2017 Silicon Quantum Electronics Workshop
Talk Abstracts

Trade-offs in engineering a scalable cryogenic controller for solid-state spin-qubits

J.P.G. van Dijk [1][2], E. Kawakami [3], R.N. Schouten [1][2], M. Veldhorst [1][2], L.M.K. Vandersypen [1][2][4], M. Babaie [1], E. Charbon [1][2][4][5], F. Sebastiano [1]

[1] QuTech, Delft University of Technology, Delft, The Netherlands
[2] Kavli Institute of Nanoscience, Delft, The Netherlands
[3] Okinawa Institute of Science and Technology, Okinawa, Japan
[4] Intel Corporation, Hillsboro, OR
[5] EPFL, Lausanne, Switzerland

Keywords: Spin qubits, cryogenic controller, signal specifications
Over the past few years, significant effort has been spent in scaling up the number of quantum bits (qubits) in various technologies, leading to solid-state quantum processors of up to 17 qubits. These quantum processors rely on classical electronics for the control and read-out of the quantum state, which currently includes general-purpose room-temperature instruments. This approach allegedly becomes impractical, expensive, and power inefficient when scaling up the number of qubits to beyond thousands, as required for practical quantum computing applications. As an alternative, the use of a tailor-made classical controller at an intermediate, cryogenic, temperature has been proposed.

Such a cryogenic controller should comply with the limited cooling power available at its operating temperature. Furthermore, the generated signals should be accurate enough to achieve a gate fidelity below the threshold of a quantum error correction (QEC) scheme. In general, achieving a better signal performance incurs a higher power consumption, which would limit the scalability of this solution. To tackle this problem, a systematic study of the influence of signal non-idealities on the qubit fidelity is presented, thus allowing the optimization of the power budgeted to the various control and read-out circuits.

The study focuses on single-electron spin-qubits, as this qubit technology promises large-scale integration, allows a purely electrical control, and offers long coherence times. The minimum required signal specifications have been derived for single-qubit rotations, various two-qubit gates and qubit read-out that form a universal set for quantum computations. The effect of both static and dynamic errors in the control signals are analyzed. In addition, the effect of the control electronics on a qubit's coherence during idle periods is considered. Furthermore, to improve scalability, the achievable qubit fidelity under frequency multiplexing of the qubit control has been investigated. As a result of this work, electrical specifications for the required circuits components can be derived. Examples of both specifications and control circuits are provided that help to assess the feasibility and scalability of this approach.

The authors are grateful to Intel Corporation for its support.

Design of Superconducting Gates for Si/SiGe Quantum Dot Devices

Jeffrey Wright, HRL Laboratories, LLC

Keywords: Si/SiGe, fabrication, magnetic noise.

Isotopically-enhanced Si/SiGe heterostructures form a promising structure for qubit devices, however further advances will require improvements in the gate stack materials for both magnetic noise and charge noise considerations. Here, we report enhancements in the gate stack design and fabrication of exchange-only, accumulation mode, Si/SiGe triple quantum dots that produces higher and more repeatable yield, but which introduces magnetic field gradients due to superconducting metal gates. With the adoption of aluminum as the gate metal, we have tailored the thicknesses of the aluminum gates to account for the diamagnetic response of the Meissner effect. In particular, gates are intentionally made either thick with respect to the London penetration length so that superconductivity is broken with modest applied parallel fields, or intentionally made thin so as to minimize the diamagnetism. This has been confirmed by measuring the singlet-triplet splitting of a double quantum dot, where an abrupt change in the energy splitting is observed at 17 mT, and is attributed to the breaking of the superconductivity in aluminum gates. Updates to the gate stack design, as well as yield improvements observed with adopting aluminum as the gate metal, will also be discussed.

Alternative method for interconnecting STM written quantum electronic devices

A. N. Ramanayaka [1, 2], Hyun-Soo Kim [1, 3], Ke Tang [1, 4], X. Wang [1, 5], R. M. Silver [1], M. D. Stewart, Jr. [1], and J. M. Pomeroy [1]

[1] National Institute of Standards & Technology, Gaithersburg, Maryland 20899, USA
[2] Joint Quantum Institute (JQI), University of Maryland, College Park, Maryland 20742, USA
[3] Department of Electrical and Computer Engineering, University of Maryland, College Park, Maryland 20742, USA
[4] Department of Materials Science and Engineering, University of Maryland, College Park, Maryland 20742, USA
[5] Chemical Physics Program, University of Maryland, College Park, Maryland 20742, USA

Keywords: Nanodevices, Si:P delta layers, STM lithography, P diffusion in Si

One of the key challenges in fabricating scanning tunneling microscope (STM) patterned devices is to create robust and reliable electrical contacts. Contemporary methods of fabricating electrical connections to nanoscale devices include onerous alignment procedures to accommodate electron beam lithography needs. We demonstrate an alternative scheme based on using photolithographically defined implant wires as electrical connections and present ex situ electrical measurements of a STM patterned device on Si(100) at <4 K. One of the main challenges we overcame while implementing this scheme is determination of the significant dopant diffusion during surface preparation of the Si substrates (which typically are heated up to temperatures >1200 C). Therefore, to preserve electrical isolation, a minimum separation between adjacent implant wires must be determined based on the high temperature processing requirements. We bring several (≤ 8 demonstrated), isolated, degenerately doped wires to within the STM scanner's field of view (10 um x 10 um) where the STM can detect and smoothly draw contiguous patterns for electrical connections directly to these implant wires. We present detailed results on the diffusion impact from the high temperature processing, identify optimal implant line spacing, demonstrate the ability to accurately locate implanted regions using STM and establish electrical contact via this technique.

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

Cryogenic frequency synthesis for qubit control: Analysis and Design

B. Patra [1][2], F. Sebastiano [1], E. Charbon [1][2][3][4], M. Babaie [1]
[1] QuTech, Delft University of Technology, Delft, The Netherlands
[2] Kavli Institute of Nanoscience, Delft, The Netherlands
[3] Intel Corporation, Hillsboro, OR
[4] EPFL, Lausanne, Switzerland

Keywords: Qubit control, Microwave pulse, Cryo-CMOS, Oscillator

Microwave pulses are required for controlling both spin qubits and transmons. Currently, bulky and expensive Vector Signal Generators (VSGs) at room temperature are used to up-convert the baseband signal and generate modulated microwave signals for qubit control. Although, the spectral purity of the signals generated by these instruments is not currently the limiting factor for qubit fidelity, such a system is not scalable due to impractical wiring requirements between room-temperature electronics and a large number of cryogenic qubits. On the other hand, using a cryogenic CMOS (cryo-CMOS) frequency synthesizer has several advantages in terms of compactness, reduced latency, complexity and cost; apart from being scalable.

In this contribution, the effect of phase noise of a microwave pulse on qubit dephasing time is analyzed. This is further translated into design tradeoffs and specifications of a phase-locked loop (PLL) required for frequency synthesis. Furthermore, to demonstrate the feasibility of cryogenic PLL, a digitally controlled oscillator is designed in 40-nm CMOS technology. The oscillator works properly across a wide temperature range from 4-300 K. Its frequency is tunable from 5.4 GHz to 7 GHz with a frequency resolution of 5 MHz. The oscillator achieves a phase noise performance of -162 dBc/Hz at 30 MHz offset frequency from a 6.3 GHz carrier while consuming 12 mW. The frequency noise of the oscillator is as low as 3.4 KHzRMS over an integration bandwidth of ~ 10 MHz and embedding this oscillator in a PLL, one can easily attain the tolerable noise limit, required to drive spin qubits. A detailed analysis of the measurement results (phase noise, tuning range, frequency resolution) over temperature is also presented. Finally, the advantages and disadvantages of designing a cryogenic frequency synthesizer is investigated.

The authors would like to acknowledge Intel Corporation for its support.

Two-hole spin resonance and spin-orbit coupling in a silicon metal-oxide-semiconductor field-effect transistor

K. Ono [1,2], G. Giavaras [2], T. Tanamoto [3], T. Ohguro [3], X. Hu [2,4], and F. Nori [2,5]
[1]. Advanced device laboratory, RIKEN, Wako-shi, Saitama 351-0198, Japan
[2]. CEMS, RIKEN, Wako-shi, Saitama 351-0198, Japan
[3]. Corporate R&D Center, Toshiba Corporation, Kawasaki-shi, Kanagawa 212-8582, Japan
[4]. Department of Physics, University at Buffalo, SUNY, Buffalo, New York 14260-1500, USA
[5]. Department of Physics, The University of Michigan, Ann Arbor, MI 48109-1040, USA

Keywords: two-hole spin resonance, spin blockade, Si-MOSFET, EDSR

We study two-hole spin resonance in a p-channel silicon metal-oxide-semiconductor field-effect transistor [1]. In the sub-threshold region, the measured source-drain current reveals a double dot in the channel. The observed spin resonance spectra agree with a model of strongly coupled two-spin states in the presence of a spin-orbit-induced anti-crossing. Detailed spectroscopy at the anti-crossing shows a suppressed spin resonance signal due to spin-orbit-induced quantum state mixing. This suppression is also observed for multi-photon spin resonances. Our experimental observations agree with theoretical calculations.

Reference:
[1] K. Ono, G. Giavaras, T. Tanamoto, T. Ohguro, X. Hu, and F. Nori, arXiv:1707.03106.

We thank M. Kawamura, K. Ishibashi, K. Itoh, S. Kohler, and S. Shevchenko for discussions. This work was supported by JSPS KAKENHI Grant No. 15H04000. This work was partially supported by the RIKEN iTHES Project, the MURI Center for Dynamic Magneto-Optics via the AFOSR Award No. FA9550-14-1-0040, the Japan Society for the Promotion of Science (KAKENHI), the IMPACT program of JST, CREST, US ARO, and a grant from the John Templeton Foundation.

Measurements of valley splitting in novel Si/SiGe heterostructures

Samuel F. Neyens [1], Ryan H. Foote [1], T. J. Knapp [1], Brandur Thorgrimsson [1], Thomas McJunkin [1], L. M. K. Vandersypen [2], Payam Amin [3], Nicole K. Thomas [3], James S. Clarke [3], D. E. Savage [1], M. G. Lagally [1], Mark Friesen [1], S. N. Coppersmith [1], M. A. Eriksson [1]

[1] University of Wisconsin-Madison
[2] Delft University of Technology
[3] Intel Corporation

Keywords: valley splitting, Si/SiGe heterostructure

Achieving an appropriate valley splitting is important for making quantum dot qubits in Si/SiGe heterostructures. Theoretical predictions for valley splitting in ideal Si/SiGe heterostructures have been on the order of 1 meV [1]; however, due to disorder, real Si/SiGe heterostructures often yield valley splittings on the order of tens of μeV or lower and which are also difficult to predict. We investigate a technique, based on a recent theoretical proposal [2], to enhance valley splitting in Si/SiGe heterostructures. We measure valley splittings in novel heterostructures grown with an interfacial layer of Ge between the Si quantum well and the SiGe barrier, as well as in a control sample with no interfacial layer. For one of the experimental heterostructures, the CVD growth was interrupted prior to growth of the interfacial Ge layer, to improve its compositional abruptness. We analyze STEM images to compare compositional abruptness and roughness of the upper quantum well interface in these heterostructures. We measure the valley splitting using an activation energy technique in Hall bar devices at filling factors $\nu = 3$ and $\nu = 5$, in the first and second Landau level, respectively. We find the relative valley splitting of the samples has a strong dependence on magnetic confinement radius (r). At $\nu = 5$, when $r \sim 25$ nm, the control sample has the highest valley splitting (165 +/- 2 μeV), but at $\nu = 3$, where $r \sim 15$ nm, the sample with the growth-interrupted interfacial Ge layer has the highest valley splitting, (203 +/- 4 μeV).

[1] T. B. Boykin, G. Klimeck, M. A. Eriksson, M. Friesen, S. N. Coppersmith, P. von Allmen, F. Oyafuso, & S. Lee. Phys. Rev. B 70, 165325 (2004).
[2] L. Zhang, J.-W. Luo, A. Saraiva, B. Koiller, & A. Zunger. Nature Comm. 4, 2396 (2013).

This work was supported in part by ARO (W911NF-17-1-0274, W911NF-12-0607), NSF (DMR-1206915, DGE-1256259), 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 N00014-15-1-0029. Development and maintenance of the growth facilities used for fabricating samples is supported by DOE (DE-FG02-03ER46028). This research used facilities supported by NSF through DMR-1121288. 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 (ARO), or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein.

Fully tunable coherence and control of acceptor qubits in Si

J. C. Abadillo-Uriel [1, 2] , Joe Salfi [2], Xuedong Hu [2, 3], Sven Rogge [2], M. J. Calderón [1], Dimitrie Culcer [4]

[1] Instituto de Ciencia de Materiales de Madrid, ICMM-CSIC.
[2] School of Physics and Centre for Quantum Computation and Communication Technology, The University of New South Wales.
[3] Department of Physics, University at Buffalo.
[4] School of Physics and Australian Research Council Centre of Excellence in Low-Energy Electronics Technologies, The University of New South Wales.

Keywords: acceptor, spin-orbit, magnetic field anisotropy, decoherence free subspace

Electrical control of quantum bits could pave the way for scalable quantum computation. An acceptor spin qubit in Si, based on spin-3/2 holes, can be controlled by electrical means using a gate electrode, which offers fast one- and two-qubit rotations and long coherence times at certain \textit{sweet spots}. The relaxation time T_1, while allowing $>10^5$ operations, is the primary limiting factor. Here we show that, due to the interplay of the T_d symmetry of the acceptor in the Si lattice and the spin-3/2 characteristic of hole systems, an applied in-plane magnetic field strongly enhances the performance and coherence properties of the qubit. An appropriate choice of magnetic field orientation leads to a near-total suppression of spin relaxation as well as full tunability of two-qubit operations in a parameter regime in which dephasing due to charge fluctuations can be eliminated. Interestingly for spintronic applications, we find an extreme in-plane anisotropy such that the in-plane \textit{g}-factor can vanish under certain circumstances.

This work was partially supported by Ministerio de Economía, Industria y Competitividad (Spain) via Grants No FIS2012-33521, BES-2013-065888, and FIS2015-64654-P and from CSIC (Spain) via grant No 201660I031. Also by the Australian Research Council Centres of Excellence FLEET (CE170100039), ARC DECRA fellowship (DE160101490), and CQC2T (CE110001027). It was also partially supported by US ARO through grant W911NF1210609, and Gordon Godfrey Fellowship from UNSW School of Physics.

Quantum dots built in 28 nm FD-SOI advanced CMOS technology

Pascal Lemieux [1], Philippe Galy [2], Franck Arnaud [2], Julien Camirand Lemyre [1], Étienne Grondin [1], Dominique Drouin [3] and Michel Pioro-Ladrière [1,4]

[1] Institut Quantique, Université de Sherbrooke, Sherbrooke, QC, J1K 2R1, Canada
[2] STMicroelectronics, Crolles, 38920, France
[3] Institut interdisciplinaire d'innovation technologique (3IT), Université de Sherbrooke, Sherbrooke, QC, J1K 2R1, Canada
[4] Quantum Information Science Program, Canadian Institute for Advanced Research, Toronto, ON, M5G 1Z8, Canada

Keywords: FD-SOI, N-MOS, cryogenic operation, quantum dots

Silicon offers compelling opportunities for scaling up spin qubits by leveraging industry-standard microfabrication techniques. In this framework, dedicated N-MOS structures have been fabricated entirely inside STMicroelectronics' foundry using 28 nm ultra-thin body and buried oxide fully depleted silicon on insulator (UTBB FD-SOI) technology. The MOS structure is functional at 20 mK with front and back gate controls and achieve subthreshold slopes as low as 2 mV/decade. Quantum-dots behavior with charging energies as high as 10 meV is observed in transport measurements when the back gate is activated. From capacitive coupling triangulation, the quantum-dots estimated locations correspond to areas around corners at the center of the silicon channel. Further designs and simulations are currently in process to better understand the characteristic of those quantum-dots. Our results represent a first step towards spin qubits implementation on the well-established 28 nm FD-SOI technology, and open new research avenues for co-integration of qubits and CMOS technologies.

This work was supported by Institut quantique, the National Science Engineering Research Council of Canada, the Canadian Foundation for Innovation, and Fonds de recherche du Québec - Nature et Technologies.

Probing low noise at the MOS interface with a spin-orbit singlet-triplet qubit

Ryan M. Jock[1], N. Tobias Jacobson[2], Patrick Harvey-Collard[1,3], Andrew M. Mounce[1], Vanita Srinivasa[1], Dan. R. Ward[1], John Anderson[1], Ron Manginell[1], Joel R. Wendt[1], Martin Rudolph[1], Tammy Pluym[1], John K. Gamble[2], Andrew D. Baczewski[2], Wayne M. Witzel[2], and Malcolm S. Carroll[1],

[1] Sandia National Laboratories, Albuquerque, NM, 87185, United States
[2] Center for Computing Research, Sandia National Laboratories, Albuquerque, NM 87185, USA
[3] Département de physique et Institut quantique, Université de Sherbrooke, Sherbrooke, QC, J1K 2R1, Canada

Keywords: Interface Spin-Orbit Interaction, Metal-Oxide-Semiconductor Charge Noise, Semiconductor Spin Qubit

The silicon metal-oxide-semiconductor (MOS) material system is technologically important for the implementation of electron spin-based quantum information technologies. Researchers predict the need for an integrated platform in order to implement useful computation [1], and decades of advancements in silicon microelectronics fabrication lends itself to this challenge. However, fundamental concerns have been raised about the MOS interface (e.g. trap noise, variations in electron g-factor and practical implementation of multi-QDs). Furthermore, two-axis control of silicon qubits has, to date, required the integration of non-ideal components (e.g. microwave strip-lines, micro-magnets, triple quantum dots, or introduction of donor atoms). In this paper, we introduce a spin-orbit (SO) driven singlet-triplet (ST) qubit in silicon, demonstrating all-electrical two-axis control that requires no additional integrated elements and exhibits charge noise properties equivalent to other more model, but less commercially mature, semiconductor systems [2,3,4,5]. We demonstrate the ability to tune an intrinsic spin-orbit interface effect, which is consistent with Rashba and Dresselhaus contributions that are remarkably strong for a low spin-orbit material such as silicon. The qubit maintains the advantages of using isotopically enriched silicon for producing a quiet magnetic environment, measuring spin dephasing times of 1.6 μs using 99.95% 28Si epitaxy for the qubit, comparable to results from other isotopically enhanced silicon ST qubit systems [6,7,8]. This work, therefore, demonstrates that the interface inherently provides properties for two-axis control, and the technologically important MOS interface does not add additional detrimental qubit noise.

[1] L. M. K. Vandersypen et al., arXiv.org (2016), arXiv:1612.05936.
[2] K. Petersson et al., Physical Review Letters 105, 246804 (2010).
[3] Z. Shi, et al. Phys. Rev. B 88, 075416 (2013).
[4] O. E. Dial et al., Physical Review Letters 110, 146804 (2013).
[5] X. Wu et al., Proceedings of the National Academy of Sciences 111, 11938 (2014),
[6] P. Harvey-Collard et al., arXiv.org (2015), 1512.01606v1.
[7] K. Eng et al., Science Advances 1, e1500214(2015).
[8] M. Rudolph et al., arXiv.org (2017), arXiv:1705.05887.

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 by Los Alamos National Laboratory (Contract DE-AC52-06NA25396) and Sandia National Laboratories (Contract DE-NA-0003525). Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the DOE's National Nuclear Security Administration under contract DE-NA0003525.

High-fidelity singlet-triplet readout and exchange control of spin qubits in a silicon-MOS double quantum-dot

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], 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, TU Delft, 2600 GA 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.

Key words:

1. Pauli spin blockade
2. Singlet-triplet
3. Exchange Control
4. Silicon-MOS

Abstract Text:

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 via encoding parity onto the singlet-triplet basis of ancillary qubits. Here we demonstrate single-shot spin-blockade singlet-triplet readout for a pair of spin qubits in a SiMOS double quantum dot. High-fidelity readout visibility is achieved using a reservoir-charge state-latching protocol. Using this, we characterize the two-spin system by coherently controlling oscillations between the S/T- and S/T0 states. Furthermore, our preliminary measurements show that spin-blockade readout is compatible with single spin control via electron spin resonance (ESR) in these devices. 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 (~4 GHz), allowing more flexible engineering of future quantum processors.

Acknowledgements:

We thank Thaddeus Ladd and Mark Gyure for helpful discussions. We acknowledge support from the Australian Research Council (CE11E0001017 and CE170100039), the US Army Research Office (W911NF-13-1-0024) and the NSW Node of the Australian National Fabrication Facility. M.V. and B.H. acknowledge 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.

Interfacing qubits: Cryogenic control electronics

Lotte Geck (1), Carsten Degenhardt (1), Stefan van Waasen (1),(2)

(1) ZEA-2 Electronic Systems, Forschungszentrum Jülich GmbH
(2) Communications Systems, NTS, University of Duisburg-Essen

Keywords: interface, electronics

Recent advances in increasing the numbers of functioning qubits on one chip [1] show that qubit fabrication as well as the understanding how to control and operate them have developed tremendously during the last years. This paves the road towards a quantum computer with thousands of qubits operating in parallel. However, studies into the development of a scalable interface between the qubits and the necessary control electronics are rare.
We present a high-level system model which aims at placing the control electronics as close to the qubits as possible in order to enable a truly scalable solution. The work is focussed on solid state qubits but can in principle be adapted to other types of qubits.
The considered system is based on integrated electronics and uses complementary metal oxide semiconductor (CMOS) technology. CMOS devices are promising to implement control electronics due to their area and power efficient functionality. Especially area is still expected to decrease with further advancing technology nodes. There are first indications, that advanced commercial CMOS processes still work at temperatures below 1K [2]. Results show that the behaviour of the devices can be similarly described at cryogenic temperatures as at room temperature with only a few model adjustments.
We compare our approach of placing the electronics as close to the qubits as possible with other approaches like the cryogenic use of FPGAs or scaling of room temperature electronics [3] [4]. Especially the connectivity towards room temperature is a key aspect and will be examined in detail. Next to connectivity, other important challenges for the control electronics are area demand and power consumption. Both have been investigated and the figures of merit of different implementations will be shown. The placement of the electronics next to the qubits into the cryogenic environment shows additional advantages like improved noise behaviour. We will show how this aspect influences the choice of component architectures.
For demonstration of the suitability of our approach first results for a modelled electronic system will be presented.

[1] IBM Builds Its Most Powerful Universal Quantum Computing Processors. http://www-03.ibm.com/press/us/en/pressrelease/52403.wss , 2017, accessed June 2017
[2] E. Charbon, F. Sebastiano, A. Vladimirescu, H. Homulle, S. Visser, L. Song, and R. M. Incandela, in Electron Devices Meeting (IEDM), 2016 IEEE International (IEEE, 2016) pp. 13-5.
[3] H. Homulle, S. Visser, B. Patra, G. Ferrari, E. Prati, F. Sebastiano, and E. Charbon, Review of Scientific Instruments 88 (2017).
[4] R. Courtland and E. Lucero, "Google plans to demonstrate the supremacy of quantum computing," IEEE Spectrum article (2017), accessed 04.07.2017.

High-precision transport of single electrons using a silicon quantum dot

M. Möttönen [1], R. Zhao [2], A. Rossi [3], S. P. Giblin [4], T. Tanttu [2], K. Y. Tan [1], K. W. Chan [2], J. D. Fletcher [4], F. E. Hudson [2], A. Mäkinen [1], K.-E. Huhtinen [1], I. Iisakka [5], G. C. Tettamanzi [2], S. Rogge [2], M. Kataoka [4], A. S. Dzurak [2]

[1] Aalto University
[2] University of New South Wales
[3] University of Cambridge
[4] National Physical Laboratory
[5] VTT MIKES Metrology

Keywords: Silicon quantum dot, single-electron tunneling, electron pumping, charge sensing

Implementation of high-precision long-distance two-qubit gates stands as an important milestone in quantum computing with spins in silicon. Such operations have been proposed to be achievable using stationary spins where the qubit-qubit interaction can be mediated, for example, by electric dipole moments or a quantum bus. However, we are motivated by a scenario where the individual electrons carrying the quantum information are transported to an interaction site and back. Namely, we have carried out a series of experiments on high-precision electron pumping using silicon quantum dots. Our latest results show that a quantum dot may be used to transport single electrons at gigahertz frequencies, simultaneously making less than a single error in a million cycles. In comparison to the typical gate operation times of the order of 100 ns and to the gate error of the order of 10^-4 allowed by efficient implementation of quantum error correction codes, the charge transport errors do not seem to pose a hurdle on the way to high-precision long-distance two-qubit gates. In fact, modest additional improvement of the electron pumping accuracy together with error counting would render silicon quantum dots ideal implementations of the emerging quantum standard of electric current.

This work was supported by the Australian Research Council (Grant Nos. DP120104710, DP160104923, DE120100702), the Academy of Finland (Grant No. 284621, 251748, 135794, 272806, 276528), the U.S. Army Research Office (W911NF-13-1-0024), the Australian National Fabrication Facility for device fabrication, Aalto University at Micronova Nanofabrication Centre, the Australian Nanotechnology Network, the Australian Research Council FT scheme (Grant No. FT100100589), Jenny and Antti Wihuri Foundation, and the Finnish Cultural Foundation, the Marie Sklodowska-Curie grant agreement No 654712 (SINHOPSI), the project EMPIR 15SIB08 (e-SI-Amp), and the UK department for Business, Innovation, and Skills.

Hard superconducting gap in Ge/Si core/shell nanowires

J. Ridderbos [1], M. Brauns [1], A. Li [2], E.P.A.M. Bakkers [2], F.A. Zwanenburg [1]

[1] NanoElectronics Group, MESA+ Institute for Nanotechnology, University of Twente
[2] Photonics & Semiconductor Nanophysics Group, Department of Applied Physics, TU Eindhoven

Keywords: Josephson nanowire superconductivity hard-gap

Ge/Si core/shell nanowires are proposed candidates for observing Majorana fermions [1] where a hard superconducting gap is essential for topological protection at zero energy [2].
We present a Josephson junction using semiconducting Ge/Si core/shell nanowires and superconducting Al leads. A gate-tuneable supercurrent is observed with a maximum of ~60 nA. We identify three different regimes tuneable via backgate voltages: Cooper pair tunnelling, quasiparticle transport and finally full suppression of transport.
In the quasiparticle regime, we observe multiple Andreev reflections as well as a hard superconducting gap (subgap conductance suppression by a factor of ~100) indicating a very sudden and clean interface between the superconducting and the semiconducting material. Since we use a combination of e-beam evaporation and thermal annealing, the emergence of the hard gap is surprising. We provide a hypothesis where a previously unknown superconducting phase is formed during thermal annealing consisting of an alloy of Al/Si or Al/Si/Ge. A further indication of the presence of two superconductors is obtained from a magnetospectroscopy of the junction in the Cooper pair tunnelling regime. Here, two highly different critical current – critical temperature (I_c – T_c) and critical current – critical field (I_c – B_c) relations are extracted for Al and the other superconductor.

[1] Maier, F., Klinovaja, J., Loss, D., Majorana fermions in Ge/Si hole nanowires. Phys. Rev. B 90, 195421 (2014).
[2] Chang, W. et al. Hard gap in epitaxial semiconductor–superconductor nanowires. Nano Lett. 17 2690-2696 (2017).

We acknowledge support from the Foundation for Fundamental Research on Matter (FOM), which is part of the Netherlands Organization for Scientific Research (NWO).

Electric Dipole Spin Resonance for electrons in a silicon quantum dot

Andrea Corna [1, 2] Leo Bourdet [3,2] Romain Maurand, [1, 2] Alessandro Crippa, [1, 2]
Dharmraj Kotekar-Patil, [1, 2] Heorhii Bohuslavskyi, [1, 4, 2] Romain Lavieville, [1,4, 2]
Louis Hutin, [4, 2] Sylvain Barraud, [4, 2] Xavier Jehl, [1, 2] Maud Vinet, [4, 2]
Silvano de Franceschi, [1, 2] Yann-Michel Niquet, [3, 2] and Marc Sanquer[1, 2]

1 CEA, INAC-PHELIQS, Grenoble,
2 University Grenoble Alpes, Grenoble,
3 CEA, INAC-MEM, Grenoble,
4 CEA, LETI-MINATEC, Grenoble,

Keywords: Electric dipole spin resonance, Valley splitting, Silicon corner dots, Spin-orbit coupling

We demonstrate electric dipole spin resonance (EDSR) for single electrons accumulated in a silicon quantum dot electrically defined at the corner of a nanowire field effect transistor. The EDSR spectrum consist in four lines which are accurately simulated by tight binding calculations of our device. The experiment and its associated model unveiled that EDSR results from the interplay between valley mixing and spin-orbit coupling. Only the four ground states (two spin-two valleys) are involved, other excited orbital states lying far above in energy (singlet-triplet spacing of 1.9 meV). EDSR is possible only when states with different valleys (valley splitting of 36ueV) and spins are nearly degenerate and when the quantum dot is of low symmetry (to couple different valley states by electric field). These conditions are realized in the specific geometry of our corner quantum dots based on CMOS trigate technology. This opens a road to design Silicon-on-insulator intrinsic quantum dots where the electron spin is rotated by the RF field applied to the control gate and where the strength of the spin-orbit coupling is finely tuned by the design parameters and the substrate bias.

This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 688539 MOSQUITO. Part of the calculations were run on the TGCC/Curie and CINECA/Marconi machines using allocations from GENCI and PRACE.

Charge-noise-limited coherence and three-nines fidelity of an enriched Si/SiGe spin qubit

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], S. Tarucha[1]

[1] RIKEN
[2] Tokyo Institute of Technology
[3] University of Tokyo
[4] Nagoya University
[5] Keio University

Keywords: quantum dot qubit, isotope purification, fidelity, dephasing noise

A single-qubit control fidelity well above 99% would be vital to fault-tolerant entangling gates comprising a sequence of primitive single-qubit operations. This naturally involves improving the qubit controllability and identifying the dephasing source, at the same time. In this work, we demonstrate a >99.9% single-spin-qubit gate fidelity by introducing spin-electric coupling with an on-chip cobalt magnet to an isotopically-clean Si/SiGe quantum-dot qubit. We find that the induced size of spin-electric coupling barely touches the dephasing time (20 microseconds) while reducing the control time by two orders of magnitude (tens of nanoseconds). Dynamical decoupling and Ramsey oscillation analyses reveal 1/f dephasing noise over seven decades of frequency, revealing the free-evolution phase coherence of a single electron spin limited purely by charge noise, rather than conventional magnetic noise.

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

A programmable two-qubit quantum processor in silicon

T. F. Watson [1], S. G. J. Phillips [1], E. Kawakami [1], D. R. Ward [2], P. Scarlino [1], M. Veldhorst [1], D. E. Savage [2], M. G. Lagally [2], Mark Friesen [2], S. N. Coppersmith [2], M. A. Eriksson [2], L. M. K. Vandersypen [1]

[1] Delft University of Technology
[2] University of Wisconsin-Madison

Keywords: Si/SiGe heterostructure, two-qubit gate, electric dipole spin resonance, quantum algorithms

Building small-scale quantum computers where initialisation, readout, single- and two-qubit gates are combined to perform computation result in new challenges such as qubit cross talk, state leakage, and calibration. Here, we overcome these challenges to demonstrate a programmable two-qubit quantum processor using single electron spins in silicon. In the natural Si/SiGe double quantum dot device, single qubit gates with fidelities > 98% are achieved using electric dipole spin resonance mediated by a magnetic field gradient generated by micromagnets. This magnetic field gradient also results in well separated qubit frequencies (~1.3 GHz) allowing the qubits to be independently addressed. A two-qubit CZ gate (5-20 MHz) is realised by combining this large frequency separation with a detuning pulse towards the (0,2) turning on the exchange coupling. We characterise entanglement in our processor by performing quantum state tomography on Bell states. Finally, we demonstrate the programmability of the processor by successfully running both the Deutsch-Jozsa and the Grover search algorithms.

Synchronized high-fidelity quantum gates in Si/SiGe Double Quantum Dots

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

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

Keywords: Si/SiGe quantum dots, Micromagnet, Coherent spin control, two-qubit gates

Spin qubits in silicon quantum dots are a promising candidate for high-fidelity quantum computation due to the long decoherence times in these devices. The use of an additional micromagnet allows for high fidelity single-spin operations through electric dipole spin resonance (EDSR). The slanting magnetic field allows electric driving of the electron spin positions to induce transitions between the spin states. Motivated by recent experiments at Princeton (contribution by D. M. Zajac et al.), we theoretically describe high-fidelity two-qubit gates 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 parameter settings for the gate operation. We present a synchronization method which avoids detrimental spin flips during the gate operation and thus increases the overall gate fidelity.

Research was sponsored by the ARO through grant No. W911NF-15-1-0149.

Coherent Spin Manipulation in a Si/SiGe Double Quantum Dot

D. M. Zajac [1], A. J. Sigillito [1], M. Russ [2], J. M. Taylor [3], G. Burkard [2], and J. R. Petta [1]
[1] Department of Physics, Princeton University, Princeton, NJ 08544, USA
[2] Department of Physics, 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

Keywords: Si/SiGe quantum dots, Micromagnet, Coherent spin control

Si quantum dots are promising candidates for long-lived high fidelity spin qubits due to the clean spin environment that Si provides. Here we demonstrate high fidelity single qubit gates in a Si/SiGe quantum dot using a cobalt micromagnet to introduce an artificial spin-orbit coupling. By modulating the position of the electron in the fringing field of the micromagnet we are able to drive spin transitions through electron dipole spin resonance (EDSR) (1), and readout the spin state through energy selective tunneling to the neighboring Fermi sea (2). Through Ramsey and Hahn echo pulse sequences we measure a T_2^*= 1.4 µs and T_2^{echo}= 80 µs. We achieve Rabi frequencies greater than 10 MHz and gate fidelities as high as 99.7% measured through Clifford randomized benchmarking. We will also describe recent efforts to implement a two-qubit gate in this system.

1. K. Takeda et al., A fault-tolerant addressable spin qubit in a natural silicon quantum dot. Sci. Adv. 2, e1600694 (2016).
2. J. M. Elzerman et al., Single-shot read-out of an individual electron spin in a quantum dot. Nature 430, 431 (2004).

Research was sponsored by the ARO through grant No. W911NF-15-1-0149, the Gordon and Betty Moore Foundation's EPiQS Initiative through Grant GBMF4535, and NSF DMR-1409556. Devices were fabricated in the Princeton University Quantum Device Nanofabrication Laboratory. The views and conclusions contained in this report are those of the authors and should not be interpreted as representing the official policies, either expressly or implied, of the United States Department of Defense or the U.S. Government.

The case for always-on, exchange-only spin qubits

Charles Tahan, Yun-Pil Shim, Rusko Ruskov (Laboratory for Physical Sciences)

Keywords: spin quantum computers

Future quantum computers may utilize multiple types of encoded spin qubits each optimized for their role within the system, be it computation, communication, initialization, or readout. In this talk I will discuss a new encoded qubit, the so-called “always-on, exchange-only” (AEON) qubit, which offers a true sweet spot to charge noise on the quantum dot energy levels, allows for all single- and two-qubit gate operations to be done at sweet spots using only DC-pulses to tune the tunnel couplings between the dots, and requires only a single exchange pulse to implement an encoded two-qubit entangling operation. The AEON qubit can be considered as a generalization of the symmetric operating point (demonstrated for two-dot systems) to three spin systems and can serve as an intermediary to convert between different types of encoded qubits. Composite spin qubit systems of this type can enable previously unexplored readout and resonator-coupling approaches opening new physics opportunities to the spin qubit community, in addition to new tools for spin-based quantum computing.

High mobility in thin-oxide Si/SiGe field-effect transistor on 300 mm Si wafers

D. Sabbagh [1], L. Yeoh [1], A. Sammak [1], N. Kalhor [1], L. M. K. Vandersypen [1], D. Brousse [2], N. Thomas [3], J. Roberts [3], R. Pillarisetty [3], P. Amin [3], H. C. George [3], K. J. Singh [3], J. S. Clarke [3], G. Scappucci [1].

[1] QuTech and Kavli Institute of Nanoscience, TU Delft, P.O. Box 5046, 2600 GA Delft, The Netherlands.
[2] QuTech and TNO, Stieltjesweg 1, 2628 CK Delft, The Netherlands.
[3] Components Research, Intel Corporation, 2501 NW 229th Ave, Hillsboro, OR 97124, USA.

Keywords: Si/SiGe heterostructure, gate-first architecture, high-mobility 2DEG

Undoped Si/SiGe heterostructures are a promising material stack for the development of spin qubits in silicon. We have developed a gate-first integration scheme that allows measurements of a thin-oxide Hall bar field-effect transistor in which the Si/SiGe heterostructure and a high-k/metal gate stack are deposited on 300 mm wafers within the framework of advanced semiconductor manufacturing. Two overlapping gates control separately the electron densities in the Ohmics and in the Hall bar region. This integration scheme allows to access a peak mobility in the strained Si quantum well of $3x10^5$ cm^2/Vs at a temperature of 1.7 K. These results are benchmarked against a control device fabricated with a gate-last integration scheme in which the high-k/metal gate stack is deposited in an academic research environment.

Non-destructive imaging of atomically-thin nanostructures buried in silicon

Alex Kölker[1], Georg Gramse[2], Taylor Stock[1], Gabriel Aeppli[3], Ferry Kienberger[4], Steven R. Schofield[1], Neil Curson[1]

[1] London Centre of Nanotechnology, University College London, London WC1H 0AH, UK
[2] Johannes Kepler University, Biophysics Institute, Gruberstrasse 40, 4020 Linz, Austria
[3] Paul Scherrer Institut, Villigen CH-5232, Switzerland and Department of Physics, ETH, Zurich CH-8093 Switzerland
[4] Keysight Technologies Austria GmbH, Keysight Labs, Gruberstrasse 40, 4020 Linz

Keywords: subsurface imaging, 3D dopant nanostructures, microwave microscopy, silicon

Semiconductor nanostructures consisting of areas of buried dopant atoms are crucial components for present and future CMOS transistor technologies as well as for emerging quantum computing architectures. While much of the technology to create these structures has been developed for some time [1,2], until now there has been no demonstrated technology enabling non-invasive imaging and electrical characterization of buried nanostructures, with precise lateral and depth resolution.
I will describe the fabrication of three-dimensional (3D) phosphorus nanostructures fabricated via scanning tunneling microscope-based lithography, and subsequent characterization with scanning microwave microscopy (SMM). Our 3D nanostructures are composed of a 2-layer crossbar pattern of P rectangles, with the complex fabrication procedure requiring alignment steps for vertical overlay and the use of locking layers to minimize dopant segregation [3].
The SMM measurements, which are completely non-destructive and sensitive to as few as 1900 to 4200 densely packed P atoms 4 to 15 nm below a silicon surface, yield electrical and geometric properties (such as capacitance and conductance). The imaging resolution was 37±1 nm in the lateral and 4±1 nm in the vertical direction, both values depending on SMM tip size and depth of dopant layers [3]. Our results on three-dimensional dopant structures reveal reduced carrier mobility for shallow dopant layers and suggest that SMM could be applied to aid the development of fabrication processes for surface code quantum computers [4].

[1] F.J. Rueß et al., Nanoletters 4 1969 (2004); [2] Fueschle et al., Nature Nano 7, 242 (2012); [3] G. Gramse, A. Kölker et al., Sci. Adv. 3, e1602586 (2017); [4] Hill et al., Science Advances 1, e1500707 (2015)

This work has been supported by EU FP7 (PEOPLE-2012-ITN-317116, NANOMICROWAVE, a Marie Curie Initial Training Network, Bio-SMM FFG (Project No. 846532), FWF Project P28018-B27 and the EPSRC ADDRFSS project (EP/M009564/1) project.

Coherent electron spin control in atomically precise donor systems

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

Keywords: Electron spin qubit, STM, ESR, donor qubits

Fabricated with atomic precision, STM nanostructured donor-based Si devices are promising candidates for implementation of large-scale multi-qubit architectures. Using this technique, we demonstrate the first Electron Spin Resonance (ESR) control of an electron spin qubit bound to a donor based quantum dot in silicon. We successfully integrated microwave transmission lines onto two double quantum dot devices, A and B. A dc-coupled single-electron transistor charge sensor is employed for single-shot spin readout. Using ESR spectroscopy we measure hyperfine fingerprints reflecting both a single donor and also a two-donor cluster in device A. From the hyperfine spectra we additionally determine the distance between the donors within the two-donor cluster and possible atomic configurations in the Si crystal lattice. In device B, we show coherent electron spin rotations via Rabi oscillations. 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 $T_2^* \approx 284 ns$.

Quantum tunneling microscopy of an atomic scale device in silicon

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

Keywords: Si:P, STM precise device, spatially resolved spectroscopy

High-level control of interactions for dopants in silicon is a key requirement to foster spin-based quantum technologies in this material [1]. This is challenging because of the small spatial extent of these localized wavefunctions. A scanning tunneling microscope (STM) can be used to build atomically precise donor devices [2] and can provide absolute single dopant location via imaging [3, 4]. Spatially resolved spectroscopy also allows the coupling strength between donors to be extracted and directly correlated with the dopant positions. However this direct link between geometry and behaviour hasn't been achieved to date in an atomic scale device required for scaled-up applications.

Here we have designed an atomically precise device using a hybrid of STM lithography performed at low temperature and top-down implantation. The wavefunction of single and double dots are scanned as the device is functioning, to obtain real space spectroscopic maps of the charge states on each dot. Moreover this is performed in the Coulomb blockade regime, relevant for quantum transport, with the capability of tuning the chemical potential and occupation number independently. This combination of complex device fabrication with local measurements, both at the atomic scale, opens new ways to control and probe large-scale arrays of interacting quantum states.

References

[1] F. Zwanenburg et al., Review of Modern Physics 85, 961 (2013)
[2] M. Fuechsle et al., Nature Nanotechnology 7, 242-246 (2012)
[3] J. Salfi et al., Nature Materials 13, 605-610 (2014)
[4] M. Usman et al., Nature Nanotechnology 11, 763-768 (2016)

Precision arrangement of phosphorus atoms on Si(100) through chlorine mask

T.V. Pavlova, V.M. Shevlyuga, B.V. Andryushechkin, G.M. Zhidomirov, and K.N. Eltsov
A.M. Prokhorov General Physics Institute, RAS

Keywords: STM lithography, qubit implementation

Realization of the silicon quantum computer on nuclear spins 31P:28Si requires the placement of phosphorus atoms (qubits) with very high accuracy. The most accurate method for donor-based silicon devices is the scanning tunneling microscopy (STM) lithography which allows to place P atoms with precision ~ 10 Å. This spatial limitation is related to a need to have three clean Si dimers (without H) for the phosphine (PH_3) dissociation on the Si(100)-2x1-H surface.
We propose a method for the incorporation of phosphorus atoms into the upper Si(100) layer with atomic precision on the place of the selected Si atom. The mask on the Si(100) surface is formed by the chlorine monolayer and then it is patterned with the STM tip to create the Si vacancy. The difference from the case of the Si(100)-2x1-H surface is that the action of the STM tip on the Si(100)-2x1-Cl surface can lead to the creation of the defect with a Si vacancy (it is well known that $SiCl_2$ is desorbed from the Si(100)-2x1-Cl surface, in contrast to the case of Si(100)-2x1-H where hydrogen is desorbed as H_2).
To investigate the phosphine adsorption on the Si(001)-2x1-Cl surface with mono- and bivacancies (Cl, Cl_2) in the adsorbate layer and combined vacancies with removal of silicon atoms (SiCl and $SiCl_2$), we performed DFT calculations. Phosphine adsorbed on the Si(001)-2x1-Cl surface without atomic defects does not bind with silicon, since the reaction is endothermic. In the case of the SiCl vacancy, phosphorus was found to occupy the vacant place in the silicon lattice in the form of compound PH, while in the case of the $SiCl_2$ vacancy – in the form of PH_2. Calculated activation barriers for phosphine dissociation in SiCl and $SiCl_2$ vacancies are about 0.1-0.5 eV. Therefore, PH or PH_2 incorporate in the surface layer selectively within local defects (SiCl or $SiCl_2$) at room temperatures.
As a starting point of our method realization, we prepared Si(100)-2x1-Cl surface with a low defect density (0.4%). A STM tip is used to desorb Cl with or without Si atoms. Observed STM images were compared to simulated images that helps to identify the type of the created defects.

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

Achieving the Strong-Coupling Regime with Cavity-Coupled Si Double Dots

X. Mi [1], J. V. Cady [1], D. M. Zajac [1], P. W. Deelman [2], J. R. Petta [1]
[1] Department of Physics, Princeton University, Princeton, NJ 08544, USA
[2] HRL Laboratories LLC, 3011 Malibu Canyon Road, Malibu, CA 90265, USA

Keywords: Valley splitting, Circuit QED, Charge Noise

Coupling the spin and charge degrees of freedom of single electrons in gate defined silicon quantum dots to microwave frequency superconducting cavities may allow for high fidelity quantum non-demolition qubit readout, as well as entanglement of distant quantum dot qubits. We demonstrate a hybrid circuit quantum electrodynamics (cQED) device where a silicon charge qubit is coupled to a superconducting cavity via the electric dipole interaction. The strong-coupling regime is achieved in the hybrid system with a charge-cavity coupling rate $g_c/2\pi = 6.7$ MHz, cooperativity $C = 17$ and an exceptionally low charge decoherence rate of 2.6 MHz. In the same system, we measure the cavity transmission to sensitively probe the valley states in our device. We extract a valley splitting of 51 μeV and show the visibility of valley states may be enhanced by increasing the device temperature or applying a source-drain bias. Lastly, we discuss the prospect of using this hybrid device architecture to achieve single spin-cavity coupling in silicon.

Research sponsored by ARO grant No. W911NF-15-1-0149, the Gordon and Betty Moore Foundation's EPiQS Initiative through Grant GBMF4535, and NSF DMR-1409556. Devices were fabricated in the Princeton University Quantum Device Nanofabrication Laboratory.

Towards quantum dot architectures: resonators and auto-tuning

J. M. Taylor[1,2], Sandesh Kalantre[2], Xiao Mi[3], Jason Petta[3], Michael Stewart[2], Neil Zimmerman[2]

[1] Joint Center for Quantum Information and Computer Science, University of Maryland
[2] National Institute of Standards and Technology
[3] Princeton University

Keywords: hybrid quantum systems; machine learning

As efforts in gate-defined quantum dot experiments move towards large arrays of gate-defined confinement regions, a substantial classical control problem awaits: how does one, in moderate time, find a point in the space of allowed gate voltages that enables single charge isolation, readout, and spin manipulation? We examine two solutions to this problem. In the first, we consider a hybrid approach, coupling the one, two, or three spins with microwave photons in a high quality factor superconducting or mechanical resonator, thus restricting the classical control problem to a few gates per register. Benefits and drawbacks of this approach are considered for silicon-based devices. In the second, we consider how to use modern machine learning tools to estimate and monitor the states of one dimensional semiconductor nanowires in the quantum regime with an aim towards tuning large arrays of quantum dots. We use a simple physics model to train a convolutional deep neural network (CNN) to learn the correspondence between experimentally observable parameters -- current through the wire at small bias -- and the underlying model state: number of dots and their charge configuration. We find better than 90% agreement between CNN characterizations of the nanowires and the model predictions. We also show preliminary success in solving the nonlinear optimization problem of training a computer to create single electron occupied-quantum dots from the ground up.

NSF MRSEC at Princeton University

Long decoherence time in Silicon Isolated Double Quantum Dot charge qubits at 4.2 K

Aleksey Andreev, Tsung-Yeh Yang, Thierry Ferrus,

Kiyotaka Hammura, Koichi Watanabe, David A. Williams

Hitachi Cambridge Laboratory

Keywords: decoherence time, charge qubit, double quantum dot

Long decoherence times (T2) up to tens of microseconds were observed in a silicon-based charge quantum bit (qubit) device at 4.2 K. The coherence times demonstrated in this work are two orders of magnitude longer, and the operating temperature is two orders of magnitude higher than the reported semiconductor charge qubit systems. In contrast to other approaches, in this work the qubits are formed by trench isolated double quantum dots instead of surface gate-defined quantum dots. The devices were fabricated on industry-standard SOI wafers. The silicon layers were doped with phosphorus. The device patterns were defined by means of both photo- and electron-beam lithographies. Reactive-ion etching was then applied to form the trenches. The thermal oxidation was then performed to form thin SiO2 cap layers. The one or two qubit devices consist of single electron transistor (for qubit state readout), isolated double quantum dot as charge qubit and electrostatic gates for qubit state manipulation. The obtained results have been analysed using the developed comprehensive model that takes the 3D details of the device as an input and then uses self-consistent solution of the Poisson and Shrodinger equations with many-body effects for qubit quantum states and master equations for qubit detection and time-dependent qubit state evolution taking account of possible decoherence and quantum leakage mechanisms. We demonstrate that the qubit quality factor can be significantly increased by choosing the optimum working points and pulse amplitudes and also by changing the design of the device.

Quantum chaos and multi-qubit operations within a single 123-Sb donor in silicon

S. Asaad [1], V. Mourik [1], H. Firgau [1], M.A.I. Johnson [1], A. Laucht [1], M. Madzik [1], F. Hudson [1], J. McCallum [2], G. Milburn [3], C. Holmes [3], A.S. Dzurak [1], J.J. Pla [1], A. Morello [1]

[1] UNSW
[2] The University of Melbourne
[3] The University of Queensland

Keywords: Spin qubit, quantum chaos, qudit, donor

The 123-Sb atom is a group-V element with a nuclear spin quantum number of 7/2, resulting in an 8-dimensional nuclear spin Hilbert space. It can be implanted in a silicon-MOS structure, and operated using our existing spin-qubit infrastructure, with high-fidelity control [1] and single-shot readout [2] capabilities already proven with the 31-P donor. Crucial to this modified system is that any strain on the silicon crystal lattice results in a quadrupole interaction with the 123-Sb nucleus . This introduces a term in the Hamiltonian that is quadratic in the spin operators. 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]. This will enable a unique experimental study of the emergence of chaos and the quantum-to-classical crossover in the dynamics of a single quantum system [3]. From a quantum-information perspective, the 123-Sb nuclear spin can be treated as an 8-dimensional qudit or, alternatively, as three encoded qubits, where NMR provides universal quantum gates. This can be exploited to demonstrate basic quantum error correction protocols within a single atom. In this presentation, we will provide a detailed theoretical description of the system, as well as an update on the ongoing experiments.

[1] J.P. Dehollain et al., New J. Phys. 18, 103018 (2016)
[2] J.J. Pla et al., Nature 496, 334 (2013)
[3] V. Mourik et al., arXiv:1703.04852 (2017)

This research was funded by the Australian Research council through a Discovery Project (DP150101863) and the Centre for Quantum Computation & Communication Technology.

All-electric control of donor nuclear spins in silicon

A. J. Sigillito [1], A. M. Tyryshkin [1], T. Schenkel [2], A. A. Houck [1], S. A. Lyon [1]
[1] Princeton University, Princeton, NJ 08544
[2] Lawrence Berkeley National Laboratory, Berkeley, California 94720

Keywords: donor spin qubits, nuclear magnetic resonance, electrically driven spins

Donor nuclear spin qubits are typically manipulated using radiofrequency magnetic fields, but in recent years there has been growing interest in driving spins through electric fields. Electrically driving spins allows for addressable control, improving the prospects for scalability, and may enable strong coupling between donors and superconducting circuits. In this work, we demonstrate for the first time all electric field manipulation of neutral 31P and 75As donor nuclear spins in silicon.

When driving 31P donors, our technique relies on electric-field manipulation of the electron spin's g-tensor which leads to a modulated hyperfine field seen by the nuclear spin. This hyperfine field directly drives donor nuclear spin transitions when modulated at the subharmonic of the NMR resonance frequency, or at their resonance frequency in the presence of a DC field or strain. When measuring 75As donors, we find that this g-factor modulation mechanism cannot explain the much faster Rabi frequencies observed. We discuss the possibility of quadrupolar modulation enhancing the electrically driven nuclear magnetic resonance and show data revealing the ability to drive double quantum transitions for arsenic donors.

In this proof-of-principle experiment we demonstrate electrically driven nuclear spin Rabi frequencies exceeding 50 kHz for widely spaced (10 micron) gates, which should reach MHz rates for nanoscale devices.

Work at Princeton was supported by the NSF through the Princeton MRSEC (Grant No. DMR-01420541) and by the ARO (Grant No. W911NF-13-1-0179). Work at LBNL was performed under the auspices of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Spin-relaxation mechanisms of donors in Si in a nano-electronic device

Yu-Ling Hsueh [1], Bent Weber [2], Thomas F. Watson [3], Sam Hile [4], Lukas Fricke [4], Lloyd C. L. Hollenberg [5], Michelle Y. Simmons [4], and Rajib Rahman [1]
[1] Purdue University
[2] Nanyang Technological University
[3] TU Delft
[4] University of New South Wales
[5] University of Melbourne

Keywords: Spin-relaxation, donors in Si, spin-orbit

Understanding and controlling the spin-relaxation mechanism is crucial for realizing a spin-qubit based quantum computer. The spin-lattice relaxation time (T1) is one of the two important timescales of a qubit, and in addition, it can provide valuable information about the qubit and its interaction with the device environment. Here, we investigate the T1 time of electronic spins bound to donors in silicon in a scanning tunneling microscopy (STM) fabricated device. We show that under applied gate bias, an unconventional spin-orbit coupling the external electric field and magnetic field dominates over Rashba spin-orbit for donors in Si. Various spin-relaxation mechanisms are investigated, considering both the valley repopulation and single valley effects. We find that T1 is strongly dependent on the directions of the external magnetic and electric fields relative to the crystalline directions. We show good agreements between this theory and recent experimental measurements.

This research was conducted by the Australian Research Council (ARC) Centre of Excellence for Quantum Computation and Communication Technology (project number CE110001027), the US National Security Agency and the US Army Research Oce under contract number W911NF-08-1-0527, and the ARC Discovery Project scheme.