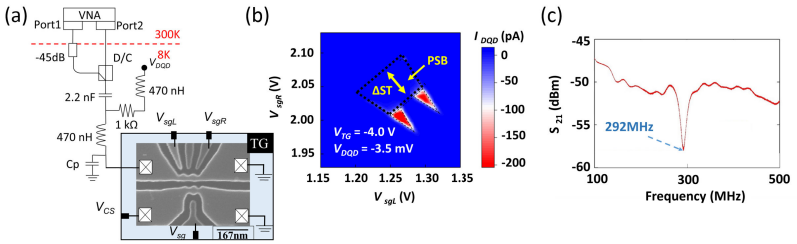


Figure 1: (a) SEM image of p-channel double QDs and schematic image of simultaneous RF and DC measurement setup. (b) PSB at 1.5 K. (c) Resonance at 8 K using RF reflectometry.

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Coherent electron spin control in atomically precise donor systems

S.J. Hile[1], L. Fricke[1], L. Kranz[1], S.K. Gorman[1], P. Pakkiam[1], W. Baker[1], M.A. Broome[1], M.G. House[1], J. G. Keizer[1], Y. Wang[2], C.Y. Chen[2], Y. Hsueh[2], R. Rahman[2], C.L.Hollenberg[3], M.Y. Simmons[1]

[1] *Centre of Excellence for Quantum Computation and Communication Technology, School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia*
[2] *Network for Computational Nanotechnology, School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907, USA*
[3] *Centre of Excellence for Quantum Computation and Communication Technology, University of Melbourne, Melbourne, Victoria 3010, Australia*

We report the progress in precision donor qubits in silicon. We demonstrate the successful integration of a microwave transmission line onto two few electron double donor dot qubits in silicon fabricated with the atomic precision of a scanning tunneling microscope (STM). The transmission line is used for magnetically driven Electron Spin Resonance (ESR) and a DC-coupled SET charge sensor is employed for single-shot spin readout.

In the first device we use ESR spectroscopy to identify the characteristic hyperfine spectra of a single donor 1P and two-donor 2P dots. We demonstrate how, from the hyperfine spectra, we can determine the distance between the donors within the 2P quantum dot. Atomistic NEMO modelling is used to determine possible donor configurations within the 2P dot in the Si crystal lattice.

In the second device, we demonstrate coherent electron spin rotations via Rabi oscillations on the right dot with 3 electrons. Using the Hahn spin echo sequence, we partially compensate for Overhauser field fluctuations in order to measure an electron spin decoherence time $T_2 \approx 298\mu s$, three orders of magnitude larger than the observed pure dephasing time $T_2^* \approx 246ns$.

Localization of a magnetic moment using a two-qubit probe

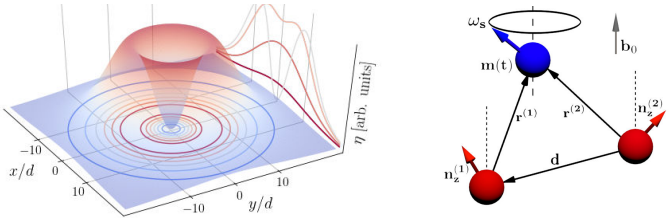
Jan Krzywda, Łukasz Cywiński, and Piotr Szańkowski

Institute of Physics, Polish Academy of Sciences, Warszawa, Poland

Spin qubits such as NV centers in diamond are currently used as nanoscale-resolution sensors of magnetic field noise, generated by nuclear spins of molecules localized in the neighbourhood of the sensor [1,2]. Subjecting the qubit to a periodic sequence of rotations makes it sensitive only to fluctuations of given frequency [3]. When the magnitude of the fluctuating field associated with given source and the form of qubit-source interaction are known, measurement of the qubit decoherence allows one to find a surface on which the source is located.

Extending this idea to the multi-qubit sensor should enable to pin-point the exact location of the source (cf. the classical triangulation procedure). Here we show that already with two qubits, each subjected to a given sequence of rotations, one can localize the fluctuating magnetic moment [4]. The method can be viewed as an application of a general protocol for performing noise cross-correlation spectroscopy [5] to the case of two qubits interacting with a precessing magnetic moment. We consider not only the case of the sensors localized in predefined spots, interacting via dipolar coupling with the moment, but also situations with less *a priori* knowledge available, e.g. when the relative position of the two qubits is unknown or different coupling is present. We show that source localization is also possible then, provided we have control over external magnetic field direction.

Alternatively, when the form of the qubit-moment coupling is not known, we describe the idea of symmetry detector, capable of narrowing down the possible source location. We emphasize the existence of sensor-source arrangement leading to robust decoherence-free evolution, and provide its geometrical interpretation.



(Left) The spatial map of attenuation factor χ of coherence given by $e^{-T^2\chi}$, where T is the evolution time. (Right) Schematic picture of two detectors interacting with magnetic moment.

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Entanglement dynamics of NV centers coupled to a bath of ^{13}C nuclear spins

Damian Kwiatkowski[1] **and Łukasz Cywiński**[1]

[1]*Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, PL 02-668 Warsaw, Poland*

The $m_s = 0$ and $m_s = 1$ levels of nitrogen-vacancy (NV) center in diamond form a qubit that can be initialized, controlled, and read out at room temperature, and which is intensively researched in the context of nanoscale magnetic imaging applications [1-4]. The main source of decoherence of this qubit is its interaction with the bath of ^{13}C nuclei. Recently, entanglement between two NV centers (separated by ≈ 20 nm) was created [5]. We present an extension of calculation of decoherence due to the nuclear bath (using the state-of-the-art Cluster-Correlation Expansion method [6,7]) to the case of two qubits. We also include the presence of magnetic field gradient which is helpful for separate addressing of the two qubits, but which modifies the nuclear dynamics.

Entanglement of two-qubit Bell states calculated in pure dephasing approximation is simply related to two-qubit coherences $\rho_{01,10}$ and $\rho_{00,11}$. When two qubits interact with a partially common bath (as is the case for two nearby NV centers), the decay of these coherences can be slower or faster than the decay of product of single-qubit coherences, depending on whether the bath is source of correlated/anticorrelated noise, respectively.

We investigate the common bath effects for a set of spatial realizations of the nuclear bath, and compare the obtained results with predictions of Gaussian noise models. For the latter, the common bath affects Ψ and Φ states in opposite ways, enhancing coherence of one while suppressing for the other. This indeed happens when common bath consists only of the weakly coupled nuclei. Nuclear pairs located close to the NV center, contribute very characteristically to decoherence, leaving strong fingerprints (oscillations in coherence). Likelihood of finding such pairs is as high as 50 %. If qubits are so close to each other that such strongly coupled dimers occur in the common part of the bath, the Gaussian noise model is no longer sufficient to describe the effects of common bath on decoherence of entangled states.

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Parity Symmetry Protected Spin Entanglement in the Two Impurity Model

B. Lechtenberg[1] and F. B. Anders[2]

[1] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[2] *Lehrstuhl für Theoretische Physik II, Technische Universität Dortmund, 44221 Dortmund, Germany*

We consider the Two Impurity Kondo Model (TIKM) where two spin 1/2 impurity spins, separated by a distance R, are coupled via a Heisenberg interaction J to the electron spin densities of a conduction band. The equilibrium properties of the TIKM have been investigated extensively in the literature[1–5] and it has been recently shown[6,7] that for a 1D inversion symmetric dispersion and the specific distances $k_{\mathrm{F}}R = n\pi$, with k_{F} being the Fermi momentum, conduction electron states with even ($n = \{1, 3, \ldots\}$) or odd ($n = \{0, 2, \ldots\}$) parity symmetry decouple from the impurities at low temperatures. For a parity symmetric model this decoupling also enforces a local parity conservation for the impurity spins.
In this work, we study the non-equilibrium dynamics of the TIKM employing the time-dependent numerical renormalization-group (TD-NRG)[8] which was developed to treat the real-time dynamics of quantum-impurity systems after a sudden quench. While doing so, we focus our examination on the real-time dynamics of the impurity spin-spin correlation function $\langle \vec{S}_1 \vec{S}_2 \rangle(R, t)$ for different distances after quenches in the coupling J or magnetic fields H applied to the impurity spins. Starting from initially decoupled impurity spins, the build up of this spatial correlation function is investigated and it is shown that spatial and temporal correlations propagate along a light-cone determined by the Fermi-velocity v_{F}. We demonstrate that for the specific distances $k_{\mathrm{F}}R = n\pi$ the local parity conservation at low energy scales prevents the impurity spin-spin correlation function from decaying to its equilibrium value for long times.

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

R.C.C. Leon [1], J.C. Lemyre [2,3], J.C.C. Hwang [1], M. Pioro-Ladrire [2,3,4], F.E. Hudson [1], A. Morello [1] and A.S. Dzurak [1]

[1] *Centre for Quantum Computation and Communication Technology, School of Electrical Engineering, UNSW, Sydney 2052, Australia*
[2] *Département de Physique, Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada*
[3] *Institut quantique, Université de Sherbrooke, Sherbrooke, Québec, J1K 2R1, Canada*
[4] *Quantum Information Science Program, Canadian Institute for Advanced Research, Toronto, ON, M5G 1Z8, Canada*

Recently, both one- and two-qubit logic gates with high control fidelity [1,2] have been demonstrated using silicon metal-oxide-semiconductor (Si-MOS) quantum dots formed in silicon-28 enriched substrates. These qubit manipulations utilise electron spin resonance (ESR), a technique that can control spin qubits using an oscillating magnetic field generated via a microwave strip-line.

The electrical control of single spin qubits [3,4] based on semiconductor quantum dots provides an alternative approach for scalable quantum computing, due to the fact that electric fields can be generated easily and can be more spatially focused than magnetic fields. By incorporating a permanent magnet, the qubits can be driven using an oscillating electric field, via electric dipole spin resonance (EDSR). Here we present a number of design considerations and simulations on a microwave coplanar waveguide for Si-MOS quantum dot qubit devices. At 1mW input, a Rabi frequency of 10 MHz is generated by EDSR with minimal noise. The Rabi frequency can be further maximised by changing the quantum device architecture and applying microwave signals on various metallic control electrodes.

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Spin filling of holes in a silicon quantum dot

Scott D. Liles[1], Ruoyu Li[1,3], C. Henry Yang[2], Fay E. Hudson[2], Menno E. Veldhorst[3], Andrew S. Dzurak[2], Alexander R. Hamilton[1]

[1] *School of Physics, University of New South Wales, Sydney NSW 2052, Australia*
[2] *Centre for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney NSW 2052, Australia*
[3] *QuTech and Kavli Institute of Nanoscience, TU Delft, 2600 GA Delft, The Netherlands*

Heavy hole spins in quantum dots are highly suitable candidates for spin qubits. This is because holes have reduced hyperfine coupling to nuclear spins in the host crystal [1] allowing long spin coherence times [2], while the enhanced spin-orbit coupling of holes [3] enables fast all-electric spin manipulation [4]. Due to these promising spin properties, holes have recently attracted significant attention from the spin-qubit community, resulting in the publication of several exciting results [5,6]. However, the spin physics of quantum confined holes is non-trivial, and is not as well understood as for electron systems [7]. A key advance would be the determination of the energy level structure of the last few holes in surface gated silicon MOS based quantum dots. This knowledge is vital, since the orbital structure affects the spin properties and spin dynamics, which underpins spin-orbit qubits.

In this work we describe a planar silicon MOS based single hole quantum dot capable of operating down to the last hole. We characterise the spin shell filling sequence for the first eight holes using magnetospectroscopy, which is consistent with the Fock-Darwin states of a circular two-dimensional quantum dot. At low magnetic field we observe spin filling, which obeys Hunds first rule, while at high magnetic field we observe the singlet triplet transition for the two hole ground state. Finally, we investigate the orbital spectrum using pulse bias spectroscopy and find that hole-hole interaction energy is 90% of the orbital energy, which causes the two-hole system to be on the verge of having a ferromagnetic ground state.

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

Mateusz Madzik [1], Arne Laucht [1], Vincent Mourik [1], Fay Hudson [1], Kohei Itoh [2], David Jamieson [3], Andrew Dzurak [1], Andrea Morello [1]

[1] Centre for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, UNSW Australia, Sydney, New South Wales 2052, Australia
[2] School of Fundamental Science and Technology, Keio University, 3-14-1 Hiyoshi, Kanagawa 223-8522, Japan
[3] Centre for Quantum Computation and Communication Technology, School of Physics, University of Melbourne, Melbourne, Victoria 3010, Australia

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

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Exploring quantum chaos within a single 123-Sb donor in silicon

V. Mourik [1], S. Asaad [1], H. Firgau [1], J. C. McCallum [2], G. J. Milburn [3], C. Holmes [3], J.J. Pla [1], A. Morello [1]

[1] Centre for Quantum Computation and Communication Technologies, School of Electrical Engineering and Telecommunications, UNSW Sydney, Sydney, New South Wales 2052, Australia
[2] Centre for Quantum Computation and Communication Technology, School of Physics, University of Melbourne, Melbourne VIC 3010, Australia
[3] School of Mathematics and Physics, The University of Queensland, St Lucia, Brisbane 4072, Australia

The 123-Sb atom is a group-V element with a nuclear spin quantum number of 7/2, resulting in an 8-dimensional Hilbert space. This atom can be implanted in a silicon Metal-Oxide-Semiconductor structure, and its quantum state can be controlled using the same infrastructure that has been proven to yield high-fidelity control [1] and single-shot readout [2] on the 31-P donor. The key difference in 123-Sb is that the nucleus possesses a quadrupole moment, which can introduce a quadratic term in the spin Hamiltonian when the atom is placed in a strained silicon crystal. By further adding a strong periodic drive, this results in a single-atom quantum system that accurately maps a classically chaotic one: the driven nonlinear top [3]. Therefore, we can engineer a highly controllable, individual quantum system that enables an experimental study of the emergence of chaos and the quantum-to-classical crossover [3]. We show numerical results on the operational regimes in which the 123-Sb donor behaves as a quantum chaotic driven top.

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

M. Usman,[1] J. Bocquel,[2] J. Salfi,[2] B. Voisin,[2] A. Tankasala,[3] R. Rahman,[3] M.Y. Simmons,[2] S. Rogge,[2] L.C.L. Hollenberg[1]

[1]Center for Quantum Computation and Communication Technology, School of Physics, The University of Melbourne, Parkville VIC Australia
[2]Center for Quantum Computation and Communication Technology, School of Physics, The University of New South Wales, Sydney, NSW Australia
[3]Electrical and Computer Engineering Department, Purdue University, West Lafayette Indiana USA

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

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A controlled-phase gate between spin qubits of different kinds

A. Noiri[1], T. Nakajima[1], J. Yoneda[1], M. R. Delbecq[1], P. Stano[1], T. Otsuka[1], K. Takeda[1], S. Amaha[1], G. Allison[1], K. Kawasaki[2], A. Ludwig[3], A. D. Wieck[3], D. Loss[1,4], and S. Tarucha[1,2]

[1] *RIKEN, 2-1 Hirosawa, Wako-shi, Saitama, Japan*
[2] *University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan*
[3] *Ruhr-Universität Bochum, D-44780 Bochum, Germany*
[4] *University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*

Electron spins in semiconductor quantum dots offer an attractive platform for quantum computing. So far, several kinds of spin qubits having their own advantages have been developed using different spin states [1,2]. In particular, high-fidelity qubit control has been demonstrated in single-spin qubits [3,4] while fast and high-fidelity initialization and readout have been realized in singlet-triplet (ST) qubits encoded in two-spin states [5]. However, the lack of an interface between different kinds of spin qubits impedes the integration of these advantages.

In this presentation, we realize a hybrid system of a single-spin qubit and a ST qubit in a GaAs-based triple quantum dot (TQD) with a micro-magnet (see Figure) and demonstrate a controlled-phase (CPHASE) gate between the two qubits. The single-spin qubit is defined on the left dot while the other two dots are operated as the ST qubit. The exchange interaction J between the two qubits shifts the qubit frequency of the target qubit depending on the state of the control qubit [6]. The rapid control of J enables us to implement CPHASE gate in 5 ns. These results are important step for realizing combined systems made out of spin qubits of different kinds, which provide a promising route to efficient spin-based quantum computing.

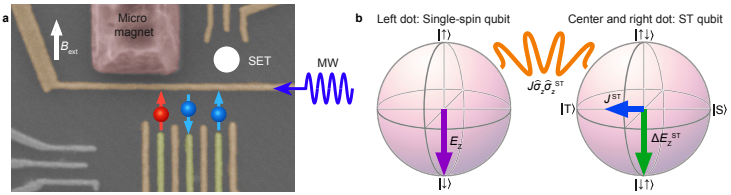


Figure: (a) The scanning electron microscope image of a TQD device identical to the one studied. (b) The hybrid system of a single-spin qubit and a ST qubit.

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

P. Pakkiam, M.G. House, M. Koch, and M.Y. Simmons

CQC2T, UNSW, Melbourne

We present the design, fabrication, and characterization of a device for hosting capacitively-coupled singlet-triplet donor qubits in silicon fabricated by scanning tunneling microscope lithography. The layout is geometrically compact and robust as each pair of dots can be independently controlled via one gate and one reservoir that also measures the singlet-triplet state of the qubit by dispersive readout [1]. We verify the STM-patterned positions of each dot by comparing measured values of the relative couplings between each dot and gate to those predicted by a finite-element electrostatic model. We measure singlet-triplet states with dispersive readout and observe a S_0 to T_- decay time of 2 ms at zero detuning and 3.3 T applied magnetic field. The design represents a scalable device building block in one dimension with minimal gate leads (two per qubit) based on atomic precision lithography and dispersive readout.

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A fibre-cavity platform

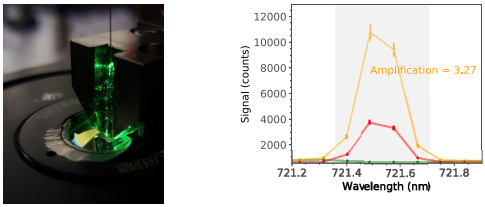
Sarath Raman Nair[1,2], Lachlan J. Rogers[1,2], Andrew Wood[1,2], Xavier Vidal[1], Jan Jeske[3], Andrew D. Greentree[3,4] and Thomas Volz[1,2]

[1] *Department of Physics and Astronomy, Macquarie University, NSW 2109, Australia*
[2] *ARC Centre of Excellence for Engineered Quantum Systems, Macquarie University, NSW 2109, Australia*
[3] *Chemical and Quantum Physics, School of Sciences, RMIT University, Melbourne 3001, Australia*
[4] *ARC Centre of Excellence for Nanoscale BioPhotonics, School of Sciences, RMIT University, Melbourne, VIC 3001, Australia*

Light confined in the very small volume of a fibre based optical cavity provides enhanced light-matter interaction with quantum emitters placed in it [1]. We report progress in the development of a fibre-based stable Fabry-Perot cavity for studying strong light matter interactions, particularly spin-photon interface with colour centres in diamond. This tunable and open micro-cavity forms between the tip of an optical fibre and a half-inch mirror. The fibre tip is Laser machined to form a curved surface and both the fibre tip and the mirror are coated with the same Distributed Bragg Reflector (DBR). We try to stabilize this cavity with both passive and active stabilization.

Spin-Photon interface with colour centres in diamond in the fibre-based cavity promises the building block of quantum networks. We envisage to install the stabilized fibre-based cavity at cryogenic temperature and to show the coupling of SiV/GeV colour centre in the diamond crystal to the cavity mode. The enhanced spin property of SiV/GeV at low temperature and the high finesse of the cavity expect to provide high cooperativity.

In the current development phase of this fibre-based cavity at room-temperature, we employ it to study NV lasing for Laser Threshold Magnetometry [2]. We report the preliminary observation of strong amplification of a ∼720nm carrier due to the stimulated emission of NV centres in this cavity.



(a) (b)

Figure 1: (a) Fibre-mirror Fabry-Perot cavity with diamond sample containing NV centres (b) Amplification of a factor ∼3.27 of NV centre emission inside the cavity. The green represents green(∼532nm) pump alone, the red represents red(∼720nm) alone and the orange represents both green and red.

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Single Ion Detectors for Deterministic Top-Down Fabrication of Donor-Qubit-Based Silicon Quantum Electronics

S. G. Robson[1,3], A.M. Jakob[1,3], V. Mourik[2,3], V. Schmitt[2,3], B. C. Johnson[1,3], F. Hudson[2,3], C. Lew[1], A. Morello[2,3], A. Dzurak[2,3] and D.N. Jamieson[1,3†]

[1]*School of Physics, University of Melbourne, Melbourne, VIC 3010 Australia*
[2]*Electrical Engineering and Telecommunications, UNSW, Sydney, NSW 2052 Australia*
[3]*ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC²T)*
† d.jamieson@unimelb.edu.au

Abstract: We present ongoing work on the development of Silicon PIN detectors for scalable deterministic Donor-Qubit placement via single ion implantation.

The remarkable success in addressing and manipulating single P-donor spins ("qubits") in ^{28}Si [1,2] represents a milestone for the realization 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 semiconductor industry's standard doping tool – very promising for scalable silicon quantum device fabrication. In order to allow a fully deterministic implantation of donor qubits into pre-defined quantum architecture sites, we employ the Ion Beam Induced Charge (IBIC) technique, which detects a single ion via free e-h-pairs induced upon the ion stopping in Silicon. A PIN diode architecture is therefore integrated into the silicon substrate to separate the induced free charge carriers and probe corresponding transients with surface electrodes [4].
However, the reliable detection of small charge signals generated by low-energetic ions raises tremendous demands on the single ion detector's noise performance.

In this systematic study, we seek to further develop our single ion detector fabrication procedure. Prototype devices are electrically characterised using I-V analysis and admittance spectroscopy and are furthermore subjected to IBIC tests using sub-15 keV P-ions.
The detectors are evaluated in terms of low-noise performance at room temperature – an essential pre-requisite for a scalable top-down fabrication of donor-qubits with highest fidelity and placement precision.

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Bayesian inference of switching rates for blinking silicon-vacancy emitters in nanodiamonds

Lachlan J. Rogers[1], Jemy Geordy[1], Thomas Volz[1] and Alexei Gilchrist[1]

[1] *QMAPP Group and EQuS, Department of Physics and Astronomy, Macquarie University, Sydney, Australia*

Single quantum emitters of light are valuable resources for engineered quantum systems. They can function as robust single-photon generators, allow optical control of single spins, provide readout capabilities for atomic-scale sensors, and provide interfaces between stationary and flying qubits. Environmental factors can lead to single emitters exhibiting "blinking", whereby the fluorescence level switches between "on" and "off" states. The silicon-vacancy centre in high-quality bulk diamond shows photostability and excellent optical properties, motivating a growing research interest [1]. However, in nanodiamonds the silicon-vacancy centre exhibits undesirable blinking [2].

Detailed characterisation of the blinking behaviour is a powerful way to gain understanding about the underlying physical mechanisms, and determining the switching rates is typically desired. Bright emitters lead to high-contrast blinking, and simple thresholds can be used to extract the "on" and "off" intervals from a time-series of photon counts (and hence determine the switching rates). However, such approaches become difficult for emitters fluorescing at low levels. We have developed a Bayesian approach capable of inferring switching rates directly from the time-series [3-4]. This is able to produce useful results even for weak blinking fluorescence traces with considerable background photon counts. Moreover, the Bayesian inference also yields a robust picture of the parameter uncertainties, providing a benefit also for bright emitters.

This Bayesian technique is demonstrated for the blinking silicon-vacancy fluorescence data [2], and shown to be superior to previous analysis techniques.

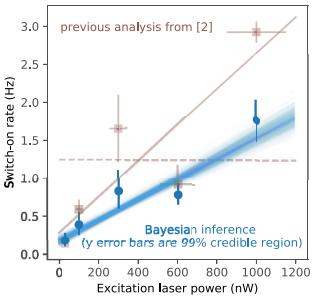


Figure 1: Comparison of the original data analysis from [2] compared with the Bayesian re-analysis of the same raw data. The Bayesian approach yields better conclusions and more meaningful uncertainty estimates.

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Germanium-vacancy centres and the quest for "perfect" diamond qubits

Lachlan J. Rogers[1,2], Petr Siyushev[2], Mathias H. Metsch[2] and Fedor Jelezko[2]

[1] *QMAPP Group and EQuS, Department of Physics and Astronomy, Macquarie University, Sydney, Australia*
[2] *Institute for Quantum Optics, Ulm University, D-89081 Germany*

A solid-state system combining a stable spin degree of freedom with an efficient optical interface is highly desirable as an element for integrated quantum optical and quantum information systems. A few colour centres in diamond are attractive architectures, but the currently available candidates are not perfect. The nitrogen vacancy (NV) centre is famous as an optically addressable electron- and nuclear-spin qubit, but its fluorescence spectrum is not ideal with a strong phonon sideband and, typically, spectral diffusion of the zero-phonon line (ZPL). More recently the related silicon vacancy (SiV) centre has been shown to have exceptional spectral properties, but it has poor quantum yield and a fundamentally limited spin coherence time of only 40 ns.

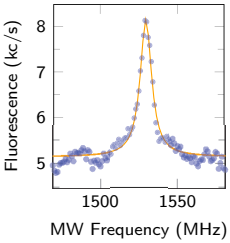


Figure 1: Microwave-optical double-resonance places the GeV centre in a small class of colour centres offering microwave control of individual spins.

Our understanding of How Colour Centres Work has increased in recent years. This information has started to enable a "smart search" for novel diamond qubits, and hopefully points towards a future where colour centres can be "engineered" for specific applications. The recently-discovered germanium vacancy (GeV) centre [1] is presented as an example of this process.

Detailed optical spectroscopy shows the GeV centre to be bright and spectrally stable like the SiV centre [2], but with a higher quantum yield close to unity. Its electronic spin degree of freedom is explored using an external magnetic field to lift the spin degeneracy. Optical and microwave control of GeV spin is demonstrated [2], placing the GeV centre in a small class of colour centres capable of optically-detected magnetic resonance. Coherent spin control combined with the possibility of GeV centres in nanophotonic devices [3] make it a promising platform for quantum optics and quantum information science applications.

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Synchronized high-fidelity quantum gates in Si/SiGe double quantum dots

M. Russ[1], J. M. Taylor[2], D. M. Zajac[3], A. J. Sigillito[3], F. Borjans[3], J. R. Petta[3], and G. Burkard[1]

[1]*Department of Physics, University of Konstanz, D-78457 Konstanz, Germany*
[2]*Joint Quantum Institute and Joint Center for Quantum Information and Computer Science, NIST and University of Maryland, College Park, MD 20742, USA*
[3]*Department of Physics, Princeton University, Princeton, NJ 08544, USA*

Motivated by recent experiments [1,2], we theoretically describe a high-fidelity controlled-NOT (CNOT) gate using the exchange interaction between the spins in neighboring quantum dots subject to a magnetic field gradient from a micromagnet. We use a combination of analytic calculations and numerical simulations to provide the optimal pulse sequences and parameter settings for the gate operation. We present a synchronization method which avoids detrimental spin flips when the state of the control qubit is $|0\rangle$, and provide details about phase mismatches accumulated during the two-qubit gate. Synchronizing the resonant and off-resonant transitions (see Figure 1) and compensating these phase mismatches by phase control the overall gate fidelity can be increased significantly. Numerical simulations demonstrate a high tolerance towards charge noise coupled to the two spins due to a partial intrinsic refocussing mechanism.

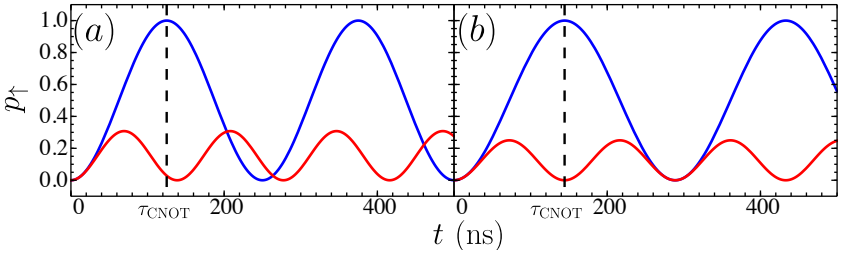


Figure 1: Schematic plot of the resonant (blue) and off-resonant (red) transition probabilities with (a) desynchronized and (b) synchronized Rabi frequencies Ω and $\widetilde{\Omega}$. A CNOT gate is provided at time t_{CNOT} where the resonant driving exactly flips the spin. (a) Using an arbitrary Rabi frequency Ω the off-resonant driving also yields a finite population of the flipped spin for control qubit in $|0\rangle$, therefore reducing the fidelity of the two-qubit operation. (b) However, if we synchronize the resonant Rabi frequency Ω and the off-resonant Rabi frequency $\widetilde{\Omega}$ we can completely avoid any undesired spin-flip.

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Donor spin qubit with robust long-distance coupling

V. Schmitt,[1] G. Tosi,[1] F. Mohiyaddin,[1] S. Tenberg,[1] F. Hudson,[1] R. Rahman,[2] G. Klimeck,[2] A. Dzurak,[1] and A. Morello [1]

[1] *Centre for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, UNSW Sydney, New South Wales 2052, Australia*
[2] *Network for Computational Nanotechnology, Purdue University, West Lafayette, Indiana 47907, United States*

Single-donor spin qubits in silicon have been shown to be among the most coherent in the solid state [1]. However, scaling up beyond one donor to build a scalable quantum computer architecture remains a great challenge. Here we propose to use the flip-flop states of electron and nucleus of an implanted phosphorus atom as a qubit [2]. We induce an electric dipole by biasing the electron wavefunction between the donor and an interface state. This dipole couples the flip-flop states to a resonant oscillating electric field, which can drive fast transitions between the qubit states. The electric dipole-dipole interaction between two donors allows robust two-qubit logic gates at long-distance (200 nm). We present simulated single- and two-qubit gate fidelities exceeding 99% in the presence of realistic values of charge noise, and show that the ability to electrically drive and couple the qubits does not result in a deterioration of their coherence properties.

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Spin-exchange via a multielectron quantum mediator

Filip K. Malinowski,[1,*] Frederico Martins,[1,*] Thomas B. Smith,[2,†] Stephen D. Bartlett,[2] Andrew C. Doherty,[2] Peter D. Nissen,[1] Saeed Fallahi,[3] Geoffrey C. Gardner,[3,4] Michael J. Manfra,[3,4] Charles M. Marcus,[1] and Ferdinand Kuemmeth[1]

[1] *Center for Quantum Devices and Station Q Copenhagen, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[2] *Centre for Engineered Quantum Systems, The University of Sydney, Sydney, Australia*
[3] *Department of Physics and Astronomy, Birck Nanotechnology Center, and Station Q Purdue, Purdue University, West Lafayette, Indiana, USA*
[4] *School of Materials Engineering, Purdue University, West Lafayette, Indiana, USA*
[*] These authors contributed equally to this work.
[†] This author is presenting the poster.

The exchange interaction, in principle, provides a fast and tunable means of coupling spin qubits. However, the interaction falls off exponentially with distance, and bringing qubits closer together to increase the strength of exchange runs the risk of qubit cross-talk. A novel solution to this problem has been proposed [1, 2], whereby an effective exchange interaction between two qubits is mediated by a system of electronic spins. Such a scheme has been examined for mediators operating in the single-electron regime [3, 4].

We demonstrate that a multielectron quantum dot can act as such a quantum mediator, giving rise to exchange interaction that is on the order of gigahertz. Furthermore, we demonstrate, through the use of a phenomenological Hubbard model, that Hund's rule effects within the multielectron dot result in an extremum in the exchange profile where the predominant exchange effect moves from being singlet-favouring to triplet-favouring. Exchange interactions at such an extremum are decoupled from charge noise at first order. We argue that multielectron dots offer a promising avenue for strong, long-distance, charge-noise resistant coupling between spin qubits.

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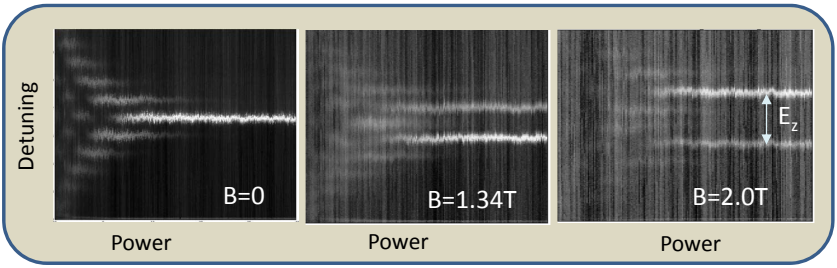
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Single and two hole spin qubits formed in a gated GaAs/AlGaAs double quantum dot

Sergei Studenikin[1], Alex Bogan[1], Louis Gaudreau[1], Marek Korkusinski[1], Piotr Zawadzki[1], Andy Sachrajda[1], Lisa Tracy[2], John Reno[3], and Terry Hargett[3]

[1] *Emerging Technology Division, National Research Council, Ottawa*
[2] *Sandia National Laboratories, Albuquerque, New Mexico, USA*
[3] *Center for Integrated Nanotechnologies, Albuquerque, New Mexico, USA*

Single holes localised in electrostatically tuneable quantum dot devices are explored as candidates for spin qubits. The motivation for developing the hole platform is based on a long list of potentially attractive features such as a predicted reduced hyperfine interaction in an optically active direct band-gap material, a tuneable effective g-factor with field direction compatible with hybridization schemes between photons and spins, and a large spin-orbit interaction for fast gate operations [1-3]. Here we study single hole and two-hole hybrid spin-charge qubits in the presence of a strong spin-orbit interaction. For the single hole regime we present results on the Landau-Zener-Stuckelberg (LZS) interferometry involving spin conserving and spin-flip processes. LZS patterns evolve with microwave frequency from discreet (often referred as PAT) at high frequencies to continuous LZS fringes at low frequencies. The figure below provides examples of LZS measurements at different magnetic fields. Two separate sets of LZS fringes are evident offset by the Zeeman energy $E_Z = g\mu_B B$. The magnetic field dependence of the single hole spin relaxation time is measured, taking advantage of the latching technique we originally developed for electron spin qubits [4-5] and which is rapidly being adopted as a standard technique for high fidelity measurements. Additionally, we extend LZS measurements to the two-hole case near the (02)-(11) transition and present results from LZS interferometry of the singlet/triplet spin qubit states.



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Tunable Electromagnetic Environment of a Superconducting Resonator Realized Through a Quantum-Circuit Refrigerator

Kuan Y. Tan[1,2], Shumpei Masuda[2], Matti Partanen[2], Russell E. Lake[2], Joonas Govenius[2], Matti Silveri[3], Hermann Grabert[4], and Mikko Möttönen[2]

[1] *Centre for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, New South Wales 2052, Australia*

[2] *QCD Labs, COMP Centre of Excellence, Department of Applied Physics, Aalto University, P.O. Box 13500, FIN-00076 Aalto, Finland*

[3] *Research Unit of Nano and Molecular Systems, University of Oulu, P.O. Box 3000, FI-90014 Oulu, Finland*

[4] *Department of Physics, University of Freiburg, D-79104 Freiburg, Germany*

Quantum electric circuits enable precise control and manipulation of quantum degrees of freedom not available in the classical regime. In particular, superconducting circuits provide a scalable platform for quantum computing and simulations. We have recently demonstrated a quantum-circuit refrigerator (QCR) [1,2] in which we directly cool a superconducting resonator mode, and subsequently show that the QCR can be utilized as a cryogenic photon source [3].

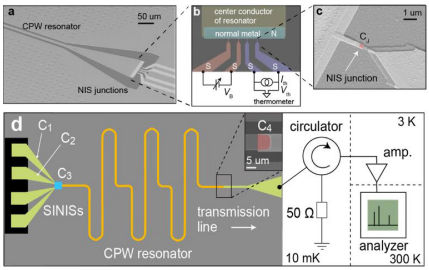


Figure 1: Sample structure. **a-c** Micrographs of the sample. **d** Schematic diagram of the cryogenic photon source and the measurement scheme.

Here, we present our latest study (Fig. 1 a–d) [4] of in-situ control of the strength of dissipation in a superconducting resonator using a QCR, revealed through a microwave reflection experiment. Coherent photons injected through a coplanar waveguide transmission line coupled to the resonator probe the remarkable controllability of the electromagnetic properties of the superconducting circuit, all through simple tuning of the dc operation voltage of the QCR. Namely, we show experimental data of the effective internal quality factor of the superconducting resonator as a function of the QCR bias voltage.

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Angular dependence of electron g-factor and Stark shift in a silicon quantum dot

Tuomo Tanttu[1], Bas Hensen[1], Kok Wai Chan[1], Henry Yang[1], Michael Fogarty[1], Fay Hudson[1], Kohei Itoh[2], Andrea Morello[1], and Andrew S. Dzurak[1]

[1] *Centre for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, New South Wales 2052, Australia*

[2] *School of Fundamental Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan*

Spin qubits based on silicon quantum dots are a promising platform for scalable quantum computing thanks to their small size and long coherence times [1,2]. However, variation of g-factor from dot to dot sets an addressability challenge in a long array of dots and two dimensional structures [3]. Both g-factor and Stark shift of electron spin qubits are determined by the spin-orbit coupling. The strength of the spin-orbit coupling is defined by Rashba and Dresselhaus terms in the Hamiltonian [4,5]. The Rashba term — typically the dominant one — is dependent on the external magnetic field orientation with respect to the crystal lattice. Experimentally it has already been shown that the difference of g-factors between two neighboring dots vanishes at certain magnetic field angles [4]. In addition, the decoherence of the qubits is caused mainly by the electric noise of the environment coupling to the dot via its Stark shift. Therefore by minimizing the Stark shift we should be able to increase the coherence time of our qubits [6].

In this work, we study experimentally the angular dependency of the g-factor and Stark shift of an electron in a silicon-MOS quantum dot. We find that both g-factor and Stark shift follow sinusoidal behavior as a function of external magnetic field angle when the field is rotated in plane with the device. The extreme values are reached at [110] and [1$\bar{1}$0] Miller index orientations. The minimal Stark shift is found when the magnetic field is aligned with [100] crystal orientation. These results are in good agreement with theory [5,6].

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A compact cryogen-free platform operating at 1 K or 50 mK

G. Teleberg[1]

[1] *Oxford Instruments NanoScience, Tubney Woods, Abingdon, OX13 5QX, United Kingdom*

We report the design and performance characteristics of a compact cryogen-free platform. The system is based around a continuous 1 K pot which operates using a small (10 m^3 h^{-1}) room temperature circulation pump. The pot cools an experimental plate to $\approx$ 1.2 K, and has a cooling capacity of 100 mW at a temperature $\approx$ 1.9 K. Cooling the pot from room temperature to $<$ 2 K takes around 12 hours.

The temperature range of the platform can be lowered to $<$ 50 mK with the addition of a small dilution refrigerator, using the 1 K pot as a pre-cooling stage for the circulating ^{3}He. The dilution stage has a typical (continuous) cooling capacity of 30 μW at 100 mK (300 μW at 250 mK) and is designed to operate with just 3 litres of (NTP) ^{3}He.

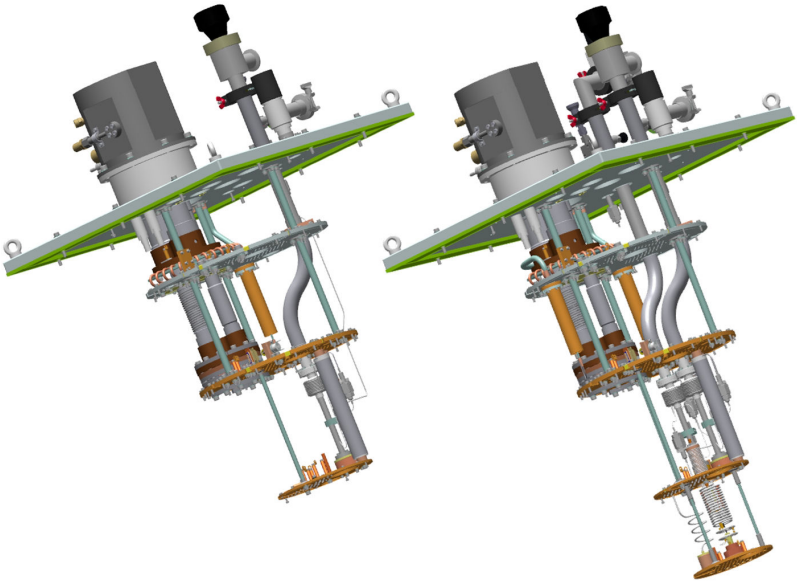


Figure 1: Models of both the 1 K platform (left) and the 50 mK platform (right) showing how the system can be configured.

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

Chih-Hwan Henry Yang[1], Kok Wai Chan[1], Wister Huang[1], Jason C. C. Hwang[1], Bas Hensen[1], Arne Laucht[1], Robin Harper[2], Fay E. Hudson[1], Steve Flammia[2], Stephen Bartlett[2], Kohei M. Itoh[3], Andrea Morello[1], Andrew 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]*Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, NSW 2006, Australia*
[3]*School of Fundamental Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan*

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

We thank Robin Blume-Kohout and Kenneth Rudinger for making available their gate set tomography code and for helpful discussions. We acknowledge support from the US Army Research Office (W911NF-13-1-0024 and W911NF-17-1-0198), the Australian Research Council (CE11E0001017), and the NSW Node of the Australian National Fabrication Facility. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Office or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein. B.H. acknowledges support from the Netherlands Organization for Scientific Research (NWO) through a Rubicon Grant. K.M.I. acknowledges support from a Grant-in-Aid for Scientific Research by MEXT, NanoQuine, FIRST, and the JSPS Core-to-Core Program.

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An isotopically-enriched silicon spin qubit with >99.9% fidelity and charge-noise-limited coherence

J. Yoneda[1], K. Takeda[1], T. Otsuka[1], T. Nakajima[1], M. R. Delbecq[1], G. Allison[1], T. Honda[2], T. Kodera[2], S. Oda[2], Y. Hoshi[3], N. Usami[4], K. M. Itoh[5] and S. Tarucha[1]

[1] *RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan*
[2] *Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, Japan*
[3] *University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, Japan*
[4] *Nagoya University, Furocho, Chikusa-ku, Nagoya, Japan*
[5] *Keio University, 3-14-1 Hiyoshi, Yokohama, Japan*

Qubit control fidelity is closely related to the coherence time (T_2^*) and the manipulation time (T_π). For quantum-dot spin qubits, T_2^* has been prolonged by several orders of magnitude in the emergent isotopically-purified materials [1] compared to those in early developed GaAs devices. T_π, on the other hand, can be enhanced by introducing sizable spin-electric coupling [2,3]. However, one must note the coherence-controllability trade-off, as T_2^* can be degraded due to charge noise in the presence of spin-electric coupling.

In this work[4], we establish how to strike a balance between controllability (short T_π) and coherence (long T_2^*) at an isotopically-enhanced level. This is done by carefully introducing "artificial" spin-electric coupling fields with local magnets to an electron spin in a ^{28}Si/SiGe quantum dot. In the device where $T_\pi < 20$ ns is achievable, we measure $T_2^* = 20$ μs. This allows us to demonstrate the single-qubit control fidelity reaching 99.93%, measured through randomized benchmarking.

To understand phase coherence of our high-fidelity qubit, we utilize dynamical decoupling and Ramsey sequences and reveal the $1/f$ dephasing noise over seven decades of frequency (Fig. b). The result indicates that the free-evolution phase coherence of an electron spin is limited purely by charge noise, rather than conventional magnetic noise.

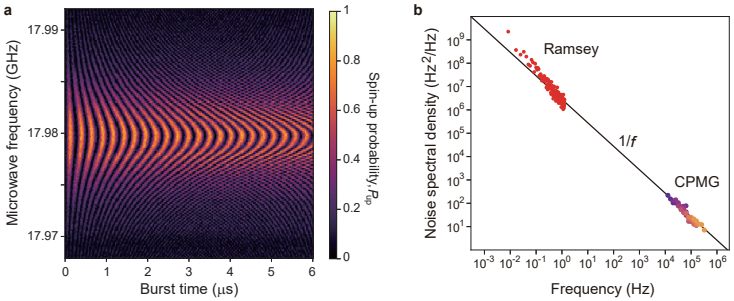


Figure (**a**) Spin chevron. (**b**) Dephasing noise spectrum.

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List of Attendees

Mr	William (CQC2T, UNSW Sydney)	Andrew	w.andrew@student.unsw.edu.au
Prof	David (University of Chicago)	Awschalom	awsch@uchicago.edu
Prof	Stephen (The University of Sydney)	Bartlett	stephen.bartlett@sydney.edu.au
Mr	Mihir (Harvard University)	Bhaskar	mbhaskar@g.harvard.edu
Dr	Nathaniel (Laboratory for Physical Science)	Bishop	nbishop@lps.umd.edu
Dr	Brad (IARPA)	Blakestad	brad.blakestad@iarpa.gov
Prof	Hendrik (RWTH Aachen University and Forschungszentrum Jülich)	Bluhm	bluhm@physik.rwth-aachen.de
Prof	Michael (University of Technology Sydney)	Bremner	michael.bremner@uts.edu.au
Prof	Guido (University of Konstanz)	Burkard	Guido.Burkard@uni-konstanz.de
Dr	Robert (Laboratory for Physical Sciences)	Butera	rbutera@lps.umd.edu
Mr	Julien (Institut quantique)	Camirand Lemyre	julien.camirand.lemyre@usherbrooke.ca
Dr	Malcolm (Sandia National Laboratories)	Carroll	mscarro@sandia.gov
Ms	Georgina (CQC2T)	Carson	georgina.carson@unsw.edu.au
Dr	Kok Wai (CQC2T, UNSW Sydney)	Chan	kokwai@unsw.edu.au
Dr	Yousun (CQC2T)	Chung	yousun.chung@unsw.edu.au
Prof	Susan (University of Wisconsin-Madison)	Coppersmith	snc@physics.wisc.edu
Ms	Emma (CQC2T)	Cottenham	e.cottenham@student.unsw.edu.au
Ms	Xanthe (The University of Sydney)	Croot	xcro1784@uni.sydney.edu.au
Mr	Matthew (University of New Mexico)	Curry	mjcurry@unm.edu
Dr	Michael (Oxford Instruments NanoScience)	Cuthbert	michael.cuthbert@oxinst.com

Mr	Christian (CQC2T)	Dangel	c.dangel@student.unsw.edu.au
Dr	Silvano (CEA)	De Franceschi	silvano.defranceschi@cea.fr
Prof	Andrew (The University of Sydney)	Doherty	fran.vega@sydney.edu.au
Mr	Matthew (CQC2T)	Donnelly	m.donnelly@unsw.edu.au
Prof	Andrew (School of EE&T, The University of NSW)	Dzurak	a.dzurak@unsw.edu.au
Prof	Mark (University of Wisconsin-Madison)	Eriksson	maeriksson@wisc.edu
Prof	Jonathan (Walter Schottky Institut, TU-Munich)	Finley	finley@wsi.tum.de
Mr	Michael (CQC2T)	Fogarty	m.fogarty@unsw.edu.au
Mr	Will (CQC2T, UNSW Sydney)	Gilbert	will.gilbert89@gmail.com
Dr	Marissa (Google)	Giustina	mgiustina@google.com
Mr	Samuel (CQC2T)	Gorman	samuel.gorman@unsw.edu.au
Dr	Arne (The University of Sydney)	Grimsmo	arne.grimsmo@sydney.edu.au
Prof	Alexander (UNSW, Sydney)	Hamilton	alex.hamilton@unsw.edu.au
Mr	Robin (The University of Sydney)	Harper	quantum.administration@sydney.edu.au
Dr	Yu (CQC2T)	He	yu.he@unsw.edu.au
Dr	Bas (CQC2T, UNSW Sydney)	Hensen	b.hensen@unsw.edu.au
Dr	Charles (University of Melbourne)	Hill	cdhill@unimelb.edu.au
Mr	Mark (QxBranch)	Hodson	mark.hodson@qxbranch.com
Mr	Mark (CQC2T)	Hogg	m.hogg@unsw.edu.au
Prof	Lloyd (The University of Melbourne)	Hollenberg	cqc2t-Admin@unimelb.edu.au
Ms	Danielle (University of Melbourne)	Holmes	dholmes1@student.unimelb.edu.au

Dr	Matthew	House	matthew.house@unsw.edu.au
	(CQC2T)		
Mr	Wei	Huang	wister.huang@student.unsw.edu.au
	(CQC2T, UNSW Sydney)		
Dr	Fay	Hudson	f.hudson@unsw.edu.au
	(UNSW Sydney)		
Dr	Jason	Hwang	jason.hwang@unsw.edu.au
	(CQC2T, UNSW Sydney)		
Dr	Alexander Malwin	Jakob	alexander.jakob@unimelb.edu.au
	(University of Melbourne)		
Ms	Marie Claire	Jarratt	marieclaire.jarratt@sydney.edu.au
	(The University of Sydney)		
Mr	Benjamin	Joecker	b.joecker@unsw.edu.au
	(CQC2T, UNSW Sydney)		
Mr	Mark	Johnson	mark.johnson.ai@gmail.com
	(CQC2T, UNSW Sydney)		
Mr	Noah	Johnson	ndjohnson4@wisc.edu
	(CQC2T, UNSW Sydney)		
Mr	Michael	Jones	m.t.jones@student.unsw.edu.au
	(CQC2T)		
Mr	Daniel	Keith	daniel.keith@unsw.edu.au
	(CQC2T)		
Dr	Joris	Keizer	j.g.keizer@unsw.edu.au
	(CQC2T)		
Mr	Mizuki	Kobayashi	kobayashi.m.bb@m.titech.ac.jp
	(Tokyo Institute of Technology)		
Dr	Tetsuo	Kodera	kodera.t.ac@m.titech.ac.jp
	(Tokyo Institute of Technology)		
Mr	Ludwik	Kranz	l.kranz@unsw.edu.au
	(CQC2T)		
Mr	Felix	Krauth	f.krauth@student.unsw.edu.au
	(CQC2T)		
Msc	Jan	Krzywda	jankrzywda9@gmail.com
	(Institute of Physics, Polish Academy of Sciences)		
Dr	Ferdinand	Kuemmeth	kuemmeth@nbi.dk
	(University of Copenhagen)		
MSc	Damian	Kwiatkowski	dkw9113@gmail.com
	(Institute of Physics, Polish Academy of Sciences)		
Dr	Thaddeus	Ladd	tdladd@gmail.com
	(HRL Laboratories, LLC)		
Dr	Arne	Laucht	a.laucht@unsw.edu.au
	(CQC2T, UNSW Sydney)		

Dr	Benedikt (Kyoto University)	Lechtenberg	lechtenberg.benedikt.54m@st.kyoto-u.ac.jp
Mr	Ross (CQC2T, UNSW Sydney)	Leon	ross.leon@unsw.edu.au
Dr	Junyun (Oxford Instruments NanoScience)	LI	Junyun.li@oxinst.com
Mr	Scott (UNSW Sydney)	Liles	s.liles@unsw.edu.au
Prof	Daniel (University of Basel)	Loss	DANIEL.LOSS@UNIBAS.CH
Mr	Mateusz (CQC2T, UNSW Sydney)	Madzik	m.madzik@student.unsw.edu.au
Dr	Michael (LPS)	Mandelberg	immandelberg@gmail.com
Dr	Frederico (UNSW Sydney)	Martins	f.rodriguesmartins@unsw.edu.au
Mr	Jean-Eric (CEA-LETI)	Michallet	jean-eric.michallet@cea.fr
Mr	A F M Saiful (CQC2T)	Misha	a.misha@student.unsw.edu.au
Prof	Andrea (UNSW Sydney)	Morello	a.morello@unsw.edu.au
Dr	Vincent (CQC2T, UNSW Sydney)	Mourik	vincentmourik@gmail.com
Dr	Usman (University of Melbourne)	Muhammad	musman@unimelb.edu.au
Dr	Akito (RIKEN)	Noiri	akito.noiri@riken.jp
Mr	Lucas (Harvard University)	Orona	orona@g.harvard.edu
Mr	Prasanna (CQC2T)	Pakkiam	prasanna.pakkiam@student.unsw.edu.au
Mr	Sebastian (The University of Sydney)	Pauka	s.pauka@sydney.edu.au
Dr	Jarryd (UNSW Sydney)	Pla	jarryd@unsw.edu.au
Dr	Rajib (Purdue University)	Rahman	rrahman@purdue.edu
Mr	Sarath (Department of Physics and Astronomy & ARC Centre of Excellence for Engineered Quantum Systems, Macquarie University)	Raman Nair	sarath.raman-nair@hdr.mq.edu.au

Prof	David	Reilly	david.reilly@sydney.edu.au
	(The University of Sydney/Microsoft)		
Dr	Lachlan	Rogers	lachlan.rogers@mq.edu.au
	(Macquarie University, Department of Physics and Astronomy)		
Mr	Maximilian	Russ	maximilian.russ@uni-konstanz.de
	(University of Konstanz)		
Mr	Mykhailo	Savytskyi	m.savytskyi@unsw.edu.au
	(UNSW Sydney)		
Dr	Vivien	Schmitt	v.schmitt@unsw.edu.au
	(CQC2T, UNSW Sydney)		
Mr	Vikas	Sewani	v.sewani@unsw.edu.au
	(CQC2T, UNSW Sydney)		
Mr	Alexis	Shaw	alexis@alexisshaw.com
	(CQC2T, UNSW Sydney)		
Prof	Michelle	Simmons	michelle.simmons@unsw.edu.au
	(CQC2T)		
Mr	Thomas	Smith	thomas.b.smith@sydney.edu.au
	(University of Sydney)		
Dr	Sergei	Studenikin	sergei.studenikin@nrc.ca
	(National Research Council of Canada)		
Dr	Tim Hugo	Taminiau	t.h.taminiau@tudelft.nl
	(Delft University of Technology)		
Dr	Kuan Yen	Tan	kuan.tan@aalto.fi
	(CQC2T, UNSW Sydney)		
Dr	Tuomo	Tanttu	t.tanttu@unsw.edu.au
	(CQC2T, UNSW Sydney)		
Prof	Seigo	Tarucha	tarucha@ap.t.u-tokyo.ac.jp
	(The University of Tokyo)		
Dr	Andrey	Timofeev	andrey.timofeev@unsw.edu.au
	(CQC2T)		
Prof	Matthias	Troyer	mtroyer@microsoft.com
	(Microsoft)		
Prof	Lieven	Vandersypen	l.m.k.vandersypen@tudelft.nl
	(QuTech and Kavli Institute of Nanoscience, TU Delft)		
PhD	Maud	Vinet	MAUD.VINET@GMAIL.COM
	(CEA LETI)		
Dr	Thomas	Volz	thomas.volz@mq.edu.au
	(Macquarie University)		
Dr	Theodore	White	tcwhite@google.com
	(Google)		
Prof	Joerg	Wrachtrup	wrachtrup@physik.uni-stuttgart.de
	(University of Stuttgart)		

Prof	Amir (Harvard University)	Yacoby	yacoby@physics.harvard.edu
Dr	Chih-Hwan Henry (CQC2T, UNSW Sydney)	Yang	henry.yang@unsw.edu.au
Dr	Jun (Japan)	Yoneda	jun.yoneda@riken.jp
Mr	David (Princeton University)	Zajac	zajac@princeton.edu
Prof	Dominik (University of Basel)	Zumbuhl	Dominik.Zumbuhl@unibas.ch

Contacts

Conference Chairs:

Prof Andrew Dzurak *(University of New South Wales, Sydney)*

✉ a.dzurak@unsw.edu.au

Prof Andrea Morello *(University of New South Wales, Sydney)*

✉ a.morello@unsw.edu.au

Prof David Reilly *(Microsoft and The University of Sydney)*

✉ dareill@microsoft.com

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Dr Arne Laucht *(University of New South Wales, Sydney)*

✉ a.laucht@unsw.edu.au

☎ +61 4135 21268

Karen Jury *(University of New South Wales, Sydney)*

✉ karen.jury@unsw.edu.au

☎ +61 4117 63048

Mateusz Mądzik *(University of New South Wales, Sydney)*

✉ m.madzik@student.unsw.edu.au

☎ +61 4050 65075

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