REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
28-06-2019	Final Report	1-Oct-2012 - 31-Aug-2018

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Final Report: Solid State Quantum Computing Using Spin Qubits in Si/SiGe Quantum Dots	W911NF-12-1-0607
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
University of Wisconsin - Madison Suite 6401 21 N Park Street Madison, WI 53715 -1218	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 62285-PH-OC.58

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Mark Eriksson
UU	UU	UU	UU		19b. TELEPHONE NUMBER 608-263-6289

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 29-Aug-2019

Agency Code:

Proposal Number: 62285PHQC **Agreement Number: W911NF-12-1-0607**

INVESTIGATOR(S):

Name: Alexander J Rimberg ajrimberg@
Email: Alexander.J.Rimberg@Dartmouth.edu
Phone Number: 6036466569
Principal: N

Name: Mark Friesen
Email: FRIESEN@PHYSICS.WISC.EDU
Phone Number: 6082652496
Principal: N

Name: GERHARD KLIMECK Phd
Email: GEKCO@PURDUE.EDU
Phone Number: 7654949212
Principal: N

Name: Lieven Vandersypen
Email: l.m.k.vandersypen@tudelft.nl
Phone Number: 31152782469
Principal: N

Name: MAX LAGALLY
Email: LAGALLY@ENGR.WISC.EDU
Phone Number: 6082622281
Principal: N

Name: Mark A. Eriksson
Email: MAERIKSSON@WISC.EDU
Phone Number: 6082636289
Principal: Y

Name: ROBERT JOYNT
Email: RJJOYNT@WISC.EDU
Phone Number: 6082622281
Principal: N

Name: Susan Coppersmith Ph.D
Email: snc@physics.wisc.edu
Phone Number: 6082628358
Principal: N

Organization: **University of Wisconsin - Madison**
Address: Suite 6401, Madison, WI 537151218
Country: USA

DUNS Number: 161202122 EIN: 396006492
Report Date: 30-Nov-2018 Date Received: 28-Jun-2019
Final Report for Period Beginning 01-Oct-2012 and Ending 31-Aug-2018
Title: Solid State Quantum Computing Using Spin Qubits in Si/SiGe Quantum Dots
Begin Performance Period: 01-Oct-2012 **End Performance Period:** 31-Mar-2019
Report Term: 0-Other
Submitted By: Mark Eriksson Email: MAERIKSSON@WISC.EDU
Phone: (608) 263-6289
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 1 **STEM Participants:** 0

Major Goals: Wisconsin: The main project goals are to fabricate and measure the properties of silicon quantum dot qubits and to develop technology necessary for a Si/SiGe quantum dot quantum computer. These goals include both theory and experiment focusing on (i) the development and fabrication of qubits in the form of electron spins in silicon quantum dots, (ii) the measurement and manipulation of those qubits, and (iii) the science essential for understanding the properties of such qubits.

Delft: With our fully integrated two qubit device our goal was to benchmark the performance of the C-ROT and C-PHASE two-qubit gate using randomized benchmarking. We planned to explore varying the tunnel coupling and detuning to maximize the two-qubit gate fidelity. We also planned to implement a two qubit algorithm in this system which will serve as another test for the overall performance of this device.

Purdue: The objective of the atomistic modeling component of this effort is to understand coupled spin and valley physics in silicon quantum dots without adjustable parameters in the model. To calibrate the modeling methods, the Purdue team also seeks quantitative comparison of simulation results with available experimental data.

Dartmouth: The major goal of the Rimberg group is to develop a new charge detection scheme for readout of spin qubits in Si/SiGe quantum dots. The scheme is based on coupling a quantum dot to a Cooper-pair transistor embedded in a superconducting microwave cavity (cCPT). When operated on its supercurrent branch, the CPT acts as a charge tunable inductor that appears in parallel to the effective cavity inductance at resonance. When a charge on the dot moves, the CPT inductance will change, causing a dispersive shift in the cavity resonant frequency. By measuring the phase of a reflected carrier wave, the charge state of the dot can be inferred.

Note about participants below: senior personnel time rounded to the nearest allowed entry (natural number of months).

Accomplishments: We summarize below important results from each of the four participating groups: Wisconsin, Delft, Dartmouth, Purdue. The majority of the project activity occurred from its 2012 inception through its planned end in 2016. Work continued past that date in large part for a QuaCGR fellowship to Adam Frees. We report on that work first. Figures and references can be found in the uploaded pdf file.

Adam Frees Fellowship:

This QuaCGR involved two projects: study of the Compressed Optimization of Device Architecture (CODA) protocol to optimize the design of quantum dot devices, and using dynamical sweet spots (DSSs) to produce high-fidelity two-qubit gates in a simulated system of capacitively-coupled quantum dot hybrid qubits (QDHQs). In the CODA work, we demonstrated that this protocol can identify sparse sets of voltage changes that control quantum devices. We demonstrated that the CODA protocol scales efficiently with device size and can be used to find sparse tunings for devices with 100 quantum dots. Using a simple model of a device with m quantum dots, we compared nonlinear optimizers to find the changes in electrode voltages that add one electron to a specific quantum dot, keeping all other dot occupations and tunnel rates constant. In Fig. 1 we compare the number of device simulations used by each nonlinear optimizer as a function of the number of quantum dots, m. The CODA protocol requires roughly an order of magnitude fewer simulations than the next-most efficient optimizer, confirming that it is indeed an extensible algorithm. These results were published in Phys Rev Applied [1].

In Ref. [2], we demonstrated that the dephasing in a system of capacitively-coupled QDHQs can be mitigated by approaching dynamical sweet spots. We assume that dephasing is the primary source of error for the entangling gates considered, making the reduction of this error channel crucial. We do compare this estimated infidelity due to relaxation against the simulated infidelity due to dephasing, finding the latter to be the dominant effect. These results have been accepted for publication in npj Quantum Information.

Wisconsin:

A major advance was the development of the theory and experimental implementation of the quantum dot hybrid qubit (QDHQ). This work evolved experimentally from initial coherent manipulation of excited states in a double quantum dot [3], to coherent control of the QDHQ through baseband manipulation [4], to full ac control of the QDHQ [5]. We then were able to demonstrate experimental tunability of the qubit Hamiltonian to improve the coherence properties of the QDHQ [6], a procedure that was both inspired and guided by theoretical results from our group. We also took an important next step by demonstrating charge-state-conditional coherent control of a charge qubit in a four quantum dot device [7].

In theory work on the QDHQ, we developed a dressed-state approach to understand strong driving in this qubit, and using that approach we have shown that, if environmental noise can be sufficiently reduced, strong driving could be used in the future to achieve gate fidelities higher than 99.99%.

Valley splitting is a critical parameter in electron-based Si qubits. We measured valley splitting in Hall bars fabricated in quantum wells with and without a thin, pure Ge layer right at the top of the quantum well, and collaborators at Intel performed high resolution STEM measurements. In that work we demonstrated the importance of the substrate disorder in determining the valley splitting in silicon quantum wells [8].

We performed much work qubit nanofabrication, including processes with many steps performed on a projection stepper, working towards devices with four coupled quantum dots; that work has paid enormous dividends for the silicon qubit effort.

We studied theoretically evanescent-wave Johnson noise, extending the theory to situations where the finite spatial extent of the qubit is a factor.

Delft:

One of the major achievements was the implementation of two variants of a two-qubit gate: C-ROT and C-PHASE, and the performance of 2-qubit algorithms in devices fabricated in this project [9]. We managed to improve the level of control of the combined system to the point where we could simply program any of the four instances of the two two-qubit algorithms that can run on a two-qubit processor, the Deutsch-Jozsa algorithm and Grover's algorithm (Fig. 3). We also performed quantum state tomography on each of the four Bell states, and observed state fidelities with respect to the ideal Bell states of 85-80% (Fig. 3).This work built on a series of experiments and developments characterizing single qubit gates [10-13]. We found that spin-orbit coupling in the heterostructure is found to have influence on the orientation of the magnetic field. We also found that while nuclear spins limit T2*, the dynamical decoupling decay may be limited by charge noise. Most recently, in the two-qubit device we have demonstrated character randomized benchmarking in the two-qubit device [14].

In the Si MOS project we reached the stage of qubit measurements. Device fabrication achieved good yield on multi-layer Pd gate structures with 28Si/SiO2 substrates provided by Intel. We formed double dots on several devices and performed single-shot read-out of a single spin using Elzerman spin-charge conversion.

Dartmouth:

Together with theory colleagues at Wisconsin, Dartmouth participants developed an understanding of the valley Kondo effect in Si/SiGe quantum dots [15]. Dartmouth also designed and tested a microwave cavity that includes dc ports for applying flux bias and gate voltage to a cCPT (Fig. 4). We demonstrated that the undoped Si/SiGe substrates we use have sufficiently low loss at microwave frequencies to allow cavities fabricated on them to remain high-Q. We installed and made use of a superconducting SLUG amplifier from the McDermott group (Wisconsin). Initial characterization of the SLUG-based amplifier chain indicates an upper bound for the system noise temperature of 2.7 K. We have installed an ion mill for fabrication of Ti/Au contact pads needed for the cCPT. Finally, we have acquired a traveling wave parametric amplifier that will remove the need to frequency-match our cavities to our amplifier chain. As the project at Dartmouth ended, we had made progress toward producing and measuring cCPT devices fabricated on Si/SiGe. We resolved problems with our electron-beam evaporator that had interfered with our ability to produce microwave cavities on Si/SiGe substrates. We also received a new TWPA amplifier from Lincoln Lab, and began work on installing this amplifier in our dilution refrigerator.

Purdue:

The Purdue team performed numerical calculations for a number of experimental situations. The major results of the g-factor work include: 1) Measurements in different experiments of valley-dependent g-factors can be explained by interfacial disorder. 2) Spin-orbit (SO) parameters were extracted from tight-binding calculations. 3) The g-factor anisotropy measured in the Vandersypen group was explained quantitatively as emerging from a) valley-dependent spin-orbit coupling, and b) an average and an inhomogeneous B-field from the integrated micromagnets. 4) The anisotropy of the g-factor differences of the valleys are influenced by SO and the inhomogeneous B-fields, while the anisotropy in the ESR frequency of each valley is determined by the net polarization of the micromagnet in the presence of the external B-field [16]. In addition, charge relaxation calculations were performed in a silicon double quantum dot and relaxation hot-spots were predicted to emerge from step induced enhancement in valley-orbit coupling. Comparison with published relaxation data in the literature helped to explain the unusual trends in the relaxation rate as a function of detuning which were observed in the experiments.

Training Opportunities: Graduate students received training in the nanofabrication of Si/SiGe quantum dots and Si-MOS dots (in the case of TU Delft), the measurement of those samples, and the analysis of that data. Training was also provided on how to write papers and present talks. Graduate students also received training in the simulation and modeling of quantum device physics.

Results Dissemination: Work from this award has so far led to the publication of 54 articles in peer-reviewed journals; 3 other manuscripts are still under review.

A total of 263 public presentations were made, including both contributed or invited talks at conferences and seminars.

Honors and Awards: M. A. Eriksson was elected Fellow of the American Physical Society in 2012.

John Gamble received the Charles Elwood Mendelhall Award for Excellence in Graduate Research at the University of Wisconsin-Madison, Department of Physics on May 3, 2013.

John Gamble received the Harry S. Truman Fellowship in National Security Science and Engineering at Sandia National Laboratories in 2013.

Susan Coppersmith received a Kac lectureship at Los Alamos National Laboratory in 2014.

Susan Coppersmith received a National Security Science and Engineering Faculty Fellowship in 2014.

Mark Eriksson received a new title at the University of Wisconsin-Madison in 2016: Vilas Distinguished Achievement Professor.

Mark Eriksson became Member of the Advisory Board of Nature partner journal Quantum Information (2015-present).

Susan Coppersmith became Sigma Xi lecturer (2016-2017).

Susan Coppersmith was named guest of honor for the December 2016 Rutgers Statistical Mechanics Conference.

Lieven Vandersypen became Member of the Advisory Board of Nature partner journal Quantum Information (2015-present).

Protocol Activity Status:

Technology Transfer: U.S. Patent 9,842,921, "Direct Tunnel Barrier Control Gates in a Two-Dimensional Electron System," was granted to Mark A. Eriksson, John King Gamble, Daniel R. Ward, Susan Nan Coppersmith, and Mark G. Friesen on Dec. 12, 2017.

Patent application number 14/996918, “System and Method for Quantum Computation using Symmetrical Charge Qubits,” was filed on Jan. 15, 2016, by Mark Friesen, Mark Eriksson, and Susan Coppersmith. This patent is pending.

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Adam Frees

Person Months Worked: 4.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article
Peer Reviewed: Y
Publication Status: 1-Published
Journal: Applied Physics Letters
Publication Identifier Type: DOI
Publication Identifier: 10.1063/1.4754827
Volume: 101 Issue: 14 First Page #: 142103
Date Submitted:
Date Published:
Publication Location:
Article Title: Charge sensing in a Si/SiGe quantum dot with a radio frequency superconducting single-electron transistor
Authors:
Keywords: single-electron transistor, quantum dot, radio frequency, charge sensor, double quantum dot
Abstract: We report the operation of a radio frequency superconducting single-electron transistor (rf-SSET) as a charge sensor for single and double Si/SiGe quantum dots (QDs). Real-time electron tunneling events are observed from the reflected signal of the rf-SSET with a charge sensitivity of 4 x 10 └^6 e/Hz^1/2, which demonstrates a fast charge detection time of a few tens of microseconds. Measurements of the reflected power are used to map out the stability diagram of the double quantum dot.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article
Peer Reviewed: Y
Publication Status: 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI
Publication Identifier: 10.1103/PhysRevLett.109.250503
Volume: 109 Issue: 25 First Page #: 250503
Date Submitted:
Date Published:
Publication Location:
Article Title: Pulse-Gated Quantum-Dot Hybrid Qubit
Authors:
Keywords: qubit, silicon, quantum computing, double quantum dot, spin
Abstract: A quantum-dot hybrid qubit formed from three electrons in a double quantum dot has the potential for great speed, due to the presence of level crossings where the qubit becomes chargelike. Here, we show how to exploit the level crossings to implement fast pulsed gating. We develop one- and two-qubit dc quantum gates that are simpler than the previously proposed ac gates.We obtain closed-form solutions for the control sequences and show that the gates are fast (subnanosecond) and can achieve high fidelities.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.86.062328
Volume: 86 Issue: 6 First Page #: 62328
Date Submitted: Date Published:
Publication Location:
Article Title: Mediated gates between spin qubits
Authors:
Keywords: spin, qubit, quantum dot, triple quantum dot, quantum computing, exchange interaction
Abstract: In a typical quantum circuit, nonlocal quantum gates are applied to nonproximal qubits. If the underlying physical interactions are short-range (e.g., exchange interactions between spins), intermediate SWAP operations must be introduced, thus increasing the circuit depth. Here we develop a class of "mediated" gates for spin qubits, which act on nonproximal spins via intermediate ancilla qubits. At the end of the operation, the ancillae return to their initial states. We show how these mediated gates can be used (1) to generate arbitrary quantum states and (2) to construct arbitrary quantum gates. We provide some explicit examples of circuits that generate common states [e.g., Bell, Greenberger-Horne-Zeilinger (GHZ), W, and cluster states] and gates (e.g., ? SWAP, SWAP, CNOT, and Toffoli gates). We show that the depths of these circuits are often shorter than those of conventional SWAP-based circuits. We also provide an explicit experimental proposal for implementing a mediated gate in a
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Reviews of Modern Physics
Publication Identifier Type: DOI Publication Identifier: 10.1103/RevModPhys.85.961
Volume: 85 Issue: 3 First Page #: 961
Date Submitted: Date Published:
Publication Location:
Article Title: Silicon quantum electronics
Authors:
Keywords: Silicon, quantum, electronics, qubits, quantum dots
Abstract: This review describes recent groundbreaking results in Si, Si/SiGe, and dopant-based quantum dots, and it highlights the remarkable advances in Si-based quantum physics that have occurred in the past few years. This progress has been possible thanks to materials development of Si quantum devices, and the physical understanding of quantum effects in silicon. Recent critical steps include the isolation of single electrons, the observation of spin blockade, and single-shot readout of individual electron spins in both dopants and gated quantum dots in Si. Each of these results has come with physics that was not anticipated from previous work in other material systems. These advances underline the significant progress toward the realization of spin quantum bits in a material with a long spin coherence time, crucial for quantum computation and spintronics.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.87.155405
Volume: 87 Issue: 15 First Page #: 155405
Date Submitted: Date Published:
Publication Location:
Article Title: Probing quantum phase transitions in a spin chain with a double quantum dot
Authors:
Keywords: Quantum phase transition, spin chain, quantum dot
Abstract: Quantum phase transitions (QPTs) in qubit systems are known to produce singularities in the entanglement, which could in turn be used to probe the QPT. Recent proposals have suggested that the QPT in a spin chain could be probed via the entanglement between external qubits coupled to the spin chain. Such experiments may be technically challenging, because the probe qubits are nonlocal. Here we show that a double quantum dot coupled locally to a spin chain provides an alternative and efficient probe of a QPT. To demonstrate this method in a simple geometry, we propose an experiment to observe a QPT in a triple quantum dot, based on the well-known singlet projection technique.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Applied Physics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1063/1.4807768
Volume: 102 Issue: 21 First Page #: 213107
Date Submitted: Date Published:
Publication Location:
Article Title: Integration of on-chip field-effect transistor switches with dopantless Si/SiGe quantum dots for high-throughput testing
Authors:
Keywords: field-effect transistor, silicon, Si/SiGe, quantum dots
Abstract: Measuring multiple quantum devices on a single chip increases characterization throughput and enables testing of device repeatability, process yield, and systematic variations in device design. We present a method that uses on-chip field-effect transistor switches to enable multiplexed cryogenic measurements of double quantum dot Si/SiGe devices. Multiplexing enables the characterization of a number of devices that scales exponentially with the number of external wires, a key capability given the significant constraints on cryostat wiring. Using this approach, we characterize three quantum-point contact channels and compare threshold voltages for accumulation and pinch-off voltages during a single cool-down of a dilution refrigerator.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.88.035310
Volume: 88 Issue: 3 First Page #: 35310
Date Submitted: Date Published:
Publication Location:
Article Title: Disorder-induced valley-orbit hybrid states in Si quantum dots
Authors:
Keywords: Disorder, valley-orbit coupling, silicon, quantum dots
Abstract: Quantum dots in silicon are promising candidates for the implementation of solid-state quantum information processing. It is important to understand the effects of the multiple conduction band valleys of silicon on the properties of these devices. Here we present a systematic effective mass theory of valley-orbit coupling in disordered silicon systems. This theory reveals valley-orbit hybridization effects that are detrimental for storing quantum information in the valley degree of freedom, including nonvanishing dipole matrix elements between valley states and altered intervalley tunneling.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.87.022332
Volume: 87 Issue: 2 First Page #: 22332
Date Submitted: Date Published:
Publication Location:
Article Title: Resonant adiabatic passage with three qubits
Authors:
Keywords: Resonant adiabatic passage, qubits
Abstract: We investigate the nonadiabatic implementation of an adiabatic quantum teleportation protocol, finding that perfect fidelity can be achieved through resonance. We clarify the physical mechanisms of teleportation, for three qubits, by mapping their dynamics onto two parallel and mutually coherent adiabatic passage channels. By transforming into the adiabatic frame, we explain the resonance by analogy with the magnetic resonance of a spin-1/2 particle. Our results establish a fast and robust method for transferring quantum states and suggest an alternative route toward high-precision quantum gates.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 3-Accepted
Journal: npj Quantum Information
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 6/21/19 12:00AM Date Published:
Publication Location:
Article Title: Adiabatic two-qubit gates in capacitively coupled quantum dot hybrid qubits,
Authors: Adam Frees, Sebastian Mehl, John King Gamble, Mark Friesen, S. N. Cop-persmith
Keywords: quantum dot hybrid qubit, quantum computing, spin qubit
Abstract: The ability to tune qubits to at points in their energy dispersions ("sweet spots") is an important tool for mitigating the e♂ffects of charge noise and dephasing in solid-state devices. However, the number of derivatives that must be simultaneously set to zero grows exponentially with the number of coupled qubits, making the task untenable for as few as two qubits. This is a particular problem for adiabatic gates, due to their slower speeds. Here, we propose an adiabatic two-qubit gate for quantum dot hybrid qubits, based on the tunable, electrostatic coupling between distinct charge configurations. We con♀rm the absence of a conventional sweet spot, but show that controlled-Z (CZ) gates can nonetheless be optimized to have fi♀delities of ↑99% for a typical level of quasistatic charge noise (←sigma_eps =1 ┬ueV). We then develop the concept of a dynamical sweet spot (DSS), for which the time-averaged energy derivatives are set to zero, and identify a simple pulse sequence that
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
Journal: npj Quantum Information
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 6/21/19 12:00AM Date Published:
Publication Location:
Article Title: Enhancing the dipolar coupling of a S-T0 qubit with a transverse sweet spot
Authors: J. C. Abadillo-Uriel, M. A. Eriksson, S. N. Coppersmith, Mark Friesen
Keywords: quantum computing, quantum dot, spin, singlet-triplet qubit, microwave cavity
Abstract: A fundamental design challenge for quantum dot spin qubits is to extend the strength and range of qubit interactions while suppressing their coupling to the environment, since both eff♂ects have electrical origins. Key tools include the ability to retune the qubits, to take advantage of physical resources in di♂fferent operating regimes, and to access optimal working points, or "sweet spots," where dephasing is minimized. Here, we explore an important, new resource for singlet-triplet qubits: a transverse sweet spot (TSS) that enables (i) direct transitions between qubit states, (ii) a strong, charge-like qubit coupling, and (iii) leading-order protection from electrical fluctuations. Of particular interest is the possibility of transitioning between the TSS and symmetric operating points while remaining continuously protected. This arrangement is ideal for coupling qubits to a microwave cavity, because it combines maximal tunability of the coupling strength with leading-order
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.98.165438
Volume: 98 Issue: 16 First Page #: 165438
Date Submitted: 6/21/19 12:00AM Date Published: 10/29/18 5:00AM
Publication Location:
Article Title: Signatures of atomic-scale structure in the energy dispersion and coherence of a Si quantum-dot qubit
Authors: J. C. Abadillo-Uriel, Brandur Thorgrimsson, Dohun Kim, L. W. Smith, C. B. Simmons, Daniel R. Ward, R
Keywords: quantum dot, qubit, silicon, valley splitting, disorder
Abstract: We report anomalous behavior in the energy dispersion of a three-electron double-quantum-dot hybrid qubit and argue that it is caused by atomic-scale disorder at the quantum-well interface. By employing tight-binding simulations, we identify potential disorder profiles that induce behavior consistent with the experiments. The results indicate that disorder can give rise to “sweet spots” where the decoherence caused by charge noise is suppressed, even in a parameter regime where true sweet spots are unexpected. Conversely, “hot spots” where the decoherence is enhanced can also occur. Our results suggest that interfacial atomic structure can be used in particular cases as a tool to enhance the fidelity of Si double-dot qubits.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: npj Quantum Information
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41534-019-0127-1
Volume: 5 Issue: First Page #: 12
Date Submitted: 6/21/19 12:00AM Date Published: 1/31/19 6:00AM
Publication Location:
Article Title: Achieving high-fidelity single-qubit gates in a strongly driven charge qubit with 1/f charge noise
Authors: Yuan-Chi Yang, S. N. Coppersmith, Mark Friesen
Keywords: quantum dot, qubit, charge qubit, noise
Abstract: Charge qubits formed in double quantum dots represent quintessential two-level systems that enjoy both ease of control and efficient readout. Unfortunately, charge noise can cause rapid decoherence, with typical single-qubit gate fidelities falling below 90%. Here we develop analytical methods to study the evolution of strongly driven charge qubits, for general and 1/f charge-noise spectra. We show that special pulsing techniques can simultaneously suppress errors due to strong driving and charge noise, yielding single-qubit gates with fidelities above 99.9%. These results demonstrate that quantum dot charge qubits provide a potential route to high-fidelity quantum computation.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Applied
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevApplied.11.024063
Volume: 11 Issue: 2 First Page #: 024063
Date Submitted: 6/21/19 12:00AM Date Published: 2/25/19 6:00AM
Publication Location:
Article Title: Compressed Optimization of Device Architectures for Semiconductor Quantum Devices
Authors: Adam Frees, John King Gamble, Daniel R. Ward, Robin Blume-Kohout, M.A. Eriksson, Mark Friesen, S.
Keywords: quantum dot, qubit, simulation, optimization
Abstract: Recent advances in nanotechnology have enabled researchers to manipulate small collections of quantum-mechanical objects with unprecedented accuracy. In semiconductor quantum-dot qubits, this manipulation requires controlling the dot orbital energies, the tunnel couplings, and the electron occu- pations. These properties all depend on the voltages placed on the metallic electrodes that define the device, the positions of which are fixed once the device is fabricated. While there has been much success with small numbers of dots, as the number of dots grows, it will be increasingly useful to control these systems with as few electrode voltage changes as possible. Here, we introduce a protocol, which we call the “compressed optimization of device architectures” (CODA), in order both to efficiently identify sparse sets of voltage changes that control quantum systems and to introduce a metric that can be used to com- pare device designs. As an example of the former, we apply this method to
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 29-Aug-2019

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review X
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevX.9.021011
Volume: 9 Issue: 2 First Page #: 021011
Date Submitted: 6/21/19 12:00AM Date Published: 4/18/20 5:00AM
Publication Location:
Article Title: Benchmarking Gate Fidelities in a Si/SiGe Two-Qubit Device
Authors: X. Xue, T. F. Watson, J. Helsen, D. R. Ward, D. E. Savage, M. G. Lagally, S. N. Coppersmith, M. A. Erik
Keywords: quantum do, qubit, benchmarking, fidelity, silicon
Abstract: We report the first complete characterization of single-qubit and two-qubit gate fidelities in silicon-based spin qubits, including cross talk and error correlations between the two qubits. To do so, we use a combination of standard randomized benchmarking and a recently introduced method called character randomized benchmarking, which allows for more reliable estimates of the two-qubit fidelity in this system, here giving a 92% fidelity estimate for the controlled-Z gate. Interestingly, with character randomized benchmarking, the two-qubit gate fidelity can be obtained by studying the additional decay induced by interleaving the two-qubit gate in a reference sequence of single-qubit gates only. This work sets the stage for further improvements in all the relevant gate fidelities in silicon spin qubits beyond the error threshold for fault-tolerant quantum computation.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: npj Quantum Information
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41534-019-0146-y
Volume: 5 Issue: First Page #: 29
Date Submitted: 6/21/19 12:00AM Date Published: 4/23/19 5:00AM
Publication Location:
Article Title: Loading a quantum-dot based “Qubyte” register
Authors: C. Volk, A. M. J. Zwerver, U. Mukhopadhyay, P. T. Eendebak, C. J. van Diepen, J. P. Dehollain, T. Hens
Keywords: quantum dot, qubit, GaAs
Abstract: Electrostatically defined quantum dot arrays offer a compelling platform for quantum computation and simulation. However, tuning up such arrays with existing techniques becomes impractical when going beyond a handful of quantum dots. Here, we present a method for systematically adding quantum dots to an array one dot at a time, in such a way that the number of electrons on previously formed dots is unaffected. The method allows individual control of the number of electrons on each of the dots, as well as of the interdot tunnel rates. We use this technique to tune up a linear array of eight GaAs quantum dots such that they are occupied by one electron each. This new method overcomes a critical bottleneck in scaling up quantum-dot based qubit registers.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 29-Aug-2019

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.99.205306
Volume: 99 Issue: 20 First Page #: 205306
Date Submitted: 6/27/19 12:00AM Date Published: 5/14/19 5:00AM
Publication Location:
Article Title: Electron spin relaxation of single phosphorus donors in metal-oxide-semiconductor nanoscale devices
Authors: Stefanie B. Tenberg, Serwan Asaad, Mateusz T. Madzik, Mark A. I. Johnson, Benjamin Joecker, Arne L
Keywords: qubits, silicon, relaxation, evanescent-wave Johnson noise
Abstract: We analyze the electron spin relaxation rate 1/T1 of individual ion-implanted 31P donors, in a large set of metal-oxide-semiconductor (MOS) silicon nanoscale devices, with the aim of identifying spin relaxation mechanisms peculiar to the environment of the spins. The measurements are conducted at low temperatures (T? 100~mK), as a function of external magnetic field B0 and donor electrochemical potential ?D. We observe a magnetic field dependence of the form 1/T1?B50 for B0?3 T, corresponding to the phonon-induced relaxation typical of donors in the bulk. However, the relaxation rate varies by up to two orders of magnitude between different devices. We attribute these differences to variations in lattice strain at the location of the donor. For B0? 3T, the relaxation rate changes to 1/T1?B0 for two devices. This is consistent with relaxation induced by evanescent-wave Johnson noise created by the metal structures fabricated above the donors. At such low fields, where T1>1s, we also obser
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Figure and references for this final report:

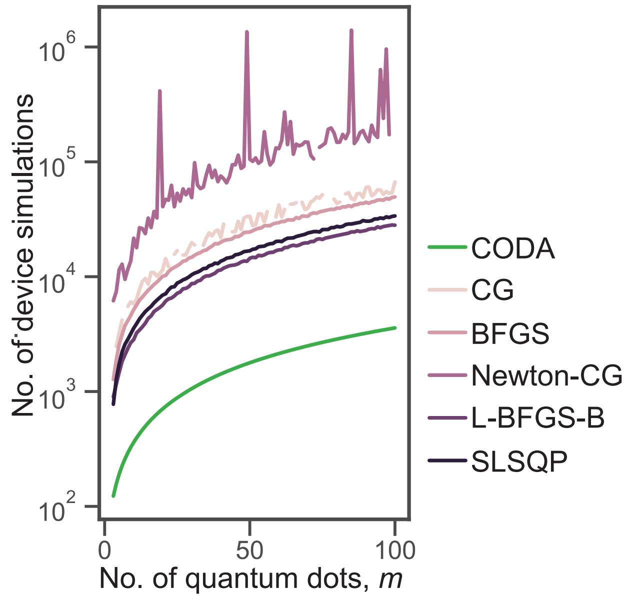

Figure 1. The number of function calls used by several nonlinear optimizers to tune a simulated device. We specifically consider the CODA protocol, the conjugate-gradient (CG) algorithm, the Broyden, Fletcher, Goldfarb, and Shanno (BFGS) algorithm, the Newton-conjugate-gradient (Newton-CG) algorithm, the limited-memory BFGS algorithm (L- BFGS-B), and the sequential-least-squares-programming (SLSQP) algorithm. CODA requires roughly an order of magnitude fewer function calls than any of the other nonlinear optimizers considered.

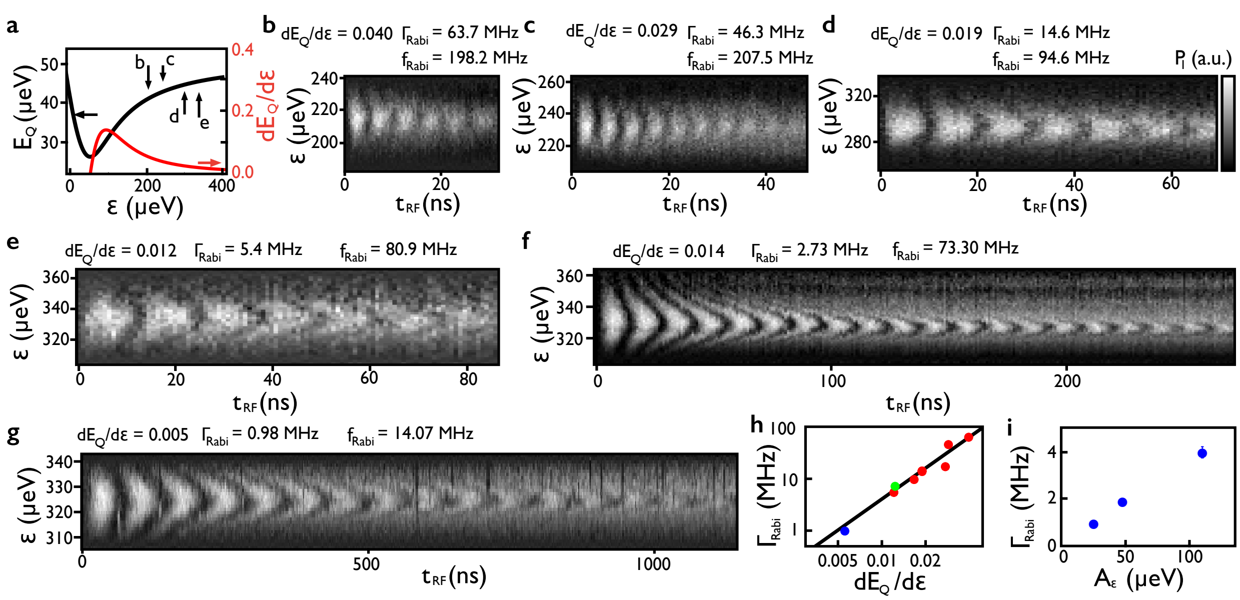

Figure 2: Examples of the role of the qubit dispersion in determining the coherence of the quantum dot hybrid qubit (QDHQ). (a) The qubit dispersion. (b-e) Rabi oscillations at the points labelled in panel (a). (f,g) Very slowly decaying Rabi oscillations of the QDHQ at two

additional tunings. (h) The Rabi decay rate as a function of the slope of the dispersion. (i) Under some conditions, the Rabi decay rate is proportional to the applied microwave power. From Ref. [6].

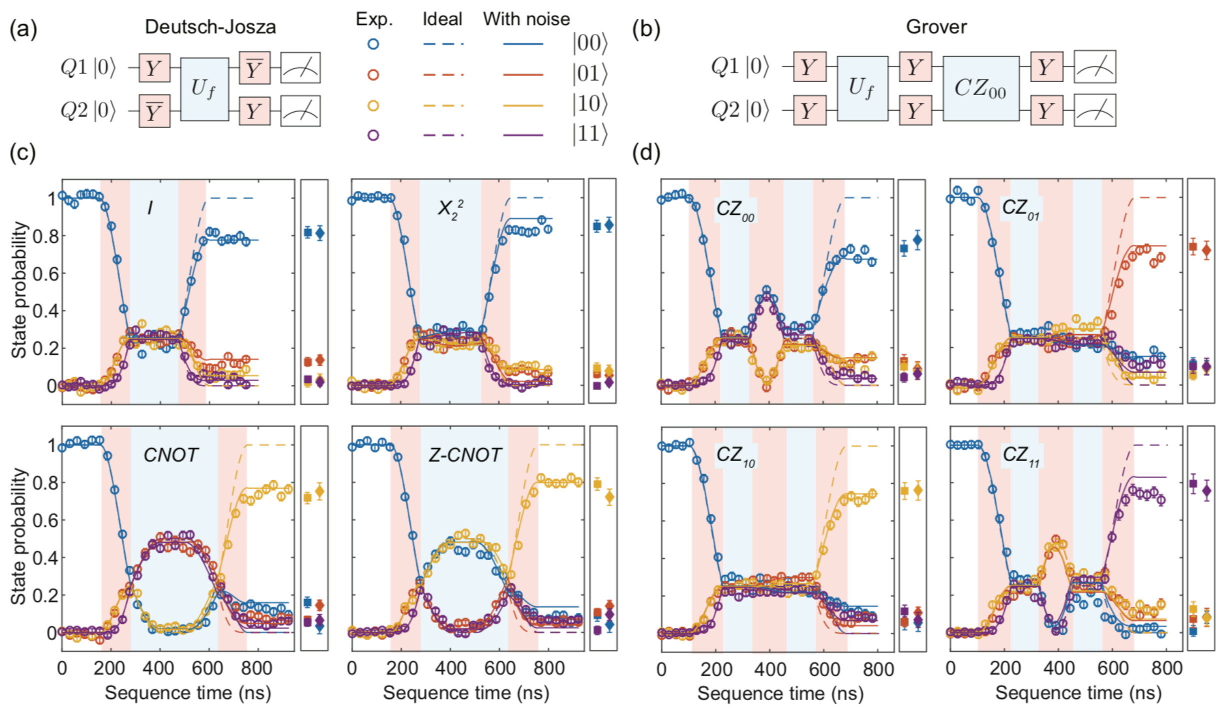

Figure 3. Two-qubit quantum algorithms in silicon. (a,b) The quantum circuits for the (a) Deutsch-Josza algorithm and (b) Grover search algorithm for two qubits. (c,d) Two-spin probabilities as a function of time throughout the sequence during the (c) Deutsch-Josza algorithm and the (d) Grover search algorithm for each of four possible functions. Each point corresponds to 4000 repetitions and has been normalized to remove readout errors. The dashed lines are the simulated ideal cases while the solid lines are the simulated results where decoherence is introduced by including quasistatic nuclear spin noise and charge noise (σ_ε = 11 μeV). For both algorithms, the square data points show the final results of the algorithms where all four functions are evaluated in the same measurement run with identical calibration. The diamonds show the result of both algorithms when using the decoupled CZ gate showing similar performance. For the Deutsch-Josza algorithm the identity is implemented as either a 200 ns wait (circle and square data points) or as $I = X_1^4 X_2^4$ (diamond data points). All error bars are 1σ from the mean. From Ref. [9].

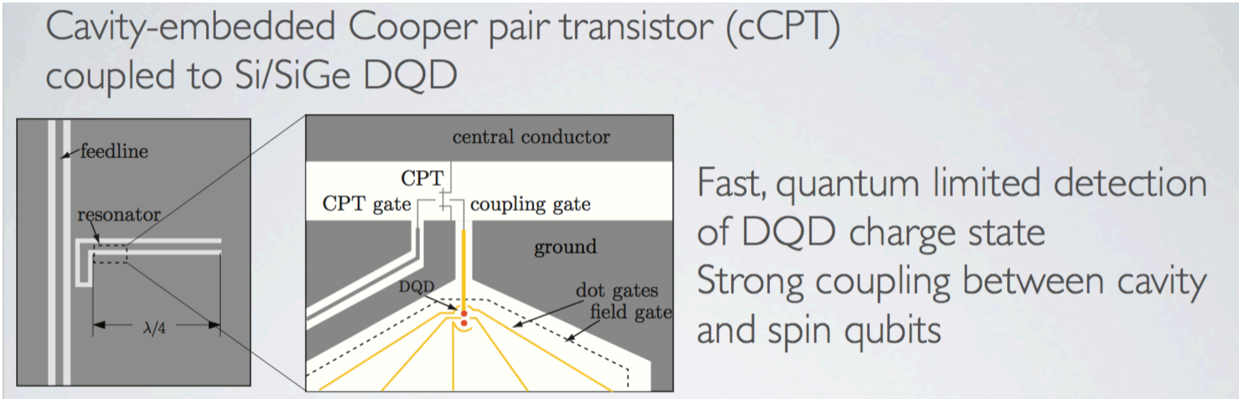

Figure 4. Schematic diagrams showing the layout of a cavity-embedded Cooper pair transistor (cCPT). Such an approach seeks to enable fast, quantum limited detection of the charge state of a double quantum dot and the achievement of strong coupling between a cavity and spin qubits.

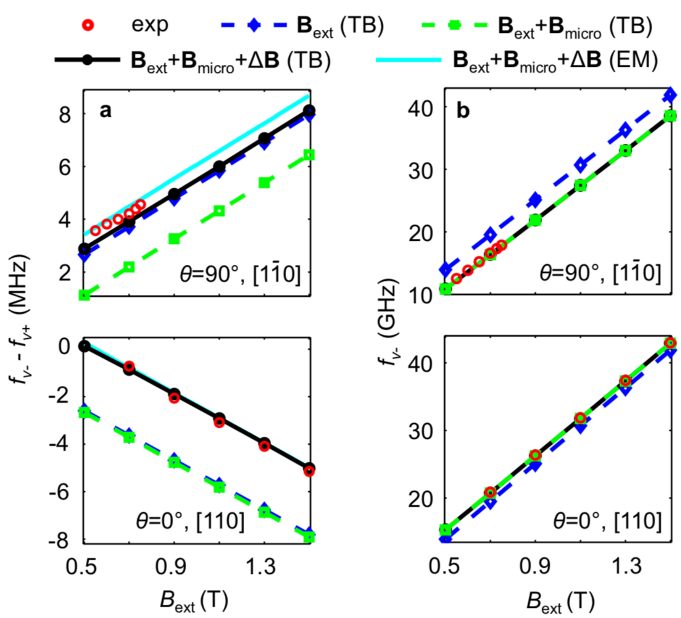

Figure 5. Measured ESR frequencies, ($f_{v\pm}$) and their differences for the two valley states as a function of the external B-field magnitude B_{ext} along two crystal directions, and comparison with theoretical calculations. a, $f_{v-} - f_{v+}$ and b, f_{v-} with B_{ext} along [110] ($\theta = 0^\circ$) (bottom panel) and [1 ̄10] ($\theta = 90^\circ$) (top panel). The calculations progressively include spin-orbit interaction (labeled 'B_{ext} (TB)'), homogeneous (labeled '$B_{ext} + B_{micro}$ (TB)'), and gradient (labeled 'B_{ext} + $B_{micro} + \Delta B$ (TB)') B-field of the micromagnet. The cyan solid lines are the effective mass calculations and the red circles are the experimental data. The dependence (slope) of $f_{v-} - f_{v+}$ on B_{ext} in (a) comes from the SOI, while the micromagnetic fields provide a shift independent of B_{ext}. From Ref. [16].

References

1. "Compressed Optimization of Device Architectures for Semiconductor Quantum Devices." A. Frees, J. K. Gamble, D. R. Ward, R. Blume-Kohout, M. A. Eriksson, M. Friesen and S. N. Coppersmith, *Physical Review Applied,* vol. 11, 024063, 2019.

2. "Adiabatic two-qubit gates in capacitively coupled quantum dot hybrid qubits." A. Frees, S. Mehl, J. K. Gamble, M. Friesen and S. N. Coppersmith, *arXiv:1812.03177.*

3. "Fast coherent manipulation of three-electron states in a double quantum dot." Zhan Shi, C. B. Simmons, D. R. Ward, J. R. Prance, X. Wu, Teck Seng Koh, John King Gamble, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson, *Nature Comm.* **5**, 3020 (2014).

4. "Quantum control and process tomography of a semiconductor quantum dot hybrid qubit." Dohun Kim, Zhan Shi, C. B. Simmons, D. R. Ward, J. R. Prance, Teck Seng Koh, John King Gamble, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson, *Nature* **511**, 70 (2014).

5. "High-fidelity resonant gating of a silicon-based quantum dot hybrid qubit." Dohun Kim, D. R. Ward, C. B. Simmons, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson, *npj Quant. Inf.* **1**, 15004 (2015).

6. "Extending the coherence of a quantum dot hybrid qubit." B. Thorgrimsson, Dohun Kim, Yuan-Chi Yang, L. W. Smith, C. B. Simmons, D. R. Ward, R. H. Foote, J. Corrigan, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson, *npj Quant. Inf.* **3**, 32 (2017).

7. "State-conditional coherent charge qubit oscillations in a Si/SiGe quadruple quantum dot." D. R. Ward, Dohun Kim, D. E. Savage, M. G. Lagally, R. H. Foote, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson, *npj Quant. Inf.* **2**, 16032 (2016).

8. "The critical role of substrate disorder in valley splitting in Si quantum wells." S. F. Neyens, R. H. Foote, B. Thorgrimsson, T. J. Knapp, T. McJunkin, L. M. K. Vandersypen, P. Amin, N. K. Thomas, J. S. Clarke, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson, *Appl. Phys. Lett.* **112**, 243107 (2018).

9. "A programmable two-qubit quantum processor in silicon." T. F. Watson, S. G. J. Philips, E. Kawakami, D. R. Ward, P. Scarlino, M. Veldhorst, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, M. A. Eriksson, and L. M. K. Vandersypen, *Nature* **555**, 633 (2018).

10. "Electrical control of a long-lived spin qubit in a Si/SiGe quantum dot." E. Kawakami, P. Scarlino, D. R. Ward, F. R. Braakman, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, M. A. Eriksson, and L. M. K. Vandersypen, *Nature Nanotech.* **9**, 666 (2014).

11. "Second Harmonic Coherent Driving of a Spin Qubit in a Si/SiGe Quantum Dot." P. Scarlino, E. Kawakami, D. R. Ward, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, M. A. Eriksson, and L. M. K. Vandersypen, *Phys. Rev. Lett.* **115**, 106802 (2015).

12. "Gate fidelity and coherence of an electron spin in an Si/SiGe quantum dot with micromagnet." E. Kawakami, T. Jullien, P. Scarlino, D. R. Ward, D. E. Savage, M. G. Lagally, V. V. Dobrovitski, Mark Friesen, S. N. Coppersmith, M. A. Eriksson, and L. M. K. Vandersypen, *Proc. Natl. Acad. Sci.* **113**, 11738 (2016).

13. "Dressed photon-orbital states in a quantum dot: Inter-valley spin resonance." P. Scarlino, E. Kawakami, T. Jullien, D. R. Ward, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, M. A. Eriksson, and L. M. K. Vandersypen, *Phys. Rev. B* **95**, 165429 (2017).

[14] "Benchmarking Gate Fidelities in a Si/SiGe Two-Qubit Device." X. Xue, T. F. Watson, J. Helsen, D. R. Ward, D. E. Savage, M. G. Lagally, S. N. Coppersmith, M. A. Eriksson, S. Wehner, and L. M. K. Vandersypen, *Phys. Rev. X* **9**, 021011 (2019).

[15] "Signatures of the valley Kondo effect in Si/SiGe quantum dots," Mingyun Yuan, R. Joynt, Zhen Yang, Chunyang Tang, D. E. Savage, M. G. Lagally, M. A. Eriksson, and A. J. Rimberg, Phys. Rev. B **90**, 035302 (2014).

[16] "Valley dependent anisotropic spin splitting in silicon quantum dots." Rifat Ferdous, E. Kawakami, P. Scarlino, Michal P. Nowak, D. R. Ward, D. E. Savage, M. G. Lagally, S. N. Coppersmith, Mark Friesen, M. A. Eriksson, L. M. K. Vandersypen, and Rajib Rahman, *npj Quant. Inf.* **4**, 26 (2018).