ABSTRACT BOOK

SiQEW 2025

Silicon Quantum Electronics Workshop 2025

HRL | LABORATORIES

UCLA

Semiconductor Spin Qubits: Where Do We Go From Here?

Thaddeus Ladd

The silicon spin qubit community has reached a remarkable progress point, where many of the critical proofs of concept, across physics, fidelity, and scaling, have been reached, albeit by different groups with different devices at different times. But of course, the spin qubit technology continues to face challenges. The Silicon Quantum Electronics Workshop (SiQEW) has historically addressed a primary class of challenges: namely our many open technology problems, including yield and pitch difficulties in fab across all spin qubit types from donors to dots, management of valley splitting in SiGe epitaxy, adaptation of atomic-scale disorder in MOS or hole-based systems, understanding and mitigation of charge noise, and numerous issues with scalable control and read-out electronics. A second class of challenges is also present, however, in perception and communication. Although most SiQEW constituents carry the genuine belief that only some semiconductor approach can practically reach the tremendous challenge of utility-scale, fault-tolerant quantum computing, the vast majority of external attention is focused on non-semiconductor qubits. Both classes of challenges point to a similar response: the SiQEW community should promote and coordinate constructive cooperation, in both technical problem-solving and external communication, as much our various institutions allow. In that light, I will summarize two directions HRL is taking in the community cooperation direction. One is foundry-availability of performant Single-Layer Etch-Defined Gate Electrode (SLEDGE) devices for Loss-DiVincenzo, Exchange-Only, and potentially other qubit types. The other is the development of open-source software for spin-qubit control using inexpensive off-the-shelf RF SoC components, with the spin Quantum Instrumentation Control Kit (spinQICK). I aim to contextualize the many fine advances we can expect to see in the 2025 SiQEW, and to help frame the critical question for the community: when and how do we prove to ourselves and to others that semiconductor spin qubits genuinely exhibit the technology advantage they have long promised?

Session: Monday 9:00

EUV SiMOS spin qubits fabricated in a 300 mm pilot line

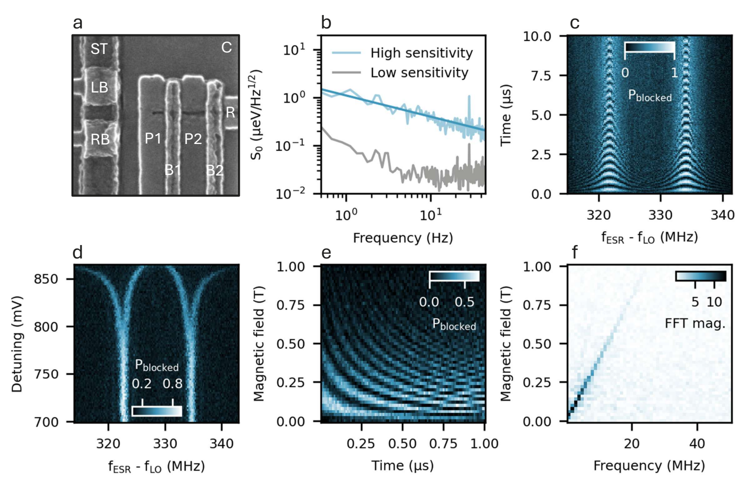
Thomas Van Caekenberghe, Bart Raes, Sofie Beyne, Clement Godfrin, Imri Fattal, Arne Loenders, Vukan Levajac, Gulzat Jialiele, Stefan Kubicek, Sugandha Sharma, Sylvain Baudot, Yannick Hermans, Yosuke Shimura, Roger Loo, Massimo Mongillo, Danny Wan and Kristiaan De Greve

We report on the initial characterization of SiMOS spin qubits fabricated in imec's 300 mm pilot line using extreme ultraviolet (EUV) lithography for the critical device layers. All-optical lithography enables scalable, high-throughput manufacturing, marking a key step toward industrially viable quantum processors. In this work, we perform a preliminary investigation of the performance of our EUV SiMOS qubits. The two-qubit device shown in Figure 1a is used as a test vehicle. We investigate the presence of low-energy excited valley states and whether both single- and two-qubit operation can be achieved with our devices. Excited valley states are probed by measuring the magnetic field dependence of coherent singlet-triplet oscillations (Figure 1e,f) at the single-qubit operation point. We measure the exchange interaction through exchange oscillations and the splitting of the ESR spectrum (Figure 1d) to determine the range in gate space where single- and two-qubit operation is possible. Our preliminary results demonstrate the feasibility of using EUV lithography for scalable quantum device fabrication.

Figure 1: Collection of characterization measurements on a two-qubit device. a. SEM image of the device showing a double quantum dot and SET charge sensor. b. Charge noise measurement. c. Single-qubit Rabi chevrons. d. ESR spectrum as a function of detuning. e, f. Singlet-triplet oscillations and corresponding FFT spectrum indicating no excited valley states up to 115μeV.

work in progress

Session: Monday 9:20



Design of High-Fidelity Spin Qubit Arrays With the Semiconductor Ecosystem at Intel

Fahd A. Mohiyaddin and Intel Quantum Computing Group

A full stack error corrected quantum processor with high-fidelity spin qubits requires expertise from various domains of semiconductor technology. Here, we employ Intel's advanced semiconductor ecosystem for the demonstration of high-fidelity Exchange Only (EO) spin-qubits in isotopically purified 50 ppm Si-29 Si/SiGe heterostructures. We will present our latest experimental results in cryogenic characterization of EO qubits with 1Q and 2Q fidelities exceeding 99.9% and 99% respectively in 1D dot arrays, and utilize multi-scale simulations to corroborate experimental results. We further demonstrate the realization of various EO qubit configurations on small scale 2D arrays with average 1Q fidelities exceeding 99.5%. We then use a tight feedback loop consisting of qubit device modeling, integration and cryogenic characterization - along with control, packaging and software – to codesign various aspects of full stack qubit system capable of demonstrating quantum error correction. Finally, we propose specifications on the devices, control and packaging using multi-physics models and further quantify the resultant performance of logical qubits encoded with extensible 2D qubit arrays.

work in progress

Session: Monday 9:40

Control of a bilinear 18-dot germanium spin qubit array

Xin Zhang, Achilleas Bardakas, Daniël Bouman, Alice Cuzzocrea, Jurgen J. Dijkema, David van Driel, Davide Girardi, Lucas E.A. Stehouwer, Giordano Scappucci, Anne-Marije J. Zwerver and Nico W. Hendrickx

Spin qubits in quantum dots are promising candidates for building practical quantum computers, as their small size enables dense integration and interconnection on a chip. Their compatibility with advanced semiconductor fabrication technologies further adds to their advantages as a quantum computing platform [1]. However, scaling up the number of spin qubits while maintaining high connectivity requires the fabrication of extensive two-dimensional qubit arrays with high device yield and the ability to characterize such arrays at scale.

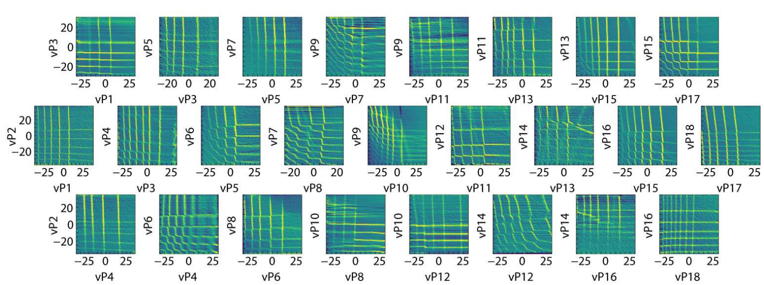
Recently, quantum processors based on spin qubits in strained germanium quantum wells have been scaled to 10 quantum dots in a 3-4-3 configuration [3], showcasing the scalability of this material platform. Devices on this platform have demonstrated fast two-qubit gates and high-fidelity control at both the single- and two-qubit level [2,3]. Beyond their performance, germanium quantum wells ease lithographic constraints, offer efficient built-in control mechanisms, and are fully compatible with semiconductor foundry processes [1,2,3].

Here, we present recent progress towards scaling semiconductor spin qubits within this platform. Specifically, we designed an extensible 2xN qubit architecture based on the replication of 2x3-qubit unit cells, where charge-sensors are integrated along one side of each unit cell; this approach allowed us to fabricate QPU's with a 2x9 array of quantum dots (see figure). Throughout this array, we demonstrate reliable qubit initialization, readout, and coherent qubit control. In addition, we present advances in the systematic characterisation of our multi-qubit devices, with a particular focus on the reproducibility of key quantum dot and qubit metrics, such as threshold voltages, charge noise measurements and gate fidelities. These improvements enable us to increase the quantum processor size, while maintaining high robustness and fabrication yield.

[1] Scappucci, G., et al., Nature Reviews Materials 6 (2021)
[2] Hendrickx, N.W. et al., Nature 591 (2021)
[3] Wang, C-A et al., Science 385 (2024)

work in progress

Session: Monday 10:00



An 11-qubit atom processor in silicon

Hermann Edlbauer, Junliang Wang Wang, A M Saffat-Ee Huq, Ian Thorvaldson, Michael T. Jones, Saiful Haque Misha, William J. Pappas, Christian M. Moehle, Yu-Ling Hsueh, Henric Bornemann, Sam Gorman, Yousun Chung, Joris G. Keizer, Ludwik Kranz and Michelle Y. Simmons

Phosphorus atoms in silicon represent a promising platform for quantum computing as their nuclear spins exhibit coherence times over seconds with high-fidelity readout and single-qubit control. By placing multiple phosphorus atoms within a radius of a few nanometers, they couple via the hyperfine interaction to a single, shared electron. Such a nuclear spin register enables high-fidelity multi-qubit control and the execution of small-scale quantum algorithms [1]. An important requirement for scaling up is the ability to extend high-fidelity entanglement non-locally across multiple spin registers. Here, we address this challenge with an 11-qubit atom processor composed of two multi-nuclear spin registers which are linked via electron exchange interaction [2]. Through the advancement of calibration and control protocols, we achieve single- and multi-qubit gates with all fidelities ranging from 99.1% to 99.99%. By entangling all combinations of local and non-local nuclear-spin pairs, we map out the processor's performance and achieve state-of-the-art Bell-state fidelities of up to 99%. We then generate Greenberger-Horne-Zeilinger (GHZ) states with an increasing number of qubits and show entanglement of up to 8 nuclear spins. By establishing high-fidelity operation across interconnected nuclear-spin registers, we realise a key milestone towards fault-tolerant quantum computation with atom processors.

References

[1] I. Thorvaldson et al., Nature Nanotechnology 20, 472-477 (2025)

[2] H. Edlbauer et al., arXiv:2506.03567 (2025)

H. Edlbauer et al., arXiv:2506.03567 (2025)

Session: Monday 10:20

Circuit Quantum Electrodynamics with Atomic Precision Qubits

Ashutosh Mukund Bhudia, Andrey Timofeev, Stephan Plugge, Joris Keizer, Yousun Chung, Samuel K. Gorman, Benoit Voisin, Michelle Y. Simmons and Sven Rogge

Multi-nuclear atom qubit registers with record two-qubit operations and multi-qubit entanglement fidelities have been demonstrated in exchange-based processors [1]. Embedding these atomic qubits in quantum electrodynamics circuits further enables long-range atomic qubit coupling. Here, we report on the demonstration of charge and spin-photon coupling in an atomic quantum device comprising a high-impedance resonator.

We first discuss the development of high-quality factor superconducting microwave resonators based on high kinetic inductance superconducting films. We achieve Qi > 40,000 for a 1 kΩ-impedance NbTiN resonator in the single-photon regime. We design a novel type of LC filter geometry based on an inductive link between the capacitor and the ground plane, achieving both high attenuation around 5 GHz to prevent microwave capacitive leakage and high cut-off above 1 GHz to maintain qubit control capability [2]. We use this superconducting circuitry on an atomic qubit device, performing spectroscopic measurements of the electron-resonator system in the dispersive regime. Measuring the resonator dispersive shift and the charge qubit dispersion across the qubit transition translates to a charge-photon coupling of 72MHz. Magneto-spectroscopy further reveals resonator-driven singlet-triplet transitions, mediated by the hyperfine interaction intrinsic to these atom qubits. These results pave the way towards resonator-mediated nuclear spin entanglement in atomic devices.

[1] H. Edlbauer, J. Wang et al., arxiv:2506.03567

[2] A. Bhudia et al., in preparation

A. Bhudia et al., in preparation

Session: Monday 11:10

Charge Sensing in Si:P Dopant-based quantum dot arrays using radio frequency reflectometry

Fan Fei, Brian Courts, Mark-yves Gaunin, Pradeep Namboodiri, FNU Utsav, Vijith Kamalon Pulikodan, Joshua Pomeroy, Jonathan Wyrick and Richard Silver

Artificial lattices fabricated using dopant-based quantum dot arrays in silicon are a promising platform to realize the analog quantum simulation of a Fermi-Hubbard model. Difficult to calculate numerically, charge and spin correlation are essential fundamental information in a strongly correlated system. To compare and correlate experimental quantum simulations with theory models, it is crucial to provide an accurate mapping of the electron configuration within the artificial lattice. We have developed and optimized an RF reflectometry circuit that provides improved charge sensitivity and significantly higher measurement bandwidth for measuring transient dynamics.

We examine the charge occupation of a few-dopant 3×3 quantum dot array operating in the weak tunnel coupling regime. Charge rearrangements within the array appear as additional quantum capacitances, leading to measurable phase shifts in the reflected RF signal. This approach enables us to pinpoint the exact addition site for each electron and extract tunnel coupling constants between adjacent sites from interdot charge transition signals. We also assess how input RF power influences the electron temperature, allowing us to determine the optimal power for spin measurements. Under a finite magnetic field, we observe Pauli spin blockade and measure the singlet-triplet exchange energy. These results underscore the advantages of RF reflectometry for probing charge and spin configurations in two-dimensional multi-dot quantum systems. Finally, we discuss improved fabrication of atomically precise quantum dot arrays using STM automation and corresponding RF measurement schemes suited to medium/large scale quantum simulators.

Session: Monday 11:30

Single donor spin readout in silicon using commercial quantum dot devices

Pratheek Malol, Antti Kanniainen, Nikolai Yurttagul, Markku Kainlauri, Janne Lehtinen and Juha Muhonen

Donor spins in silicon, with their long coherence times and high control fidelities [1], are promising qubit implementations for scalable quantum computers. We investigate a novel spin readout method for donor spins, based on a resonant, spin-dependent bound exciton transition followed by charge detection. Under an applied magnetic field, the bound exciton transition frequencies are spin-selective [2], and as the exciton state relaxes via Auger recombination, this leads to a spin-dependent ionization of the donor. The ionization can then be detected via charge or conductivity detection, giving a spin readout method.

While this transition has been observed in bulk silicon by analyzing conductivity changes [3], we advance this approach towards charge detection and single-spin sensitivity by integrating donor qubits with on-chip silicon quantum dot detectors developed by Semiqon Oy. In this work, we present our characterization studies of Semiqon's quantum dot devices. The devices, fabricated on silicon-on-insulator (SOI) platforms and equipped with on-chip multiplexers, enable control over multiple quantum dot devices on a single chip, making them well-suited for large-scale quantum systems. Our work represents a step toward an integrated platform that combines donor spins, silicon quantum dots, and photonics, unlocking new pathways in quantum sensing.

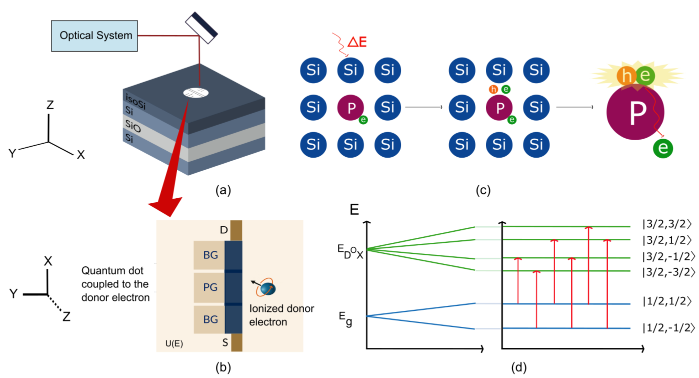
[1] Muhonen, J., Dehollain, J., Laucht, A. et al. Nature Nanotech 9, 986-991 (2014).

[2] Lo, C., Urdampilleta, M., Ross, P. et al. Nature Mater 14, 490-494 (2015).

[3] Loippo, T., Kanniainen, A., & Muhonen, J. T. Physical Review Materials 7, 016202, (2023).

Work in progress

Session: Monday 11:50



Schematic of the (a) measurement setup, (b) device geometry, (c) exciton formation and (d) energy level diagram showing the possible transitions between donor electron and hole states

How to make donor qubit arrays and highly enriched silicon-28 with ion implantation

David Jamieson

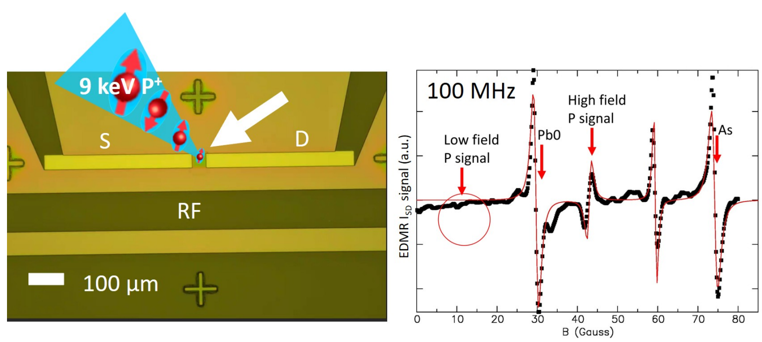
Qubits in a large-scale quantum computer using an architecture based on ion implanted dopants in silicon require a low background spin bath to prolong coherent quantum states programmed into the qubits. We have developed a method employing high fluence 28-Si ion irradiation of natural silicon to deplete the problematic nuclear spin I=½ 29-Si isotope from 47,000 parts per million (ppm) to around 2 ppm. At this extreme depletion there is, on average, less than one 29-Si atom within the Bohr radius of the donor electron qubit. We have demonstrated 2.3 ppm residual 29-Si by employing focused 45 keV 28-Si ion beams with a fluence of 1x10E19/cm2 [1]. We have also found by using a broad negative ion beam in a conventional implanter that raising the beam energy can achieve the same depletion with much less fluence [2]. We have built Electrically Detected Magnetic Resonance devices to measure the donor spin resonances of ion implanted two million donor ensembles (see figure) and have demonstrated clock transitions that are insensitive to magnetic noise in 75-As [3]. The next step is to repeat this experiment highly enriched silicon with the 123-Sb donor in which highly complex robust logical quantum states can be encoded on the I=7/2 nuclear spin donor states. Our technique to direct the 123-Sb donor qubits into ordered arrays addresses the problem of construction of a large-scale million qubit array as the first stage of the construction process.

The contributions of Experimental Condensed Matter Physics group at the University of Melbourne, the Photon Science Institute of the University of Manchester, and support from Australian and UK funding agencies are gratefully acknowledged.

[1] R. Acharya, et al., Comm Mat 2024.
[2] S.Q. Lim, et al., https://arxiv.org/abs/2504.03332
[3] R. Acharya, et al., 2025 in preparation, to be submitted to Phys. Rev. Mat

Scalable Atomic Arrays for Spin-Based Quantum Computers in Silicon, AM Jakob, SG Robson, HR Firgau, V Mourik, V Schmitt, D Holmes, M Posselt, ELH Mayes, D Spemann, JC Mccallum, A Morello, DN Jamieson, Advanced Materials, 36, (2024)

Session: Monday 12:10



Exchange, correlation, electron density, and spin configurations in triangular and hexagonal phosphorus arrays in silicon.

Maicol Ochoa, Keyi Liu, Piotr Rózanski, Michal Zielinski and Garnett W. Bryant

Dopant-based silicon devices are ideal materials for realizing modern quantum technologies, such as quantum simulators of the Fermi-Hubbard model [1] and quantum materials [2]. The near-atomic precision in impurity placement in silicon enables the engineering and control of device properties, based on the type, number, and geometric distribution of impurities within the silicon lattice. Numerical studies of the electronic structure of silicon devices, combining atomistic tight-binding simulations and many-body techniques, help rationalize this connection. In this form, one obtains single-electron tunneling energies in phosphorus arrays[3] needed to validate quantum simulations, as well as charging and binding energies in multielectron states in phosphorus dimers[4] to interpret charge stability diagrams, and as a function of impurity-impurity separation. The cost of the calculations increases significantly with device size, the number of impurities, and the number of bound electrons, generally precluding studies in large systems. Recently, we introduced the atomistic tight-binding Hartree-Fock protocol[4] (TB-HF) as a feasible alternative that provides accurate results in multielectron systems. While TB-HF calculations efficiently capture the effects of exchange and Coulomb repulsion on the electron density distribution, this method does not account for electron correlation. In this work, we develop a tight-binding Møller-Plesset protocol for impurity-based silicon devices that incorporates the effect of electron correlation perturbatively. Then, we study the ground-state electron and spin distributions for one-to-four-electron states for triangular P-arrays and in one-to-seven-electron states in hexagonal P-arrays. By comparing with the TB-HF predictions, we can identify the role of weak electron correlation in determining the array ground states. We also analyze the occurrence of exotic spin states and magnetic frustration in triangular P-arrays and their dependence on the geometry of the P-array and the dopant separation to identify interesting dopant arrays to fabricate and study.

[1] Nature Communications, 13(1),6824.(2022)
[2] Nature, 606(7915),694-699.(2022)
[3] PRB, 109(20),205412.(2024)
[4] arXiv:2503.02843.

work in progress

Session: Monday 14:00

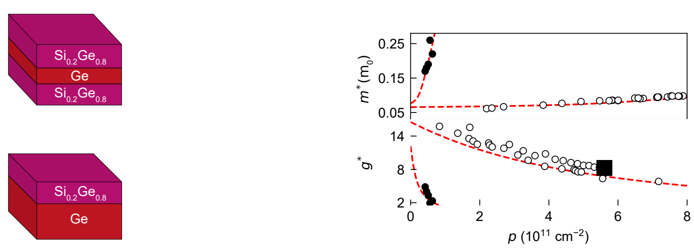
Buried unstrained germanium channels: a lattice-matched platform for quantum technology

Davide Costa, Patrick Del Vecchio, Karina Hudson, Lucas E. A. Stehouwer, Alberto Tosato, Davide Degli Esposti, Mario Lodari, Stefano Bosco and Giordano Scappucci

Ge and Si strained quantum wells have enabled the most advanced spin-qubit quantum processors, but they are deposited on defective, metamorphic SiGe substrates, which may impact device performance and scalability. We present an alternative platform based on a heterojunction between unstrained Ge and a strained SiGe barrier, which is lattice-matched to a Ge substrate. In a structure with a 52 nm-thick strained SiGe barrier, we demonstrate a low-disorder two-dimensional hole gas with a high mobility of 1.33 × 105 cm2/Vs and a low percolation density of 1.4(1) × 1010 cm-2. Quantum transport measurements reveal a strong density-dependent in-plane effective mass and out-of-plane g-factor, consistent with heavy-hole–light-hole mixing predicted by theory (Fig.1a). To further probe spin properties, we use quantum point contacts to investigate one-dimensional transport. From these measurements, we extract both out-of-plane and in-plane g-factors, confirming the reduced anisotropy compared to strained Ge quantum wells (Fig.1b). The combination of high mobility, robust spin-orbit interaction, compatibility with isotopically purified Ge, and potential to host superconducting pairing correlations makes this platform promising for scalable spin qubits and hybrid quantum systems.

https://arxiv.org/abs/2506.04724

Session: Monday 14:20



Reducing orthotropic strain fluctuations in quantum dot devices by gate-layer stacking

Collin C. Frink, Tali Oh, Emily S. Joseph, Merritt Losert, E. R. MacQuarrie, Benjamin D. Woods, Mark Eriksson and Mark Friesen

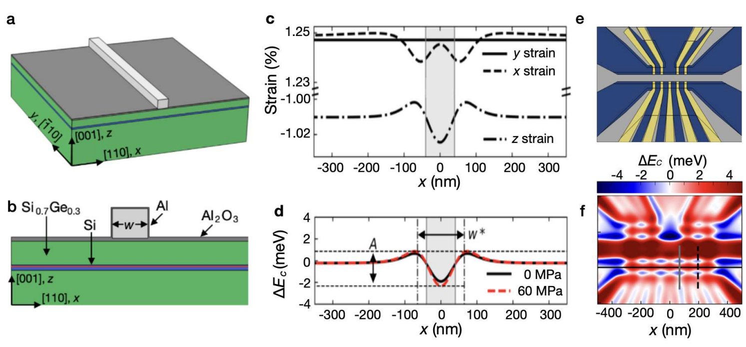
Strain-induced fluctuations in the potential energy landscape interfere with the electrostatic confinement of silicon quantum dots. These fluctuations may be of the order of meV and can therefore cause the formation of unintentional quantum dots or affect exchange interactions between neighboring qubits. More generally, the interplay between material properties, oxide thickness, and gate-stack design can induce counterintuitive strain profiles. For example, employing a thicker oxide layer between tightly stacked metal gates can amplify short-range potential fluctuations. Understanding and (ideally) suppressing such behaviors is therefore an important step towards scalability.

In this work, we present simulations showing that these effects can be suppressed through careful engineering. We study strain-induced variations of the potential energy in Si/SiGe heterostructures arising from (i) lattice mismatch, (ii) materials-dependent thermal contraction, and (iii) depositional stress in the metal gates. We simulate a range of gate geometries in silicon/silicon germanium heterostructures, ranging from simple to realistically complicated, and demonstrate that it is possible to suppress strain-induced energy fluctuations by making use of conformal overlapping gates and thin oxide layers. As an example of a simple geometry, we simulate a single-wire gate structure [Fig. 1(a–b)], with corresponding strain profiles [Fig. 1(c)] and conduction band modulations (ΔEc,) under various depositional stress conditions [Fig. 1(d)]. An example of a realistically complicated model is the quadruple-quantum-dot architecture with stacked Al gates [Fig. 1(e–f)].

We further note that isotropic elasticity is assumed in most simulations of Si-based devices. However, it is known that more-accurate strain models are orthotropic rather than isotropic. In this work, we therefore model the Si/SiGe heterostructure using an orthotropic elastic tensor. Comparing our results to conventional, isotropic treatments, we observe significant differences (≥10%) in the resulting strain fields of quantum dot devices. These results indicate that more-accurate simulations should incorporate the correct orthotropic strain model.

Frink, Collin C. D. , Woods, Benjamin D., Losert, Merritt P., et al. (2023). Reducing strain fluctuations in quantum dot devices by gate-layer stacking.

Session: Monday 14:40



How to achieve the shortest-period ^{72}Ge concentration oscillations in strained ^{28}Si quantum wells

Kevin-Peter Gradwohl, Ivo Rahlff, Maximilian Oezkent, Chen-Hsun Lu, Martin Albrecht, Carsten Richter and Jens Martin

While nuclear spin-free SiGe heterostructures have emerged as a rapidly advancing and promising material platform for electron spin quantum computing, reliably scaling the number of qubits requires a technology that can achieve large and tunable valley splitting, which is largely a material design challenge.

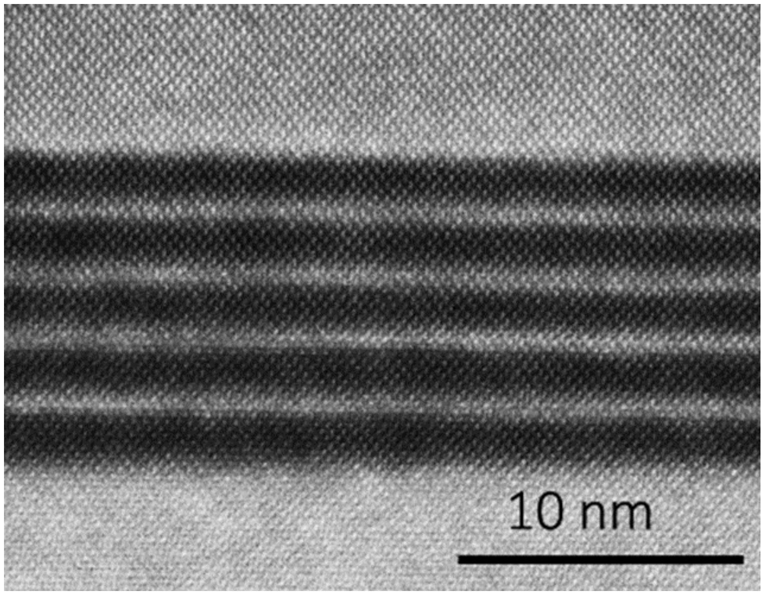
Approaches to control the valley splitting that rely exclusively on atomically flat and sharp interfaces have proven difficult, particularly on a wafer scale. A recent proposal involves short-period Ge oscillations in the Si quantum well layer, termed Wiggle Wells. Hereby, the Ge oscillations are designed with a period length at which their wave vector couples the conduction-band valley either within or between Brillouin zones, corresponding to 1.8 and 0.32 nm, respectively. By realizing low Ge concentration modulations, the adverse effects of Ge in the quantum well can be limited while still achieving high valley splitting.

This work investigates the associated epitaxial challenges for realizing sharp and substantial short-period Ge-profiles in quantum wells are explored by nuclear spin-free 28Si and 72Ge solid-source molecular beam epitaxy. In particular, approaches to suppress Ge segregation by growth temperature, while maintaining high-quality epitaxial material are studied, as shown in the transmission electron microscopy image shown in Fig. 1 (Reproduced from [1], © 2025 American Chemical Society). Furthermore, the challenges of structural characterization of Wiggle Wells by electron microscopy, X-ray reflectivity, and X-ray diffraction measurements are demonstrated.

The aim of this work is to demonstrate the experimental limits of material growth and lab-based materials characterization for Ge oscillations with shortest-period below 1.8 nm and close to 0.32 nm with various low Ge concentration amplitudes. Finally, we elucidate on the prospects of close to monolayer compositional control in molecular beam epitaxy.

[1] Gradwohl, Kevin-P., et al. "Enhanced Nanoscale Ge Concentration Oscillations in Si/SiGe Quantum Well through Controlled Segregation." Nano Letters 25.11 (2025): 4204-4210.

Session: Monday 15:00


10 nm

Selective Control of Two-Layer Vertically Stacked Silicon Quantum Dots Using Barrier Gates

Daiki Futagi, Junoh Kim, Tomoko Mizutani, Takuya Saraya, Hiroshi Oka, Takahiro Mori, Masaharu Kobayashi and Toshiro Hiramoto

Silicon quantum dot (Si QD) is a promising platform for quantum computing where high-density qubits are strongly required. We have proposed a three-dimensional (3D) qubit architecture that reduces footprint by vertically stacking QDs, instead of 2D QD arrays. Previously, we successfully fabricated a dual-layer QD device, observed Coulomb oscillations from both top and bottom QDs, and demonstrated independent control of bottom QD by substrate voltage (VSUB) [1,2]. In this work, we demonstrate the selective control of top QD, enabling independent operation of both QDs.

A dual-Si-channel device (Fig. a) was measured at 4K, where each layer contains a single QD. These two QDs share source-drain electrodes, and their currents are combined. In this measurement, top gate voltage (VTG) and VBG were swept while VSUB was kept fixed. Clear Coulomb oscillations were observed (Fig. b), confirming QDs formation in each layer. Coulomb peak positions with varied VBG were extracted (Fig. c), and it is found that the peaks are separated into two groups based on their VBG sensitivities: top QD shows higher sensitivity (steep slope) while the bottom QD shows lower sensitivity (gentle slope). The sensitivity ratio is approximately 1.5 and the difference is attributed to the distinct coupling capacitance difference between each QD and the barrier gates.

These results demonstrate that selective control of top QD is also available utilizing VBG, thereby enabling more flexible control of both QDs through the combined use of VSUB and VBG. This is an important step toward realizing high-density 3D qubit architecture.

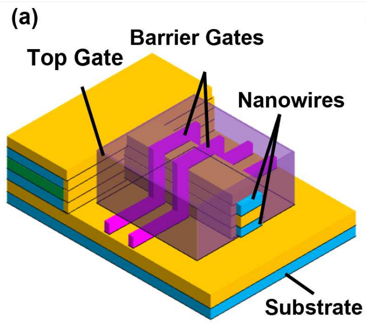
[1] J. Kim et al., International Conference on Solid State Devices and Materials (SSDM), Sep. 2025. (to be presented)

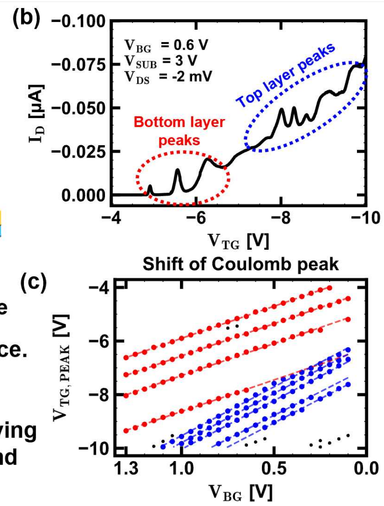
[2] D. Futagi et al., Silicon Nanoelectronics Workshop (SNW), Jun. 2025.

Supported by JST SPRING (JPMJSP2108) and JSPS KAKENHI (19H00754).

work in progress

Session: Monday 15:20





(a) Schematic of proposed device.
(b) Coulomb oscillations as a function of the V_{TG}.
(c) Coulomb peak shift with varying V_{BG}. Mean Slopes: 2.387 (red) and 3.610 (blue).

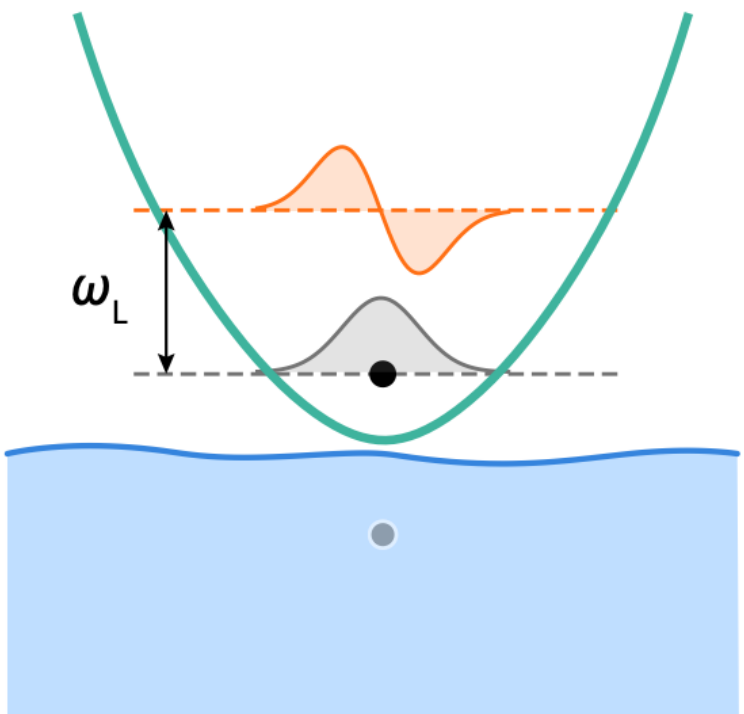
Towards engineering of qubits with electrons on helium

Elena O. Glen, Gerwin Koolstra, Niyaz R. Beysengulov, Heejun Byeon, Kyle E. Castoria, Michael Sammon, Stephen A. Lyon, Johannes Pollanen and David G. Rees

Electrons trapped above the surface of liquid helium are a promising qubit platform due to their exceptionally high mobility, compatibility with CMOS-based scaling, and the long predicted coherence times of single spins in vacuum. Here we report the control and readout of single electrons on helium, using silicon-based devices that integrate helium microchannels, dc control lines, and planar superconducting resonators which couple to the motion of the trapped electron. We demonstrate precision control of both the electron trapping and the orbital state tuning, in excellent agreement with finite-element modeling of the device. Our ability to address device fabrication challenges, reduce decoherence sources, and enhance the electron-resonator coupling pave the way for novel spin-based quantum computers.

work in progress

Session: Tuesday 9:00



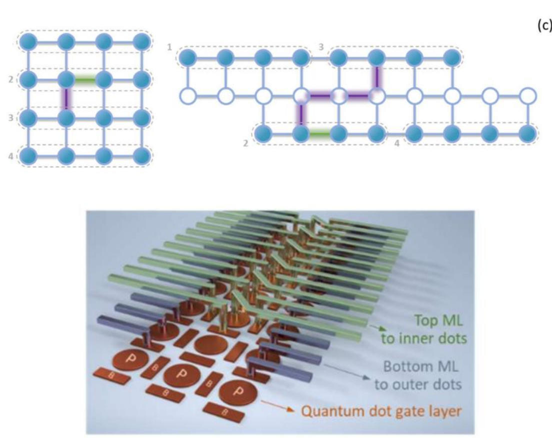
Trilinear spin qubit array – an architecture for scalable and fault-tolerant quantum computation

Vukan Levajac, Quinten Eggerickx, Ruoyu Li, Clement Godfrin, George Simion, Stefan Kubicek, Sofie Beyne, Bart Raes, Wojciech De Roeck, Massimo Mongillo, Danny Wan and Kristiaan De Greve

Spin qubits in gate-defined semiconducting quantum dots are a competitive platform for solid state quantum information processing due to their long coherence times, small size and compatibility with 300mm-wafer processing. So far, quantum processors have been demonstrated in minimal two-dimensional spin qubit arrays and single linear arrays with qubit numbers of the order of ten. Further scaling is complicated by the challenges of scalable interconnect schemes and selective qubit control and read-out in dense large two-dimensional arrays. This may explain why implementations of error correction protocols have not been reported so far - as these would necessitate two-dimensional qubit arrays of at least intermediate sizes. Here, we present a linear spin qubit architecture to which an arbitrarily large two-dimensional qubit array can be mapped to obtain an effective two-dimensional connectivity while keeping advantageous scaling properties of linear architectures. Our architecture consists of three parallel linear quantum dot arrays, where the two outer arrays host the qubits and the middle array is used for spin shuttling through which the effective two-dimensional connectivity is realized (Figure). Importantly, spin shuttling allows also for qubit interactions beyond the nearest neighbours, which makes the proposed architecture relevant for error correcting protocols with both local and non-local qubit interactions. Therefore, we simulate some representative error correcting protocols in our trilinear spin qubit array while considering the realistic qubit parameters from recent experimental demonstrations. We particularly examine the impact of spin shuttling and its operation overhead on the fault-tolerant performance of the introduced quantum processor architecture.

This work is combining the preprint arXiv:2501.17814 and other work which is in progress (QEC aspects and simulations)

Session: Tuesday 9:20



Conveyor mode charge shuttling in a T-junction in Si/SiGe

Max Beer, Ran Xue, Lennart Deda, Stefan Trellenkamp, Jhih-Sian Tu, Hendrik Bluhm and Lars R. Schreiber

Conveyor mode shuttling in Si/SiGe enables precise control over the position of shuttled electrons in a moving potential defined by four sinusoidal driving voltages applied to four periodically connected gate sets, independent of distance traversed. Recently, long distance charge shuttling [1], spin coherent shuttling [2, 3] and high-resolution valley splitting measurements [4] have been demonstrated in this platform. These features demonstrate conveyor mode shuttling as the promising basis of a future quantum computing architecture [5]. To enhance qubit connectivity for quantum error correction, realizing two-dimensional qubit matrices is imperative. These architectures require routing of qubits across junctions - a functional element, the implementation of which remains challenging for other qubit platforms [6].

In this talk we present our progress on T-junction devices. We connect three 5 µm long, orthogonal and independent conveyor mode shuttle channels, defining 51 quantum dots. We demonstrate electron transfer between two orthogonal shuttle channels by operating each channel sequentially as linear shuttling conveyors, pulsing only four gates at once. We benchmark the fidelity of electron routing across the junction to exceed 99.999% for an electron velocity of 0.22m/s and voltage driving amplitudes as low as 110mV. Any electron filling of the 51 quantum dots can be prepared by applying only 10 control signals. The native spin-SWAP gate enabled by this device topology is emulated by permutating initialized multi-electron configurations. T-junctions are an important step for sparse 2D architectures and easier to implement for spin-qubits than for other platforms.

[1] Xue, Beer et al. Nat. Commun. 15, 2296 (2024).
[2] Struck et al. Nat. Commun. 15, 1325 (2024).
[3] De Smet et al., Nat. Nanotechnol. (2025).
[4] Volmer et al., npj Quantum Inf. 10, 61 (2024).
[5] Künne et al., Nat. Commun. 15, 4977 (2024).
[6] Jain et al., Nature 627, 510-514 (2024).

work in progress

Session: Tuesday 9:40

Quantum logic encoded by the motion of a silicon spin qubit

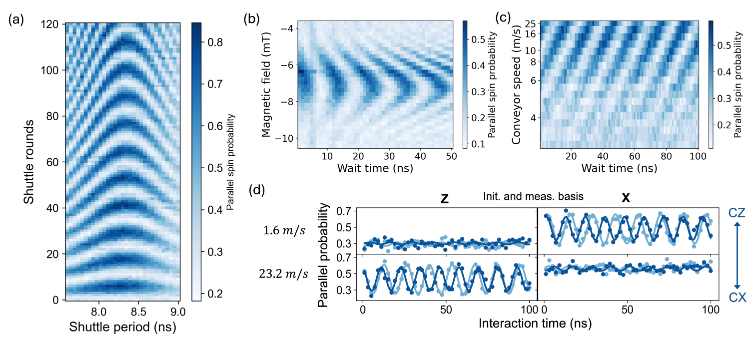
Yuta Matsumoto, Maxim De Smet, Larysa Tryputen, Sander de Snoo, Sergey Amitonov, Maximilian Rimbach-Russ, Giordano Scappucci and Lieven M.K. Vandersypen

The ability to dynamically program interactions between arbitrary pairs of qubits, a hallmark of trapped-ion and neutral-atom systems, has become a powerful architectural principle for scalable quantum computing. Recently, semiconductor spin qubits have also seen demonstrations of high-fidelity qubit transport, long-range charge transport, and two-qubit logic between mobile spins using conveyor-mode shuttling . However, a critical challenge remains to move beyond simply transporting qubits and to actively harness the shuttling dynamics for computation itself. The intrinsic speed and smooth motion of the conveyor represent an untapped resource for quantum control, and developing a method to exploit it for faster, more efficient gate operations would mark a paradigm shift for the platform.

In this work, we introduce and experimentally demonstrate novel methods for all-electrical single- and two-qubit control, driven by conveyor-mode shuttling. First, by resonantly oscillating an electron at its average Larmor frequency, we drive Rabi oscillations of up to 10 MHz with a 99.92% average gate fidelity(Fig. (a)), and show that the Rabi frequency scales with the shuttling distance. Furthermore, we utilize a positively magnetized micromagnet and a negative external magnetic field of -4 mT to engineer a localized kink in the magnetic field direction along the shuttling channel(Fig. (b)). By transporting a spin back and forth through this kink in a semi-diabatic fashion(Fig. (c)), we realize a full set of single-qubit rotations, including a Hadamard gate in 12 ns, with an average gate fidelity of 99.88%. Next, we demonstrate that we can also harness dynamic control of the electron position to achieve a variety of two-qubit gates in one step. By precisely controlling the shuttling speed of a mobile qubit as it approaches and interacts with a stationary qubit, we can deterministically select whether the exchange interaction implements a CZ or a CX gate(Fig. (d)).

work in progress

Session: Tuesday 10:00



Interacting electrons in silicon quantum interconnects: From Wigner Crystals to long-range capacitive coupling

Anantha S. Rao, Christopher David White, Sean R. Muleady, Anthony Sigillito and Michael J. Gullans

Coherent interconnects between gate-defined silicon quantum processors are essential for scalable quantum computation and long-range entanglement. We demonstrate that one-dimensional electron channels in a Si/SiGe quantum well, formed by a resistive topgate, exhibit strong coulomb interactions, realizing Luttinger liquid physics. At low densities, electrons in the channel overcome their kinetic energy to form a one-dimensional Wigner crystal—characterized by dominant 4kF correlations.

From Bosonization (Fig. b) we obtain the charge-sector Luttinger liquid parameter for different screening lengths and corroborate our findings through large-scale density matrix renormalization group (DMRG) simulations, revealing a density-driven crossover from Wigner-crystal to Friedel-dominated 2kF regime for both screened and unscreened Coulomb potentials (Fig c,d,h).

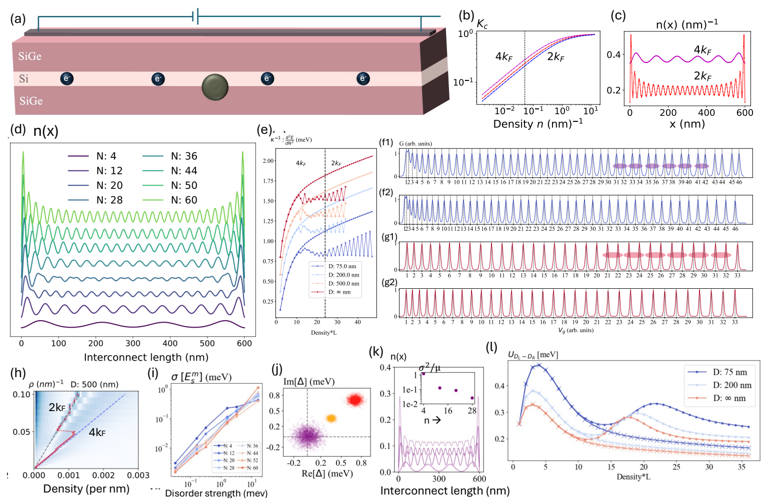
We identify signatures of this Wigner crystal, its electronic compressibility via charge transport through the interconnect (Fig e) in zero (Fig f1,g1) and high magnetic fields (Fig f2,g2), where we determine the strong electronic correlations from the Coulomb blockade spacing.

Charge sensors placed near the center of the interconnect assist in detecting the crossover and detecting the amount of disorder in the device (Fig i). We analyze effects of disorder from random alloy fluctuations (Fig i) and valley splitting variations (Fig j,k), identifying thresholds below which Wigner crystal signatures remain robust against localization effects. We find that increased quenched disorder leads to a higher variance in the energy detected by a charge sensor. In addition, we find that valley-induced Wigner crystals can be seen for different valley splitting profiles in the high-magnetic field limit.

Finally, we find that a Wigner crystal in the interconnect enables strong, long-range capacitive coupling between quantum dots across the interconnect (Fig l), suggesting a route to high-fidelity entangling gates. Our results position silicon interconnects as a platform for studying emergent many-body physics and for developing architectures for non-local quantum error correction and simulation.

Work in progress

Session: Tuesday 10:20


(a)
SiGe
Si
SiGe
(b)
K_c
$4k_F$
$2k_F$
Density n (nm)$^{-1}$
(c)
n(x) (nm)$^{-1}$
$4k_F$
$2k_F$
x (nm)
(d)
n(x)
N: 4
N: 12
N: 20
N: 28
N: 36
N: 44
N: 50
N: 60
Interconnect length (nm)
(e)
$4k_F$
$2k_F$
D: 75.0 nm
D: 200.0 nm
D: 500.0 nm
D: ∞ nm
Density*L
(f1)
(f2)
(g1)
(g2)
(h)
D: 500 (nm)
2kF
4kF
Density (per nm)
(i)
Disorder strength (mev)
(j)
Im[Δ] (meV)
Re[Δ] (meV)
(k)
n(x)
n →
Interconnect length (nm)
(l)
D: 75 nm
D: 200 nm
D: ∞ nm
Density*L

Multiplexed characterisation and automatic tune-up of 45 SEB + DQD unit cells in Si MOS for device process control

Tara Murphy, Angus Russell, Felix Ekkehard Ritter von Horstig, James Williams, David J. Ibberson, Mark A. I. Johnson, Henry Moss, M. Fernando Gonzalez-Zalba and John J. L. Morton

As arrays of spin qubits based on semiconductor quantum dots (QDs) continue to scale, a detailed understanding of device variability is required to accurately design large quantum processors. For that purpose, QD characterisation at scale has gained increasing attention in the field by making use of cryo-wafer probers (Si/SiGe), as well as cryogenic time-domain multiplexing (Si FDSOI) and device matrix arrays using shared control (Ge).

In this work, we present a quantum device matrix array (QDMA) fabricated using a 300 mm wafer metal-oxide-semiconductor process to enable device statistical characterisation. The unit cell consists of a radiofrequency single-electron box (SEB) charge sensor and a double quantum dot (DQD) in a linear topology featuring control of all tunnel barriers. Sequential access to individual cells is achieved by an on-chip multiplexed gate layout fabricated using just three polysilicon gate layers while high frequency signals are delivered through integrated circuit high-frequency multiplexers. We present QDMAs with up to 45 unit cells testable in a single cool down, the largest number for any matrix array to date.

We make use of probabilistic machine learning techniques to develop protocols for automatic tune-up of the SEBs, followed by tuning the DQD into a pre-defined electron occupation. These protocols are designed to minimise the required measurements needed to tune-up the electron occupation of the device. We characterise the QDs in terms of their lever arm matrix, addition energies, tunnel rates and coupling and compare the measurements with simulations of the unit cells. Having developed an automatic SEB + DQD tune-up routine, we are well positioned to study spin qubit dynamics at scale.

Session: Tuesday 11:10

Automated All-RF Tuning for Spin Qubit Readout and Control

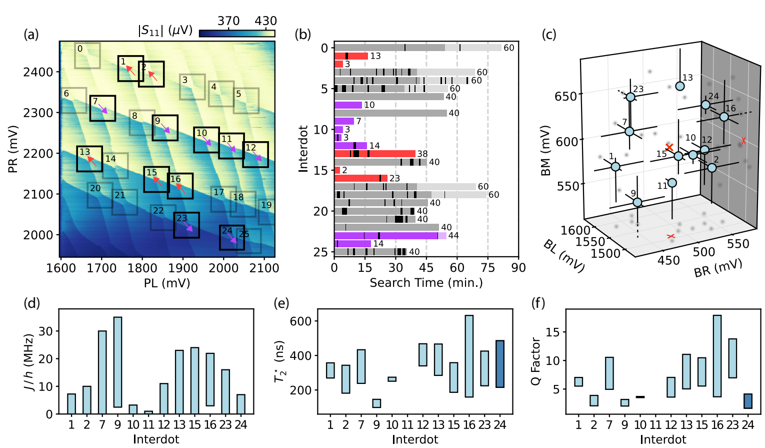
Cornelius Carlsson, Jaime Saez-Mollejo, Federico Fedele, Stefano Calcaterra, Daniel Chrastina, Giovanni Isella, Georgios Katsaros and Natalia Ares

Scaling quantum dot-based quantum processors requires rapid identification of gate voltage regimes suitable for qubit initialisation, control, and readout. We address this bottleneck by combining radio-frequency charge sensing with machine learning to autonomously tune Ge spin qubits in a median time of 15 minutes. Starting from an arbitrary double quantum dot configuration, a continuous run of our routine yields singlet-triplet oscillations at 12 distinct charge transitions in under 17 hours. Our routine combines convolutional neural networks for detecting features in charge stability diagrams and a score criterion based on maximum likelihood estimation. This enables navigation between interdot transitions, identification of voltage pulse points, and discrimination of spin-blockade features from noise. Our routine also finds barrier voltage ranges where oscillations persist, allowing the gate-voltage tunability of the exchange interaction, dephasing time, and quality factor to be unveiled—quantities that we find to vary considerably between charge configurations. These results represent a step change in high-throughput spin qubit tuning as well as laying a foundation for a systematic and automated exploration of spin physics in various qubit materials and architectures.

The figure summarises the results from an autonomous run of our routine. (a) Charge stability diagram with boxes about detected interdot transitions (IDTs). Arrows indicate readout pulse directions for which singlet-triplet oscillations were found. (b) Bar plot of the qubit search time at each IDT. Values at the bar ends show the number of tested voltage configurations. (c) Barrier voltages at which qubits were found, following the IDT numbering in (a). Line extensions indicate barrier voltage ranges over which oscillations persist. (d–f) Variability in qubit properties over the barrier ranges in (c): (d) exchange interaction strength J/h, (e) dephasing time T2*, and (f) Q factor. All raw data is acquired without active user input.

Carlsson, Cornelius, et al. "Automated All-RF Tuning for Spin Qubit Readout and Control." arXiv preprint arXiv:2506.10834 (2025).

Session: Tuesday 11:30



Automated large-scale analysis of quantum dots in germanium bilayer heterostructures

Merritt Losert, Dario Denora, Barnaby van Straaten, Menno Veldhorst and Justyna Zwolak

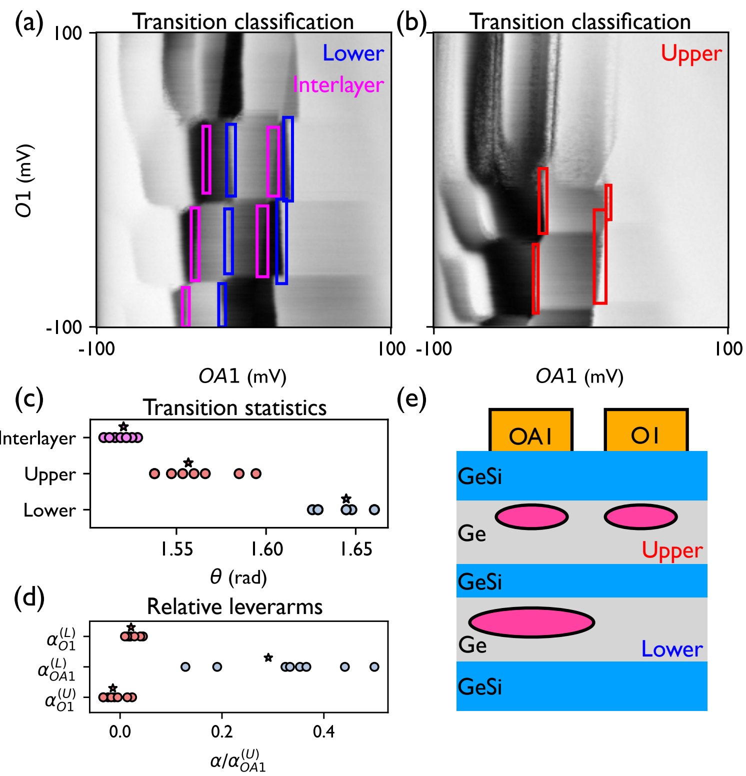
As quantum dot-based spin qubits advance toward larger and more complex device architectures [1,2], rapid and automated device characterization and data analysis tools become critical [3]. Bilayer Ge/SiGe heterostructures, shown schematically in (e), enable vertically coupled quantum dots (QDs) across closely spaced quantum wells, introducing new degrees of freedom that enrich qubit operation but complicate analysis. Charge stability diagrams (CSDs) in such devices exhibit a diverse array of transitions (a and b), including interlayer tunneling, and distinct capacitive signatures, which are not present in conventional planar systems. Manually interpreting these features is time-consuming, error-prone, and impractical.

Here, we present an automated protocol for analyzing CSDs from bilayer germanium quantum dot devices inspired by the MAViS [4] protocol designed for planar two-dimensional arrays. Our method integrates machine learning, image processing, and object detection to identify and track charge transitions across large datasets without the need for manual labeling. With machine learning, we obtain a rough classification of each transition. By filtering and tracking individual transitions through time, we can further distinguish between different types of transitions with otherwise similar features (a and b). Finally, by analyzing the properties of many such CSDs (c), we can statistically estimate physically relevant quantities, like relative lever arms (d) and capacitive couplings. Our protocol allows for a rapid extraction of useful and nontrivial information about bilayer devices, illustrating the promise of multilayer Ge/SiGe architectures.

[1] H. C. George, et al. Nano Lett., 25(2), 793-799 (2024).
[2] V. John, et al. arXiv:2412.16044 (2024).
[3] J. P. Zwolak and J. M. Taylor. Rev. Mod. Phys., 95(1), 011006 (2013)
[4] A. Rao, et al. Phys. Rev. X, 15(2), 021034 (2025).

work in progress

Session: Tuesday 11:50


(a)
Transition classification
Lower
Interlayer
O1 (mV)
OA1 (mV)
(b)
Transition classification
Upper
(c)
Transition statistics
Interlayer
Upper
Lower
1.55
1.60
1.65
θ (rad)
(d)
Relative leverarms
0.0
0.2
0.4
(e)
OA1
O1
GeSi
Ge
Upper
GeSi
Ge
Lower
GeSi

Explainable Models for Quantum Dot Qubit Readout

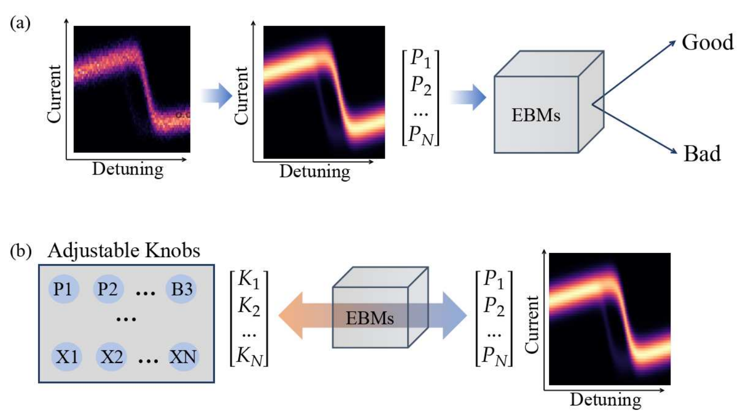
Daniel A. Schug, Joshua J. Lou, Samuel G. Carter, Adam Mills and Justyna Zwolak

In physics, many complex, real-world phenomena resist rigorous modeling, particularly when measurements are multivariate. In gate-defined quantum dot (QD) tuning, the connection between multiple gates and the dot behavior is very challenging to explain with theoretical models, hindering automated tuning. We propose relaxing the requirements for strictly theoretical models, focusing instead on mathematical modeling of the behavior. Such models, composed of simple functions such as sigmoids and Gaussians, can approximate a wide range of phenomena while requiring significantly less data than the previously proposed, complex machine learning (ML) methods.

By integrating these models with explainable ML techniques, we demonstrate their utility in automating QD autotuning processes. Specifically, we focus on leveraging the open nature of explainable ML models to produce actionable predictions and suggestions for end users working in the lab. Using GAMs (Generalized Additive Models) and tools like GAMCoach, we produce counterfactual explanations, which are utilized to determine what applied gate voltages are needed to improve the device state. Finally, we apply this approach to experiments performed at the Laboratory for Physical Sciences involving Pauli-spin blockade readout in HRL-fabricated six-dot SLEDGE devices, showing that explainable models provide valuable insights into device behavior and can optimize the device for desirable operational regimes. This approach helps overcome the current limitations of insufficient theoretical grounding by offering a practical solution that leads to more actionable tuning.

work in progress

Session: Tuesday 12:10

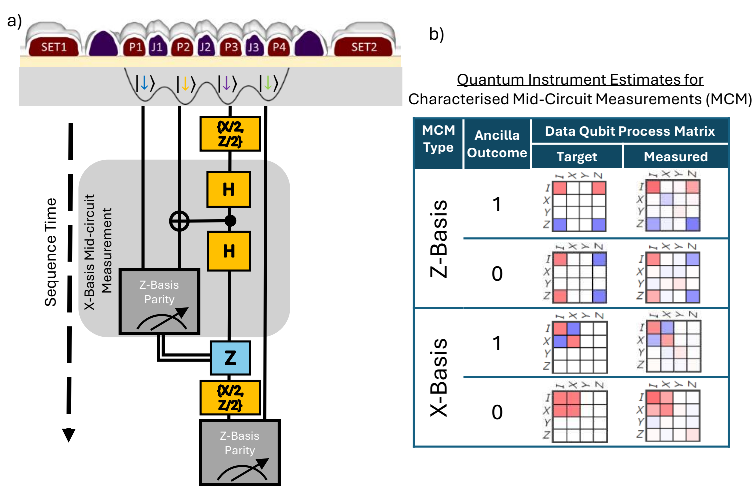


Characterisation of mid-circuit measurements and feedforward phase control in Silicon-MOS quantum dots.

Cameron A. Jones, Piper C. Wysocki, MengKe Feng, Gerardo Paz-Silva, Corey I. Ostrove, Tuomo Tanttu, Kenneth M. Rudinger, Fay E. Hudson, Wee Han Lim, Robin J. Blume-Kohout, Andrew S. Dzurak, Andre Saraiva, Arne Laucht and Henry Yang

The ability to perform mid-circuit measurements, as well as conditional feed-forward control operations based on their outcomes is an important requirement for quantum computing. Mid-circuit measurements however are impacted by not only the quality of constituent gate operations, but also the SNR and speed of the ancilla readout sensor, as well as the coherence times of data qubits. As a result, engineering high fidelity mid-circuit measurements is a challenging task, especially in cases where nominal readout times are comparable to the T2 lifetimes. Here, we present and characterise methods of performing mid-circuit measurements in a spin qubit architecture. For this work, a four-qubit Silicon-MOS array is used, which has an RF-SET at each end of the device. This allows for two independent parity PSB measurements per shot, giving separate ancilla and data qubit readout needed for mid-circuit measurements, as seen in a). We study the error mechanisms impacting the mid-circuit measurement through the use of gate-set-tomography, with the estimated quantum instruments seen in b). Using this data we verify that data-qubit decoherence during the ancilla qubit measurement is the dominant error source. Furthermore, by utilising an FPGA, we show we can use the outcome of the X-basis mid-circuit-measurement to perform real-time feedforward phase operations on a data qubit.

Session: Wednesday 9:00



Ramsey Interferometry for Many-Body Spectroscopy in a Quantum Dot Ladder

Stefano Reale, Daniel Jirovec, Pablo Cova Fariña, Christian Ventura-Meinersen, Minh T. P. Nguyen, Xin Zhang, Stefan Oosterhout, Giordano Scappucci, Menno Veldhorst, Maximilian Rimbach-Russ, Stefano Bosco and Lieven M. K. Vandersypen

Gate-defined semiconductor quantum dot arrays are a promising platform for digital and analog quantum simulations due to their scalability and precise control capabilities. Recent advancements have enabled the engineering of interacting spin systems in quantum dot arrays expected to exhibit signatures of complex many-body states. However, characterizing the energy spectrum of such systems remains challenging, since interactions give rise to many-body eigenstates that are far more complex than the simple spin-flip excitations that define the computational (Zeeman) basis.

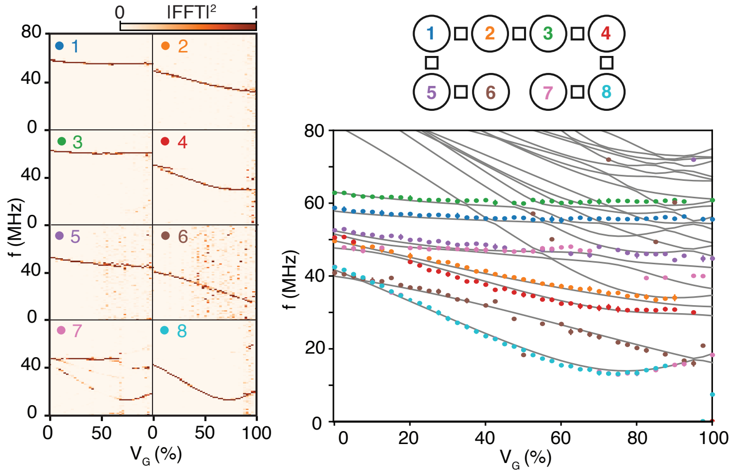
Here we demonstrate a time-domain spectroscopic technique that utilizes a one-to-one mapping from computational basis states prepared in the non-interacting regime to the many-body regime. We initialize quantum superpositions through Landau-Zener transitions at spin-orbit-induced anticrossings in Ge/SiGe quantum dots, then adiabatically evolve these states into the interacting regime and back, realizing a many-body Ramsey interferometry protocol. This approach allows us to selectively probe the energy of multiple excited states in the interacting regime and reconstruct the spectrum of a chain of up to 8 spins in a gate-defined Ge/SiGe 2x4 quantum dot ladder (see Figure).

Our spectral form factor analysis reveals a crossover from localization to chaotic behavior as interaction strength overcomes disorder, leading to level repulsion signatures characteristic of quantum chaotic systems.

To our knowledge, this work presents the first comprehensive spectroscopic characterization of many-body states in a semiconductor quantum dot array of this scale. It also constitutes the first signatures of transition from localization to quantum chaos in semiconductor quantum dots, advancing our ability to study quantum phases of matter in scalable solid-state platforms.

Work in progress

Session: Wednesday 9:20



0
IFFTI²
1
80
40
0
f (MHz)
1
2
3
4
5
6
7
8
0
50
100
V_G (%)
60
20
f (MHz)
V_G (%)

Spin Qubit Performance at the Error Correction Threshold: Advancing Quantum Information Processing Above 700 mK

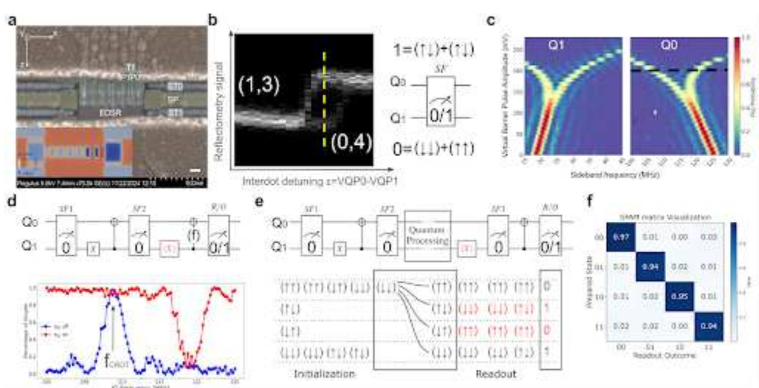
Sergey Amitonov, Mike Asker, Agostino Apra, Radu Bals, Brendan Barry, Imran Bashir, Elena Blokhina, Panagiotis Giounanlis, Maurice Harkin, Peter Hanos-Puskai, Ioanna Kriekouki, Dirk Leipold, Mathieu Moras, Niall Murphy, Nikolaos Petropoulos, Conor Power, Amir Sammak, Nodar Samkharadze, Andrii Semenov, Andrii Sokolov, David Redmond, Claude Rohrbacher and Xutong Wu

This work presents a characterization of a two-qubit processor in a 6-quantum dot array in SiGe, from the perspective of its quantum information processing capabilities. The analysis includes randomized benchmarking of single- and two-qubit gates, SPAM characterization, and Bell's state tomography; all basic functionality required for universal quantum computation. In light of our efforts to combine spin qubits with integrated cryogenic electronics, we evaluate the qubits' performance metrics at 300 mK and 740 mK. The latter temperature lies within the realistic thermal budget for integrated cryogenic electronics, making it particularly relevant for assessing qubit performance in practical scenarios.

Extracted single- and two-qubit fidelities do not show a significant decline with increasing temperature, with qubits performing at the error correction threshold at both temperatures. However, at the higher temperature, state preparation and measurement (SPAM) errors increase due to reduced sensitivity of the single electron transistor used in readout. Correcting for SPAM, we construct a Bell state with over 98.5% fidelity at both temperatures. Bell state preparation, which generates a maximally entangled two-qubit state, along with state tomography and a SPAM correction scheme, are critical components for quantum information processing in this system. Demonstrating these capabilities at elevated temperatures represents a significant milestone in advancing the SiGe platform's practical utility. Finally, we note that our qubits operate below 5 GHz, a comfortable frequency range for integration with widely-used RF technologies found in handheld and embedded devices, such as PLLs and CMOS-based RF synthesizers and realizable with commercial semiconductor processes.

https://arxiv.org/abs/2412.01920

Session: Wednesday 9:40



High-fidelity dispersive readout of a foundry fabricated spin Qubit

Guillermo Haas, Maxime Gontel, Mathieu Toubeix, Pierre Hamonic, Matthieu Dartiailh, Tristan Meunier, Maud Vinet, Biel Martinez i Diaz and Matias Urdampilleta

The reduction of readout error in spin qubit is one of the main challenges in Qubit gates implementation. It imposes to make high-fidelity measurement with an integration time as short as possible.

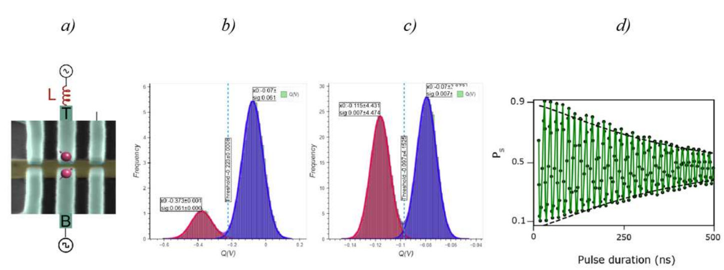
We present gate-based high-fidelity measurements of spin qubit in silicon fabricated in a 300mm foundry (figure 1.a). More precisely, we exploit LC resonator fabricated in a superconducting back-end-of-line which presents minimal parasitic capacitance and high-quality factors. By connecting the LC circuit to the gate of a qubit device we characterize the dispersive shift as a function of tunnel coupling. In a second time, by probing Pauli-spin blockade in single-shot, we obtain up to 99.3% for 5µs integration time (figure 1.b) for large tunnel coupling which surpasses the state of the art for gate-based readout.

We apply the method to operate and read a spin qubit in a regime of lower tunnel coupling. We obtain still reasonable fidelity of 99.18% in 36µs (figure 1.c) but a reduced visibility of 80% in qubit oscillations (figure 1.d). We investigate the different sources of SPAM errors and identify the state preparation as the main issue either through leakage to the T- state or bad adiabatic passage from singlet to T- state.

In conclusion, we demonstrate high-fidelity measurement of a Qubit at low integration time by gate-based reflectometry. The improvement of the visibility by reducing state preparation and transfer errors will be one of the main challenges in view of future coherent manipulations on FDSOI devices.

Session: Wednesday 10:00

Figure 1



Long coherence spin qubits in silicon quantum dots fabricated by advanced nanoelectronics fab

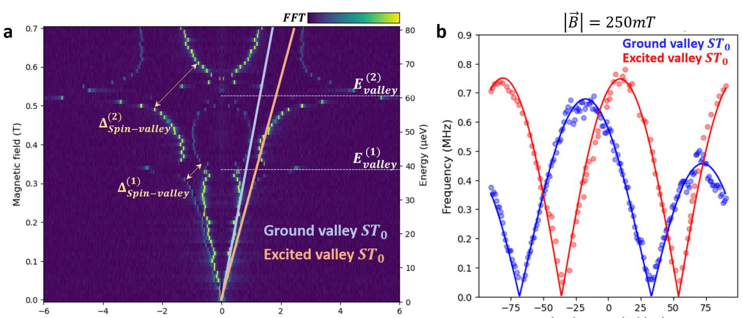
Petar Tomic, W. Huang, B. Raes, C. Godfrin, S. Kubicek, J. Jussot, Y. Canvel, Y. Hermans, Y. Shimura, R. Loo, S. Beyne, G. Jaliel, T. van Caekenberghe, V. Levajac, D. Wan, K. de Greve, T. Ihn and K. Ensslin

Building fault-tolerant quantum computers based on silicon quantum dot (Si QD) spin qubits requires reliable and reproducible large-scale quantum dot arrays. While university cleanroom fabrication offers flexibility for prototyping new device layouts, it often results in low yield and poor uniformity. The compatibility of Si QD structures with modern industrial CMOS fabrication offers a path to scalability, improved yield, uniformity, and coherence. In this work, we characterize both single-spin and composite singlet-triplet (ST0) qubits in a silicon MOS double quantum dot array, fabricated in IMEC's 300 mm state-of-the-art nanoelectronics cleanroom [1]. The devices exhibit excellent charge stability—remaining tuned over weeks—and clean charge stability diagrams with no evidence of disorder, as well as tunable exchange interaction, a key ingredient for two-qubit gates. We probe spin coherence in the non-ergodic regime using the ST0 qubit and observe long dephasing times (T2* = 100–200 μs) and state-of-the-art dynamical decoupling times (T2Hahn = 4 ms) [2]. To investigate dephasing mechanisms, we simultaneously track single-spin ESR frequencies in both dots and measure their exchange interaction. Using Bayesian estimation techniques, we extract noise correlations between the qubits and speculate on their electrical origin. The long coherence times also enable observation of oscillations related to excited valley-state ST0 qubit (see Fig a). By probing the anisotropy of the ST0 qubit frequency (Δg) in magnetic field for both the ground and excited valley states (see Fig b), we observe sensitivity of Rashba and Dresselhaus spin orbit interaction to purely valley degree of freedom.

[1] Elsayed, A. et al. npj Quantum Inf 10, 70 (2024).
[2] Stano, P., & Loss, D. arXiv:2107.06485 (2025)

work in progress

Session: Wednesday 10:20



Robust spin-qubit control in a natural Si-MOS quantum dot using phase modulation

takuma kuno, Takeru Utsugi, Andrew J. Ramsay, Normann Mertig, Noriyuki Lee, Itaru Yanagi, Toshiyuki Mine, Nobuhiro Kusuno, Raisei Mizokuchi, Takashi Nakajima, Shinichi Saito, Digh Hisamoto, Ryuta Tsuchiya, Jun Yoneda, Tetsuo Kodera and Hiroyuki Mizuno

Precise control of quantum states is a prerequisite for the realization of quantum computations. However, dephasing induced by environmental noise remains a major obstacle. Among various dressing techniques, the concatenated continuous drive (CCD) protocol has shown to be effective for suppressing dephasing arising from both environmental noise and fluctuations in the control field [1]. In this work, we present a phase-modulated control scheme for a CCD-protected electron-spin qubit in a natural silicon metal-oxide-semiconductor (Si-MOS) quantum dot (Fig. a) [2]. In the absence of CCD protection, the coherence time is limited to 1.2 μs due to interactions with 29Si nuclear spins. The CCD protocol extends the coherence time of Rabi oscillations to over 100 μs (Fig. b). Furthermore, phase-modulation enables observation of the Mollow triplet, with the sideband separation determined by the phase-modulation amplitude εm (see Fig. b inset). The modulation phase θm controls the relative amplitudes of the sidebands, providing a control means of dressed qubits. We define a protected qubit in a double-dressed basis and demonstrate a two-axis control. We further define a set of single qubit Clifford gates and perform randomized benchmarking experiment. The average single-qubit gate fidelity is improved from 95% to 99%, crossing the surface-code threshold despite the use of a natural Si device (Fig. c). These results show promise for improving control fidelity of noisy qubits, overcoming the qubit variability for global control, and maintaining qubit coherence while idling.

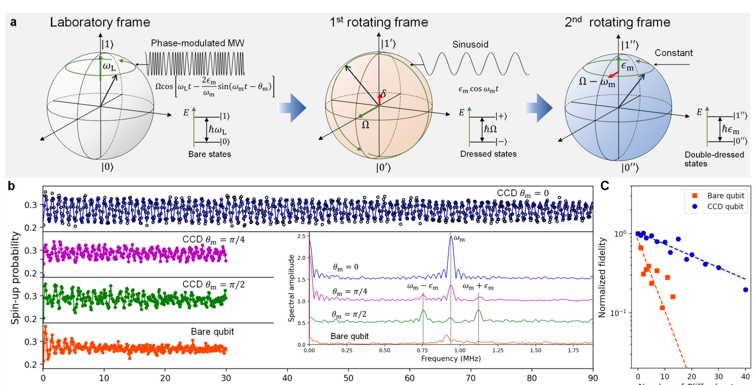
This work was supported by JST Moonshot R&D Grant Number JPMJMS2065, Grants-in-Aid for Scientific Research grant numbers JP23H05455 and JP23K17327, and JST PRESTO Grant Number JPMJPR21BA.

[1] A. J. Ramsay et al., Nat. Commun. 14, 461 (2023).

[2] T.Kuno et al., arXiv:2503.19410v1 (2025).

T.Kuno et al., arXiv:2503.19410v1 (2025).

Session: Wednesday 10:40



Simulations of ionizing radiation in silicon quantum dot-based qubits using G4CMP

Jesse James Lutz, Wondwosen M. Mengesha, Dwight Luhman and Peter A. Sharma

Ionizing radiation is known to impact the performance of superconducting quantum circuits. In silicon quantum dot-based spin qubits, however, the effects of radiation remain unclear. Recently Wolfe et al. (Phys. Rev. Appl. 22, 034044, 2024) demonstrated systematic voltage threshold shifts under optically-induced charge generation, suggesting a similar response due to radiation-induced charge generation and trapping. In this study, we utilize the Monte Carlo simulation software Geant4 for modeling radiation transport, including muons and gamma rays, coupled with the G4CMP add-on for simulation of the production and propagation of low-temperature condensed-phase acoustic phonons and electron-hole pairs. This approach enables investigation of how individual radiation strikes lead to trapped charge within a semiconductor qubit device. Our simulations focus on quantifying the fraction of liberated charge carriers that reach a critical interface, where they are assumed to become trapped and cause a threshold shift. We also conduct a parameter sensitivity study to assess the influence of device geometry and material properties. While our primary focus is on monolithic silicon, we discuss the applicability of our findings to other materials and heterostructures not presently supported in G4CMP. This work establishes a foundation for future research aimed at enhancing the resilience of quantum-dot qubits against radiation-induced charge fluctuations.

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

work in progress

Session: Wednesday 11:30

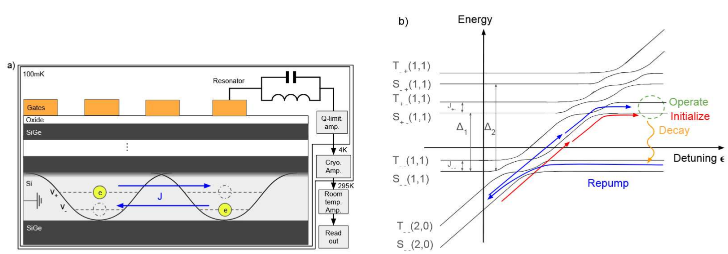
Fast charge noise sensing using a spectator valley state in a singlet-triplet qubit

David Wyman Kanaar, Yasuo Oda, Mark Gyure and Jason Kestner

Semiconductor spin qubits are a promising platform for quantum computing but remain vulnerable to charge noise. Accurate, in situ measurement of charge noise could enable closed-loop control and improve qubit performance. Here, we propose a method for real-time detection of charge noise using a silicon singlet-triplet qubit with one electron initialized in an excited valley state. The schematic of the device and initialization are shown in figure 1a and b. This valley excitation acts as a spectator degree of freedom, coupled to a high-quality resonator via the exchange interaction, which is sensitive to charge-noise-induced voltage fluctuations. Dispersive readout of the resonator enables a continuous, classical measurement of exchange fluctuations during qubit operation. Signal-to-noise analysis shows that, under realistic device parameters, sub-microsecond measurement times are possible using a quantum-limited amplifier. Even without such an amplifier, sub-millisecond performance is achievable with appropriately engineered resonator parameters. This approach allows the probe to monitor slow drift in exchange in real time, opening the door to feedback and feedforward strategies for maintaining high-fidelity quantum operations. Importantly, the protocol preserves spin coherence and can be run concurrently with qubit logic gates.

https://arxiv.org/abs/2507.14108

Session: Wednesday 11:50



Process Tensor Tomography of an atom qubit in silicon

A M Saffat-Ee Huq, Gregory A. L. White, Christian M. Moehle, Luis Fabian Pena, Henric Bornemann, Pedro Figueroa-Romero, Yousun Chung, Joris G. Keizer, Kavan Modi, Ludwik Kranz, Charles D. Hill and Michelle Y. Simmons

Correlated noise in quantum systems can be destructive for quantum error correction (QEC), particularly if the phenomenon is diffusive and spreads to future operations and nearby qubits in a non-trivial manner [1]. For efficient QEC implementations, it is important to characterise and address these complex spatiotemporal noise effects which are often non-Markovian in nature. In this work, we characterise the noise in the 14|15 platform with phosphorus atoms (element 15) in silicon (element 14). In particular we focus on the noise impacting ionised phosphorus nuclear spin qubits using process tensor tomography (PTT) [2].

PTT is a powerful technique, which unlike Gate Set Tomography (GST), captures both the Markovian and non-Markovian noise of the system. From tomographic analysis, we find that the qubit environment exhibits signatures of non-Markovian behaviour. The non-Markovianity, however, is mostly classical which corresponds to a slowly varying noise in a system. The ionised nuclear spin qubits are primarily susceptible to the magnetic environment and relatively immune to the charge environment. Therefore, we postulate that the slow magnetic field drift of the superconducting magnet is the most likely source of non-Markovianity in this system. The classical nature of non-Markovianity is an encouraging result for the atom qubit 14|15 platform as this type of noise, in contrast to quantum non-Markovianity, does not require complex control and mitigation strategies. To this end, we demonstrate experimentally that standard dynamical decoupling protocols can efficiently address the classical non-Markovian noise in our system. Additionally, we find that the PTT characterisation holds remarkably well for at least two weeks, highlighting the extremely stable environment of atom qubits in silicon. Such results bode well for the requirements for fault-tolerance.

[1] Clader, B. D., et al. Physical Review A 103.5 (2021): 052428.

[2] White, Gregory AL, et al. Physical Review X 15.2 (2025): 021047.

Session: Wednesday 12:10

Benchmarking logic operations on a high-dimensional nuclear spin qudit in silicon

Rocky Yue Su, Yu Xi, Danielle Holmes, Martin Nurizzo, Arjen Vaartjes, Benjamin Wilhelm, Yale Fan, Riley Murray, Andrew David Baczewski, Thaddeus Ladd, Kevin Young, Robin Blume-Kohout and Andrea Morello

High-dimensional nuclear spin facilitates efficient, compact, and robust schemes for logical encoding and fault-tolerant quantum computation [1,2]. Recent work demonstrated the preparation of Schrödinger cat states in $I = 7/2$ 123Sb donors in silicon, as well as single logical qubit gates by SU(2) operations [3]. However, quantifying error rates for these logical gates in a $d = 8$ Hilbert space remains a challenge. Conventional randomized benchmarking (RB), typically applied to Clifford group, is unsuitable because SU(2) operations in high-spin nucleus do not twirl noise into a uniform depolarization channel. Instead, they generate 8 distinct error classes, resulting in the return probability of the RB sequence that follows a mixture of exponential decays. In this work, we introduce synthetic-SPAM RB, a novel RB variant for SU(2) operations in high-spin nuclei, capable of isolating distinct error classes, each characterized by a single exponential decay. Using this method, we report a no-error rate of 0.975(1) for random SU(2) operations for a single ionized 123Sb donor, highlighting the potential of silicon-based high-spin donor systems for quantum error correction and fault-tolerant computation.

[1] J. A. Gross, Physical Review Letters 127(1) 010504 (2021)

Session: Wednesday 12:30

Fig1 Basics about device

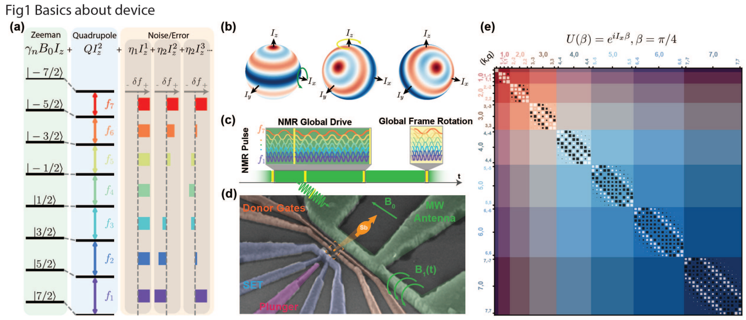


Fig2 Twriling over SU(2) channel for spin 7/2 system.

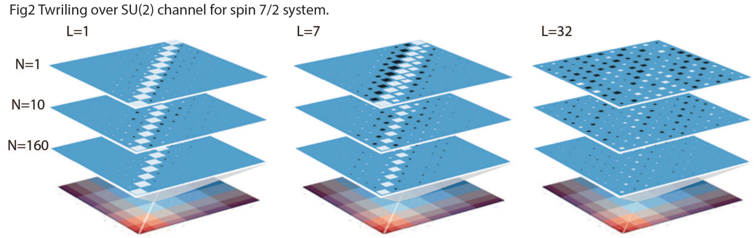
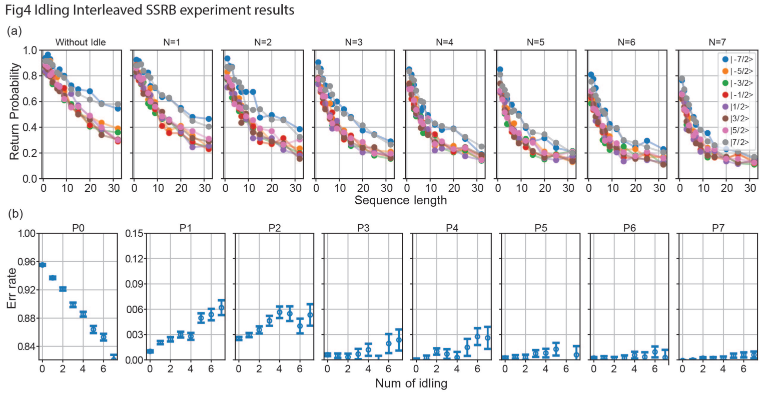


Fig4 Idling Interleaved SSRB experiment results



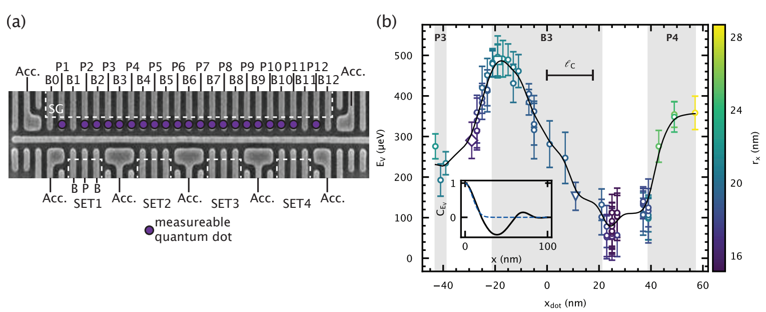
Valley Splitting Correlations Across a Silicon Quantum Well

Jonathan Marcks, Emily Eagen, Emma C. Brann, Merritt Losert, Tali Oh, John Reily, Christopher S. Wang, Daniel Keith, Fahd A. Mohiyaddin, Florian Luthi, Matthew Curry, Jiefei Zhang, F. Joseph Heremans, Mark Friesen and Mark Eriksson

Quantum dot qubits in Si/SiGe heterostructures host coherent spin qubits for scalable quantum computing, but suffer from low-lying excited valley states that impact operation and readout fidelities across multiple qubit encodings. Here, we study spatial valley splitting (EV) correlations arising from SiGe alloy disorder both within a single dot and along the 1.3 μm qubit channel of an industrially manufactured, Ge-doped Intel Tunnel Falls device [Fig. (a)]. By combining detuning axis pulse spectroscopy (DAPS) EV measurements with capacitive modeling of the dot position we use the electron wavefunction as a spatial probe of the valley energy. We first extract a valley autocorrelation length scale of 19 nm, consistent with the electron wavefunction sampling atomistic alloy disorder [Fig. (b)]. We then measure EV at 21 independent sites along the single device, finding statistics consistent with our theoretical understanding of alloy disorder-dominated valley splitting. The finite and fluctuating EV arises due to the nearly degenerate conduction band valleys in the Si quantum well coupled with inherent material disorder, necessarily causing variation across a nominally uniform device. Our results develop the mesoscopic understanding of Si/SiGe heterostructures necessary for scalable device design.

J. C. Marcks, et al. Valley Splitting Correlations Across a Silicon Quantum Well, arXiv:2504.12455 (2025)

Session: Wednesday 14:00



Thermal susceptibility of hole spin qubits in Silicon

Victor Champain, Gabriele Boschetto, Heimanu Niebojewski, Benoit Bertrand, Lorenzo Mauro, Marion Bassi, Vivien Schmitt, Simon Zihlmann, Xavier Jehl, Romain Maurand, Clemens Winkelmann, Yann-Michel Niquet, Biel Martinez, Silvano De Franceschi and Boris Brun

Electrically controlled spin qubits are rapidly progressing toward scalability, with multi-qubit processors demonstrated in Group IV semiconductors, up to six qubits in silicon and ten in germanium. However, the simultaneous operation of several qubits has been shown to degrade their individual performance, likely due to local heating from control pulses and the thermal susceptibility of spin qubits, i.e., the temperature dependence of their Larmor frequencies.

In this work, we study the thermal susceptibility of a hole spin qubit in silicon. Owing to spin-orbit coupling, hole spins exhibit a strong anisotropic response to magnetic fields. In particular, their longitudinal spin-electric susceptibility, the sensitivity of the Larmor frequency to gate voltage, varies with magnetic field orientation and can vanish at specific "sweet spots."

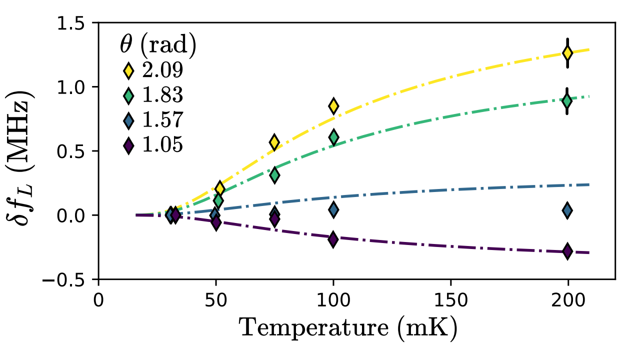
By measuring how the Larmor frequency evolves with temperature, we demonstrate that hole spins also exhibit thermal susceptibility, reaching values up to 10 MHz/K, similar to electron spins in silicon (see figure below). Rotating the magnetic field reveals a strong correlation between electrical and thermal susceptibilities, pointing to a shared origin rooted in spin-orbit interaction.

We propose a microscopic model involving a bath of electric dipoles that thermally activate and alter the local electric field experienced by the qubit. Numerical simulations with randomly distributed dipoles reproduce experimental observations and suggest a surprisingly small dipole moment on the order of 1 e·pm. Crucially, we identify magnetic field orientations for which the Larmor frequency becomes temperature-independent.

This work provides both a physical understanding of spin thermal susceptibility and practical strategies to suppress it, offering a route to protect hole spin qubits against heating effects, even at millikelvin temperatures.

In preparation

Session: Wednesday 14:20



Fast, high fidelity, on demand initialization of a quantum dot qubit out of a latched readout state

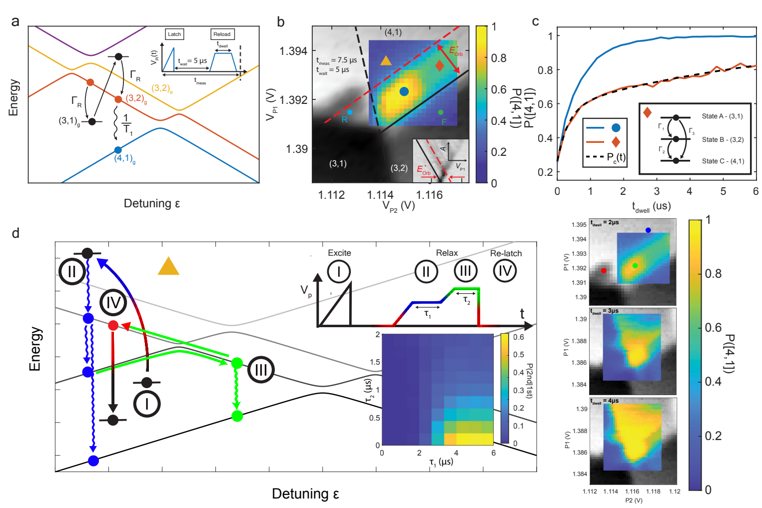
Piotr Marciniec, Michael A. Wolfe, Tyler Kovach, Jack Reily, Sanghyeok Park, Jared Benson, Mark Friesen, Benjamin Woods and Mark Eriksson

Re-initializing out of a latched readout state is critical, yet it can be slow. In this work, we demonstrate a method for fast, high fidelity, and on-demand active reset of a quantum dot qubit out of a latched readout state using only baseband pulses. This protocol circumnavigates the slow decay process of the latched state by pulsing to a region in gate-voltage space where the latched state resets in a fast two-step process. The key step is a fast inelastic tunneling even across the interdot barrier. We show that the active reset can increase the rate of initialization of the qubit on demand and more than an order of magnitude faster compared to the natural decay of the latch state. By applying the active reset in the optimal region – indicated by the blue dot in (Fig (b)) – we achieve a reset fidelity >99% in a time as short as 3.5 μs. Additionally, we explore the behavior of the reset pulse in the regions where the reset fidelity is low (red diamond in b and c and yellow triangle in b and d) where we come across new interesting device physics and use this physics to explain why these regions should be avoided when resetting.

This work is significant because latched readout techniques offer high fidelity measurement of spin qubits due to increased signal contrast. In addition, using the technique we report here, the high contrast latched signal can be maintained as long as is needed to ensure high fidelity measurement, at which point the latch can be deterministically reset resulting in qubit reinitialization.

work in progress

Session: Wednesday 14:40



Cryogenic 22nm FD-SOI CMOS 12 Channel DAC for Spin Qubit Bias

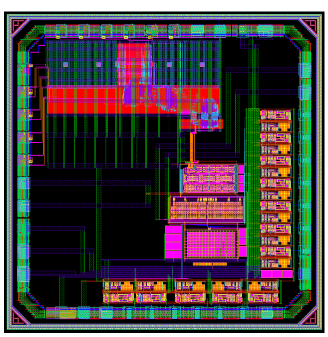
Lea Schreckenberg, Volker Christ, Andre Kruth, Sabitha Kusuma, Daniel Liebau, Jonas Mair, Patrick Vliex and Stefan van Waasen

Solid-state qubit devices, such as spin-based qubits in semiconductor quantum dots, require temperatures well below one Kelvin to perform optimally. Such low temperatures are achieved using dilution refrigerators (DRs). However, state-of-the-art DRs present a challenge to the scalability of qubits due to wiring limitations of control signals and read out, as well as constraints due to heat load. The placement of low-temperature electronics at the lowest and intermediate temperature stages of a DR has been identified as a potential solution to this wiring bottleneck. In particular, the formation of quantum dots within a two-dimensional electron gas (2DEG) in a semiconductor heterostructure represents a foundational step toward realizing qubits and necessitates the application of precise DC voltages. Here, we present a twelve-bit cryogenic digital-to-analog converter in 22 nm FD-SOI CMOS technology (Fig. 1a). The DAC circuit uses a charge redistribution topology to prevent static power consumption and offers a variable output range of 0V to 1.7V. The output comprises twelve independent channels, each with a sample-and-hold (S&H) structure. Previous iterations of the DAC using 65 nm bulk CMOS technology demonstrated low leakage in the S&H structures when used with a spin qubit device at mK temperatures [1]. This new iteration features a slow refresh of the S&H structure and a defined hold state to avoid influencing the qubit device. This presentation will provide a detailed description of the DAC architecture, alongside a discussion of the cryogenic measurement results. These results include the DAC output curve for one output channel at a base temperature of 6 K, depicted in Fig. 1b.

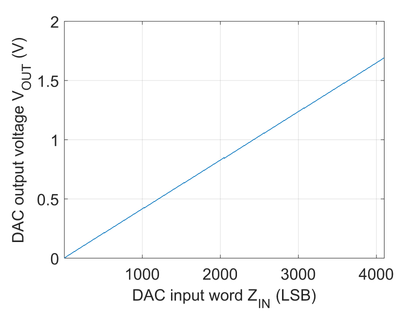
[1] L. Schreckenberg et al., "SiGe Qubit Biasing with a Cryogenic CMOS DAC at mK Temperature," IEEE 49th European Solid State Circuits Conference (ESSCIRC), 2023.

work in progress

Session: Wednesday 15:00



(a)



(b)

Improved Charge Sensing on a SiMOS Double Quantum Dot using a Cryogenic Skipper Readout ASIC

Adam Quinn, Troy England, Santiago Serrano Ramirez, Arne Laucht, Andre Saraiva, Matthew Otten and David Miller

Major outstanding questions in high-energy physics such as the nature of dark matter and the existence of interactions beyond the standard model require new measurement techniques which are extremely sensitive to minute electromagnetic fields. An array of entangled spin qubits is a promising system for building novel detectors due to its combination of sensitivity and controllability. CMOS-based electron spin qubits, which have demonstrated the operational requirements for fault-tolerant quantum computing [1], offer a particular opportunity due to their compatibility with classical electronics, which allows the leveraging of decades of development of low-noise cryogenic detectors for physics. In this work, we combine a SiMOS double-quantum dot device architecture with a state-of-the-art cryoelectronic readout circuit [2-3] aimed to demonstrate improved charge readout using a single-electron transistor (SET). We identify the design characteristics for an SET that facilitate the use of on-chip classical electronics as a low-power, high-bandwidth first amplification stage and explore opportunities for sensor-readout co-design to minimize noise. This is the first of a series of steps to demonstrate high-fidelity readout of a large array of spin qubit with enough sensitivity to probe processes of interest for the investigation of beyond-standard-model physics.

[1] P. Steinacker et al., ”A 300 mm foundry silicon spin qubit unit cell exceeding 99% fidelity in all operations”. arXiv:2410.15590

[2] F. A. Bessia et al., ”A Sub-Electron-Noise Multi-Channel Cryogenic Skipper-CCD Readout ASIC”. IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 70, no. 6, pp. 2306-2316, June 2023, doi: 10.1109/TCSI.2023.3256860.

[3] F. A. Bessia et al., ”Noise analysis of MIDNA Skipper-CCD readout ASIC,” 2023 Argentine Conference on Electronics (CAE), Cordoba, Argentina, 2023, pp. 96-101, doi: 10.1109/CAE56623.2023.10086978.

work in progress

Session: Wednesday 15:20

Cryo-control for topological qubits

Rachpon Kalra

This presentation introduces the control subsystem for topological qubits, focusing on measurement-based quantum computing with MZM architectures and cryogenic CMOS integration. It covers the evolution of control systems from single-qubit demonstrations to logical qubits, highlighting cryogenic ASIC design, thermal management, and digital control strategies.

Session: Wednesday 15:40

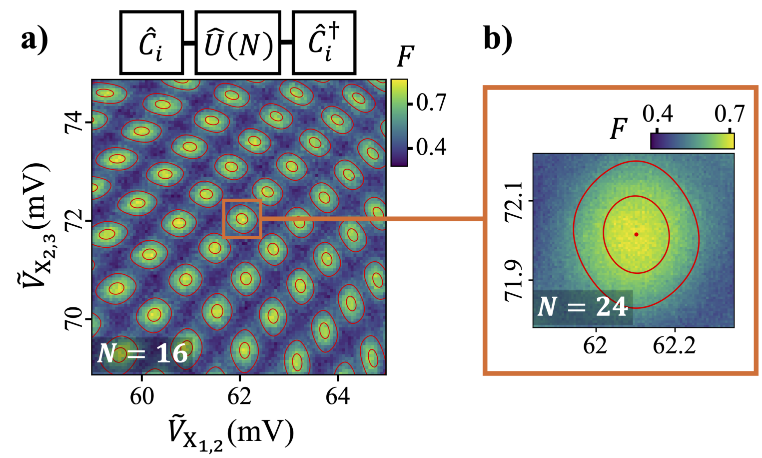
Demonstration of an always-on exchange-only spin qubit

Joseph Broz, Jesse C. Hoke, Edwin Acuna and Jason Petta

In conventional exchange-only (EO) spin qubit demonstrations, quantum gates have been implemented using sequences of individually pulsed pairwise exchange interactions with only one exchange coupling active at a time. Alternatively, multiple non-commuting exchange interactions can be pulsed simultaneously, reducing circuit depths and providing protection against leakage. We demonstrate high-fidelity quantum control of an always-on exchange-only (AEON) qubit, operated using simultaneous exchange pulses in a triangular quantum dot (QD) array. We use blind randomized benchmarking to characterize the performance of the full AEON single-qubit Clifford gate set, achieving an average Clifford gate fidelity FC1 = 99.86%. Extensions of this work may enable more efficient EO two-qubit entangling gates as well as the implementation of native i-Toffoli gates in Loss-DiVincenzo single-spin qubits.

https://doi.org/10.48550/arXiv.2508.01033

Session: Wednesday 16:30



The singlet-triplet and exchange-only flopping-mode spin qubits

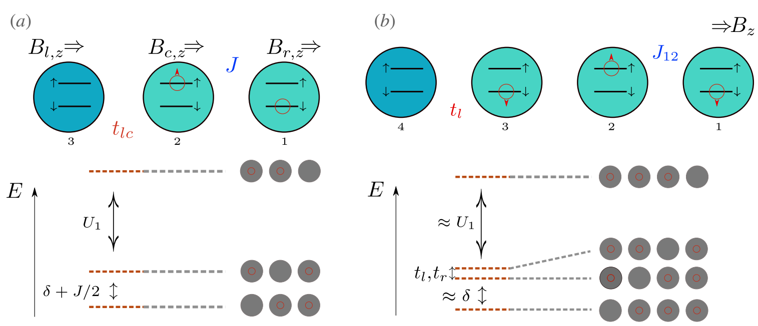
Simon Stastny and Guido Burkard

Semiconductor-based spin qubits embedded into a superconducting microwave cavity constitute a fast-progressing and promising platform for realizing fast and fault-tolerant qubit control with long-range two-qubit coupling. The flopping-mode spin qubit consists of a single electron in a double quantum dot; it combines a charge qubit with a spin qubit. With its strong and tunable cavity coupling, the flopping-mode qubit is proven to be well-suited for low-power qubit control and cavity-mediated long-range quantum gates.

The singlet-triplet (ST) and exchange-only (EO) qubits are multi-electron realizations that go without broadband control and are protected from some types of noise, but are challenging to couple to each other and to microwave cavities. We combine the flopping-mode concept with the ST and EO qubits and propose two new flopping-mode qubits that consist of three (four) quantum dots, occupied by two (three) electrons near the (1,0,1) ↔ (0,1,1) [(1,0,1,1) ↔ (0,1,1,1)] charge transition, see subfigure (a) [ST] and (b) [EO]. The two-electron system augments the ST_0 spin qubit with a charge qubit that interacts transversally and longitudinally with a cavity. Both couplings are highly tunable, and the longitudinal coupling distinguishes the flopping-mode ST qubit from the regular flopping-mode qubit. The longitudinal coupling allows for non-dissipative universal control similar to superconducting transmon qubits. The EO flopping-mode qubit comprises four dots occupied by three electrons and opens a new possibility to perform two-qubit gates for EO qubits that are challenging to perform directly with the exchange coupling. We use input-output theory to provide means of extracting the coupling strengths from cavity transmission data.

arXiv:2503.05032

Session: Wednesday 16:50



A hole spin flopping mode qubit: fast and coherent

Leo Noirot, Cécile Yu, Jose Carlos Abadillo-Uriel, Etienne Dumur, Heimanu Niebojewski, Benoit Bertrand, Romain Maurand and Simon Zihlmann

Coherent spin-photon interfaces between microwave photons and spins in silicon quantum dots are now routinely achieved [1-3]. The key ingredient in resolving this outstanding challenge was the engineering of a large electric-dipole moment linked to the spin, achieve by delocalizing a spin within a double-quantum dot under the influence of spin-orbit interaction. These spin qubits, also known as flopping-mode spin qubits, have enabled the first SWAP operations between spin qubits separated by over 250 micrometers [4], paving the way to address the wiring challenges in dense spin qubit processors.

However, the coherence properties of flopping mode spin qubits reported to date remain limited, hindering their use in practical applications. Here, we report on a hole spin delocalized in a double quantum dot formed in a silicon nanowire MOS device coupled to a high impedance superconducting microwave resonator [3]. With Rabi frequencies exceeding 100 MHz and coherence times in the microsecond range, we show that delocalized spins can achieve high qubit quality factors, enabling high-fidelity gate operations.

Furthermore, we present a comprehensive analysis of the mechanisms limiting spin relaxation and dephasing in a hybrid spin cQED architecture. Our findings reveal that spin relaxation is dominated by radiative decay due to a structured electromagnetic environment (Purcell effect); while dephasing is limited by photon shot noise at operational points where the spin is first-order insensitive to charge noise. This suggests that with an optimized cQED architecture, considerably longer coherence times can still be achieved.

With strong spin-photon coupling and promising single-qubit properties demonstrated here, hole spin flopping-mode qubits emerge as a promising platform for scalable quantum architectures.

[1]: Samkharadze et al. Science, 359 (2018)
[2]: Mi et al. Nature, 555 (2018)
[3]: Yu et al. Nat. Nanotechnol. 18 (2023)
[4]: Dijkema et al. Nat. Phys. 21 (2025)

https://arxiv.org/abs/2503.10788

Session: Wednesday 17:10

Two-qubit gates enabled by anisotropic exchange interaction in germanium hole spin qubits

Leonardo Massai, Bence Hetenyi, Kostas Tsoukalas, Eoin Gerard Kelly, Inga Seidler, Michele Aldeghi, Alexei Orekhov, Lisa Sommer, Stephan Paredes, Steve Bedell, Felix Schupp and Patrick Harvey-Collard

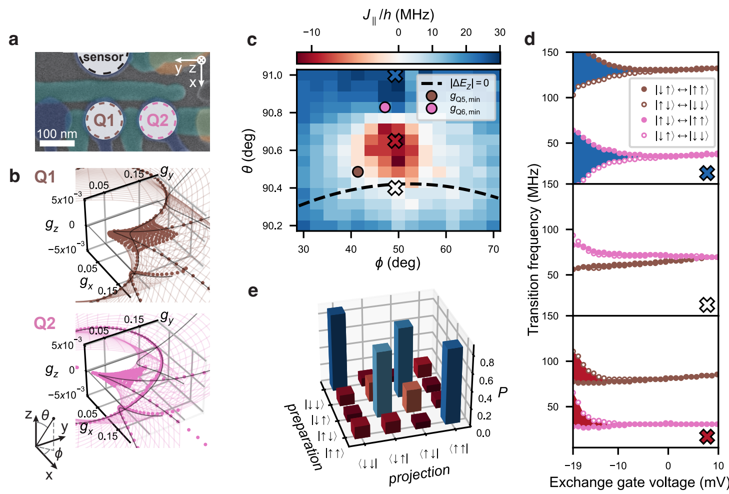
Hole spins in strained germanium (sGe) heterostructures have quickly become a promising qubit platform with favourable properties. The strong spin-orbit interaction of holes states results in the emergence of magnetic-field-dependent anisotropies in the qubit g-tensors and operational sweet-spots that can affect and improve single-qubit performance. Theory predicts that anisotropies would also arise in the exchange interaction, the main enabler of two-qubit gates, and this has been observed in holes in silicon. A natural question arises whether a similar effect can occur in sGe, and whether anisotropic exchange can lead to improved two-qubit operation.

In this work, we study two single-hole spin qubits in electrically defined quantum dots in sGe (Fig. 1a), starting with the characterisation of the g-tensors and focusing on their waist region (Fig. 1b). We map the energy spectrum of the two coupled spins, and we extract the parallel exchange component $J_{||}$ in a 2d-angular region comprising the two minima of the g tensors (Fig. 1c). We observe a strong anisotropy of $J_{||}$ in this region, explained by the g-tensors difference, rather than spin-flip tunnelling. We can distinguish two areas of positive and negative exchange, delimited by a node line, as confirmed by the measured exchange fans at three different spots (blue, red and white crosses in Fig. 1d). Furthermore, by pointing the B field to the intersection of the $J_{||} = 0$ and the $|\Delta EZ| = 0$ lines, we reduce the $|\downarrow\uparrow\rangle$, $|\uparrow\downarrow\rangle$ Hamiltonian to a Hermitian off-diagonal matrix where only $J_{\perp}$ appears. This enables a 64ns-long baseband iSWAP gate (partial tomography in Fig. 1e).

We believe that g-tensor engineering can simultaneously enable fast baseband single- and two-qubit gates, respectively via hopping spins and anisotropic exchange interaction, paving a new direction for hole spin qubits in sparse quantum dot arrays in germanium.

work in progress

Session: Wednesday 17:30



Circular-Modulated Concatenated Continuous Driving: Robust Spin Control without Rotating-Wave Approximation in the Second Rotating Frame

Takeru Utsugi, Takuma Kuno, Andrew J. Ramsay, Normann Mertig, Noriyuki Lee, Itaru Yanagi, Toshiyuki Mine, Shinichi Saito, Digh Hisamoto, Ryuta Tsuchiya and Hiroyuki Mizuno

Recently, we have shown that the coherence of an electron spin in natural silicon can be extended, and controlled using phase-modulated concatenated continuous driving (CCD) method [1]. CCD is a robust control method, originally developed for NV centers, where a drive modulated at the Rabi frequency provides a continuous dynamical decoupling of the spin. In the analysis, the rotating-wave approximation (RWA) introduces significant errors in high-speed, resonantly driven quantum operations. In this work, we propose Circular-Modulated Concatenated Continuous Driving (CMCCD) that eliminates the need for the RWA. Recognizing that RWA errors stem from the use of linearly polarized driving fields, we construct circularly polarized fields in the first rotating frame by combining phase and amplitude modulation. This cancels the counter-rotating term that is the source of RWA error.

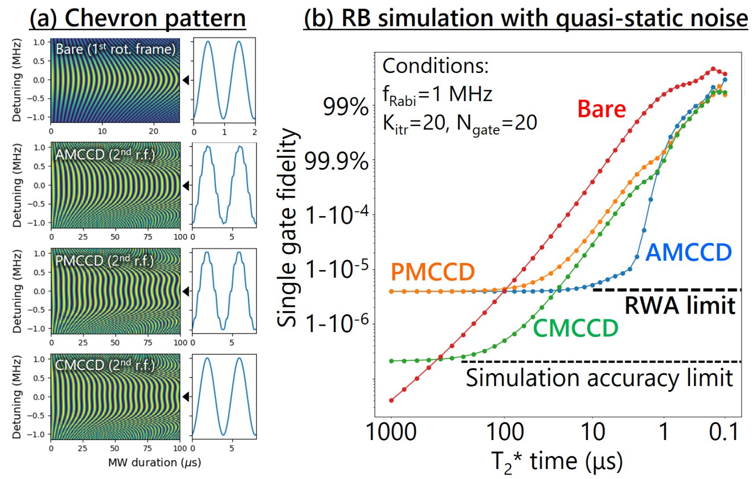
We validate the effectiveness of CMCCD through quantum dynamics simulations, comparing it with conventional methods including bare qubit, amplitude-modulated CCD (AMCCD), and phase-modulated CCD (PMCCD). Additionally, we evaluate the performance of various CCD protocols using randomized benchmarking (RB) simulations under quasi-static noise, which models nuclear spin noise—one of the dominant sources of decoherence in silicon-based qubits. Our results show that CMCCD successfully avoids the kink structure in Rabi oscillations caused by RWA errors [see fig.(a)], achieving high-fidelity and robust quantum operations beyond the RWA limit [see fig.(b)]. Moreover, CCD performance varies with the noise level, characterized by the dephasing time T2*, highlighting the importance of selecting an optimal CCD scheme tailored to the noise environment. These findings suggest that CMCCD and its variants could play a pivotal role in enabling scalable quantum computing with silicon-based qubit.

Acknowledgements: This work is supported by JST Moonshot R&D Grant No. JPMJMS2065.

References: [1] T. Kuno et al., arXiv 2503.19410 (2025)

work in progress

Session: Poster 1.1


(a) Chevron pattern
(b) RB simulation with quasi-static noise
Bare (1st rot. frame)
AMCCD (2nd r.f.)
PMCCD (2nd r.f.)
CMCCD (2nd r.f.)
Detuning (MHz)
MW duration (μs)
Conditions:
fRabi=1 MHz
Kitr=20, Ngate=20
Bare
AMCCD
PMCCD
CMCCD
RWA limit
Simulation accuracy limit
Single gate fidelity
99%
99.9%
1-10-4
1-10-5
1-10-6
1000
100
10
1
0.1
T2* time (μs)

Stabilization of spin resonance frequency by feedback control of Stark shift

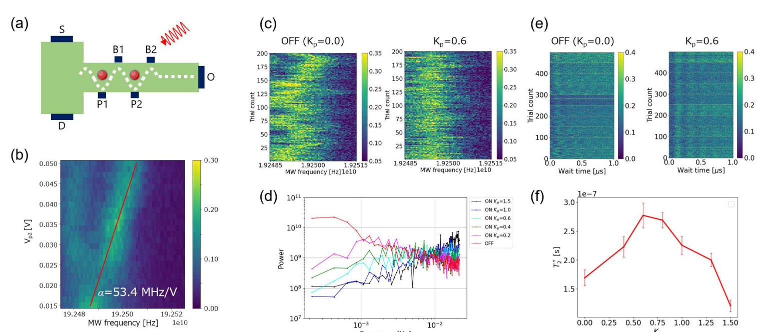
Ryuji Ukai, Atsushi Miyamoto, Takeru Utsugi, Takuma Kuno, Sofie Beyne, Yosuke Shimura, Julien Jussot, Roy Li, Clement Godfrin, Bart Raes, Roger Loo, Sylvain Baudot, Stefan Kubicek, Yann Canvel, Danny Wan, Kristiaan De Greve, Shinichi Saito, Digh Hisamoto, Ryuta Tsuchiya, Takashi Takemoto and Hiroyuki Mizuno

The resonance frequency of an electron spin is subject to fluctuation over time due to interactions with surrounding environment such as nuclear magnetic fields. This fluctuation impedes the precision of spin control. In this work, we experimentally demonstrate stabilization of spin resonance frequency by feedback control of Stark shift in a natural silicon metal-oxide-semiconductor (Si-MOS) quantum dot (Fig. a). This method is employed to stabilize the spin resonance frequency by adjusting the voltage on the plunger gate of the qubits. It leads to controllability of individual qubits and is applicable to an architecture that controls multiple qubits by electron spin resonance (ESR) using a single microwave frequency. The estimation of Stark shift sensitivity α was conducted by π-pulse ESR measurement (Fig. b). As for the feedback, the P controller was adopted: $VP2[n+1] = VP2[n] - Kp/\alpha*(fest[n] - ftarget)$, where VP2[n] and fest[n] represent the voltage on the plunger gate and the estimated spin resonance frequency at the n-th step, respectively, ftarget represents the target frequency, and Kp represents the gain factor of the feedback control. Figure c shows the measurement results for the repeated estimation of the spin resonance frequency for approximately 76 minutes, with feedback control inactivated and activated (Kp = 0.6). The power spectrum of the frequency fluctuation was analyzed with several feedback control gains (Fig. d). Figures c and d show that the fluctuation of the spin resonance frequency has been reduced in the low frequency range. In addition, we demonstrated the feasibility of stabilizing Ramsey interferometry through the implementation of feedback control by Stark shift. T2* was extended from 0.17μs to 0.28μs (Figs. e and f). Our result will contribute to the realization of high-precision multi-qubit operations through individual control of spin resonance frequencies.

This work was supported by JST Moonshot R&D Grant Number JPMJMS2065.

work in progress

Session: Poster 1.2



Coherent Control of a Silicon Hole Spin Qubit Using Concatenated Continuous Driving

Yusuke Sato, Sayyid Irsyadul Ibad, Takuma Kuno, Itaru Yanagi, Toshiyuki Mine, Ryuta Tsuchiya, Digh Hisamoto, Hiroyuki Mizuno, Raisei Mizokuchi, Jun Yoneda and Tetsuo Kodera

Hole spins in quantum dots are promising candidates for realizing quantum computers due to their intrinsic strong spin-orbit coupling, which enables fast and all-electrical control. However, this strong coupling makes qubits susceptible to charge noise, which leads to short coherence time [1]. Dynamical decoupling protocols offer an effective approach for suppressing this effect by filtering out low frequency noise. Among various schemes, the concatenated continuous drive (CCD) protocol has attracted attention for providing always-on dynamical decoupling with robustness against detuning noise as well as Rabi driving fluctuations [2,3]. In this work, we demonstrate full coherent control of a silicon hole spin qubit in the CCD frame and evaluate its coherence time by performing Rabi and Ramsey experiments (see Fig. (a) and (b)). The dressed qubit in the CCD frame shows no observable decay within the measurement duration of both Rabi and Ramsey experiments, which is limited by the maximum control time achievable in our transport current measurement setup. This underscores the effectiveness of the CCD protocol in suppressing both Rabi drive and detuning noise, thereby enhancing the coherence time relative to bare qubit operation. Our work represents the first demonstration of the CCD-dressed qubit in hole spin systems, showcasing the potential for hole spin qubits with long coherence times.

[1] N. Piot, et al., Nat. Nanotechnol. 17, 1072 (2022).
[2] A. J. Ramsay, et al., Nat. Commun. 14, 461 (2023).
[3] T. Kuno, et al., arXiv:2503.19410v1 (2025).

Session: Poster 1.3

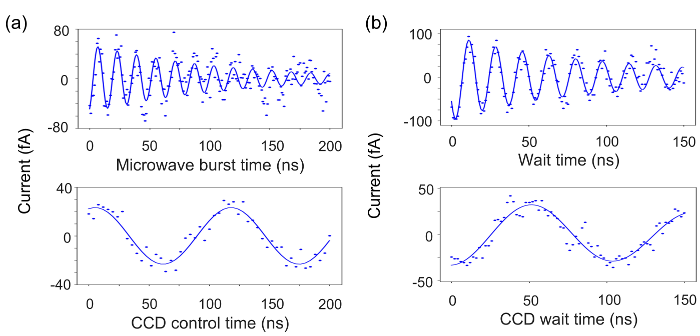


Figure (a) Coherent control of the bare qubit (top) and the CCD-dressed qubit (bottom). The trace for the bare qubit is corrected for burst time-dependent offset. (b) Ramsey experiment for the bare qubit (top) and the CCD-dressed qubit (bottom).

High fidelity EDSR in a disordered Si/SiGe Wiggle Well

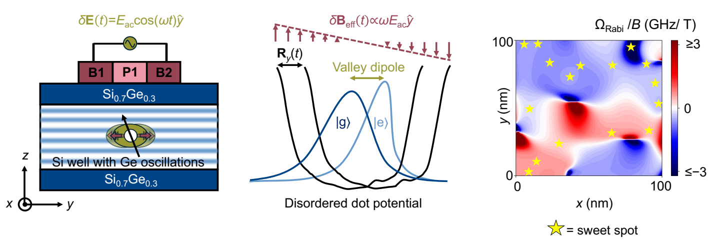
Hudaiba Soomro, Minyoung Kim, Mark Eriksson, Benjamin D. Woods and Mark Friesen

Silicon-based single-electron spin qubits commonly use micromagnets to create an artificial spin-orbit coupling (SOC) for Electric Dipole Spin Resonance (EDSR); however, this approach faces scalability challenges. Previously, it has been shown that the Wiggle Well may sufficiently enhance the otherwise weak SOC in the conduction band of Si, allowing for implementation of a strong EDSR protocol; previous calculations indicate that Rabi frequencies exceeding 500 MHz/T may be possible. However, SiGe random-alloy disorder causes spatial variations that have not been fully accounted for in these calculations.

In this work, we show that alloy disorder gives rise to two main effects relevant for EDSR: the generation of a strong valley dipole (providing an additional EDSR mechanism), and randomization of valley parameters (providing a position-dependent Rabi frequency). We find that the valley-dipole contribution to the Rabi frequency is particularly pronounced in the low-valley-splitting regime. Consequently, the Rabi frequency Ω_{Rabi} is spatially varying, with strong local enhancements caused by alloy disorder. Such enhancements boost the gate speeds but also leave the qubit vulnerable to charge-noise dephasing over the time scale $T_{2,\text{Rabi}}$. We therefore compute the quality factor $Q = \Omega_{\text{Rabi}}/T_{2,\text{Rabi}}/2\pi$. Our results show that while high quality factors are achievable over most quantum dot locations, regions with low valley splitting can degrade coherence. Importantly, we find sweet spots with especially high Q where Ω_{Rabi} is first-order insensitive to electric-field fluctuations in all three spatial directions. Therefore, our results demonstrate that optimal single-qubit gate operations can be achieved by tuning the quantum dot position.

Work in progress

Session: Poster 1.4



High fidelity control in a ^{nat}Si-MOS quantum dot using a 300 mm industrial process

Xander Peetroons, Xunyao Luo, Tsung-Yeh Yang, Normann Mertig, Charles Smith, Helena Knowles, Sofie Beyne, Yosuke Shimura, Julien Jussot, Clement Godfrin, Ruoyu Li, Roger Loo, Sylvain Baudot, Stefan Kubicek, Shuchi Kaushik, Danny Wan, Kristiaan De Greve, Takeru Utsugi, takuma kuno, Noriyuki Lee, Itaru Yanagi, Toshiyuki Mine, Satoshi Muraoka, Shinichi Saito, Digh Hisamoto, Ryuta Tsuchiya, Hiroyuki Mizuno and Andrew Ramsay

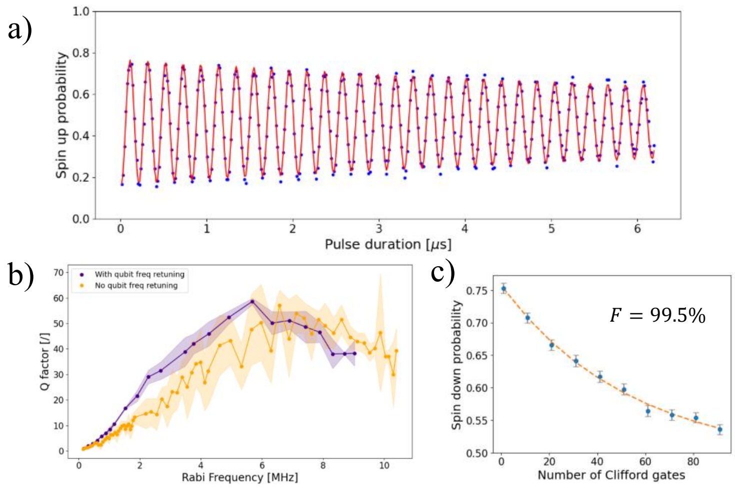
In this work, we present the coherent control of a single electron spin qubit in a Si-MOS quantum dot fabricated on natural silicon, using a 300 mm state-of-the-art industrial process. [1] Despite the nuclear spin noise in the natural silicon device, control fidelities exceeding the fault-tolerant threshold have been achieved, showcasing high-performance qubits in Si-MOS.

We realize coherent control of the spin qubit using electron spin resonance via an integrated stripline (Fig. a). To maintain high control fidelity in the presence of magnetic and charge noise, fast real-time feedback on the qubit frequency is implemented through a modified Ramsey sequence. [2] The error signal is used to study the spin noise environment and the power dependence of the coherence. After additional control pulse calibration, we achieve consistent operation with fidelity above 99% (Fig. c). Our results demonstrate robust high-fidelity spin control in a Si-MOS platform.

Figure: a) Rabi oscillation at 5 MHz using real-time feedback on qubit frequency, with a quality factor Q=T2Rabi fRabi=50. T2Rabi and fRabi, are the coherence time during driven evolution and Rabi frequency. b) Power dependence of the quality factor with and without feedback on the qubit frequency, c) Randomized benchmarking showing the decay to a fully mixed state over 100 Clifford gates, with a single gate fidelity of 99.5%.

Acknowledgement: This work was supported by JST Moonshot R&D Grant Number JPMJMS2065.
[1] Li, R. et al.IEEE International Electron Devices Meeting (IEDM) 38.3.1-38.3.4 (2020).
doi:10.1109/IEDM13553.2020.9371956.
[2] Dumoulin Stuyck, N. et al. Appl. Phys. Lett. 124, 114003 (2024).

Session: Poster 1.5


a)
Spin up probability
Pulse duration [μs]
b)
With qubit freq retuning
No qubit freq retuning
Q factor [/]
Rabi Frequency [MHz]
c)
$F = 99.5\%$
Spin down probability
Number of Clifford gates

Efficient and robust hopping gates in Si/SiGe quantum dots with enhanced spin-orbit coupling

Minyoung Kim and Benjamin D. Woods

Single-spin qubits in Si/SiGe quantum dots typically employ micromagnets, high-frequency AC driving, and large magnetic fields to perform single-qubit gates. These requirements present scalability concerns, lead to charge-noise-induced dephasing, and cause device heating. In this work, we propose to eliminate all of these requirements by implementing hopping-based single-qubit gates in a double dot within the Wiggle Well, which is a Si/SiGe heterostructure that incorporates Ge concentrations oscillations into the quantum well region, as shown in Fig. 1(a). We show that the enhanced spin-orbit coupling of the Wiggle Well produces (upon a unitary transformation) a significant misalignment of the spin quantization axes in the two dots, as shown in Fig. 1(b). This allows coherent and efficient spin rotations by shuttling the electron between the dots via slow voltage pulses, as illustrated in Fig. 1(b) and the inset of Fig. 1(c). We analyze our designed single-qubit gates under realistic experimental conditions, including finite ramp time, charge noise, the presence of alloy disorder, and finite valley splittings. We find a remarkable robustness of the gates against noise, as demonstrated in Fig. 1(c), which shows the distribution of average X gate fidelity for many charge noise and alloy disorder realizations. Furthermore, we find an interesting and potentially useful dependence of the hopping gate on the valley phase difference between the dots. Therefore, this work presents a promising route to scalable, electrically controlled, and high-fidelity spin qubits in Si.

Session: Poster 1.6

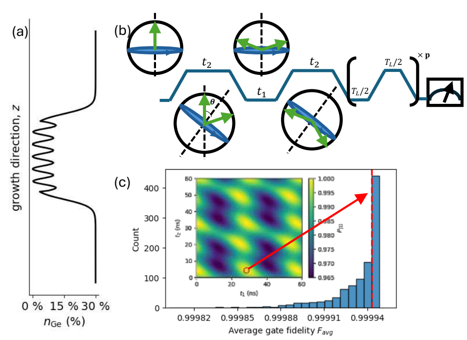


Figure 1: (a) Ge concentration profile along the growth direction (z) of a Wiggle Well heterostructure. (b) Pulse sequence for the hopping-based X gate. The spin quantization axes of the two dots are tilted by an angle θ due to spin-orbit coupling. Rotations of duration $T_L/2$ (half a Larmor period) about these tilted axes are applied $p = \lfloor \frac{\pi}{2\theta} \rfloor$ times to realize an effective π rotation about the X-axis. (c) Main panel: Average gate fidelity of the optimized X gate (red dashed line) and its distribution under realistic quasi-static charge noise (blue histogram). Inset: Probability of measuring $|1\rangle$ as a function of pulse durations t_1 and t_2; the red marker denotes the optimal (t_1^*, t_2^*) that maximizes $|1\rangle$-probability.

Demonstration of multiple-qubit noise suppression in a four-qubit silicon device

Hyeongyu Jang, Jaemin Park, Hanseo Sohn, Younguk Song, Davide Degli Esposti, Lucas E.A Stehouwer, Giordano Scappucci and Dohun Kim

Silicon-based semiconductor quantum computing is a promising platform for large-scale quantum information processing (QIP). With the recent demonstration of a scalable, state-of-the-art architecture in a semiconductor qubit platform, understanding how to address noise that scales with system size is essential for fault-tolerant quantum computation. Real-time adaptive control offers a powerful tool for stabilizing universal quantum operations, and its validation has been conducted across various platforms for QIP. However, most of these studies primarily focused on single-qubit systems, and little is known about the feasibility and control performance in multiple qubits. Here, we demonstrate a multiple active suppression of noises by implementing measurement-based feedback control involving rapid Pauli spin blockade-based parity readouts in a four-qubit array. We present a faster feedback routine utilizing the sequential Monte-Carlo method that outperforms conventional Bayesian estimation methods in terms of feedback performance. Finally, we discuss the underlying challenges, including stochastic errors and systematic (Hamiltonian) errors, as well as the path toward achieving high-fidelity entangled states.

Session: Poster 1.7

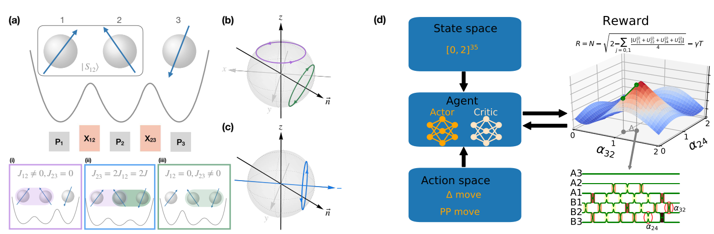
Fast quantum gates for exchange-only qubits

Guido Burkard

Exchange-only quantum computation is a version of spin-based quantum computation that entirely avoids the difficulty of controlling individual spins with radio-frequency irradiation and instead functions by sequences of base-band exchange pulses. Each exchange-only qubit comprises three electron spins, as shown in Figure (a), where intra-qubit exchange couplings generate rotations about non-collinear axes, see Figures (b) and (c). This is particularly attractive for spin qubits in the conduction band of silicon with its relatively weak spin-orbit coupling, where typically magnetic field gradients are needed to enable electrically controlled single-qubit gates. A challenge for exchange-only quantum computation is to find short sequences that generate the required logical quantum gates. A reduction in the total gate time of such synthesized quantum gates can help minimize the effects of decoherence and control errors during gate operation, thereby increasing the total gate fidelity. We present two approaches towards faster gates for exchange-only quantum computing. First, we apply reinforcement learning to the optimization of exchange-gate sequences realizing the CNOT and CZ two-qubit gates, which lend themselves to the construction of universal gate sets for quantum computation [1], see Figure (d). We obtain a significant improvement regarding the total gate time compared to previously published results. Second, we demonstrate faster implementations of single-qubit gates using simultaneous exchange pulses and outline related techniques for the construction of two-qubit gates [2]. A simultaneous exchange implementation of single-qubit X rotations in a SiGe quantum dot device has been experimentally demonstrated, characterized, and compared to the state of the art with sequential exchange pulses.

[1] V. N. Ivanova-Rohling, N. Rohling, and G. Burkard, EPJ Quantum Technology 12, 53 (2025)

Session: Poster 1.8



A cloud-accessible four-qubit electron spin quantum processor in a 300 mm metal-oxide-semiconductor process

David J. Ibberson, Giovanni A. Oakes, Virginia N. Ciriano-Tejel, Joe Finney, Sebastian Orbell, Stefan Kubicek, Danny Wan, Sofie Beyne, Kristiaan De Greve, Katarina Brlec, Julio A. Figueroa Quintana, Tuula Ritakari, Ross C. Leon, April Carniol, David F. Wise, John J. L. Morton and M. Fernando Gonzalez-Zalba

As silicon-based quantum computing develops, essential steps for scaling up the technology include transitioning device manufacturing to industrial-grade 300mm wafer processing and deploying full cloud-accessible systems in third-party facilities for validation.

In this work, we present an electron spin qubit quantum processor manufactured using a 300 mm metal-oxide-semiconductor process, featuring an overlapping polysilicon gate design, isotopically enriched silicon (800 ppm), and low charge noise level (<1 μeV/√Hz at 1 Hz). The four single-electron spin qubits are arranged in a linear topology with controllable nearest-neighbour exchange coupling.

For high-fidelity state readout, we use radiofrequency charge sensors placed non-collinearly to the qubit array, enabling further expansion of this unit cell while achieving an average spin parity readout fidelity above 99% in less than 10 μs across all qubit pairs. Single-qubit gates are performed using frequency-selective, magnetically driven electron spin resonance, demonstrating an average randomised benchmarking gate fidelity above 99%. The QPU supports CPhase gates among all adjacent qubit pairs, driven by adiabatic exchange activation.

The full system is deployed in the UK's National Quantum Computing Centre and is accessible over a remote interface. The software stack includes automated calibration routines for maintaining initialisation, readout, one and two-qubit gate fidelities. For straightforward running of circuits, there is a high-level interface to the Cirq and Qiskit frameworks with support for the PyGSTi library for benchmarking.

Session: Poster 1.9

Resonant ST oscillation in low magnetic field and noisy nuclear environment

Hideaki Yuta, Tatsuo Tsuzuki, Takafumi Fujita, Akira Oiwa, Arne Ludwig and Andreas Dirk Wieck

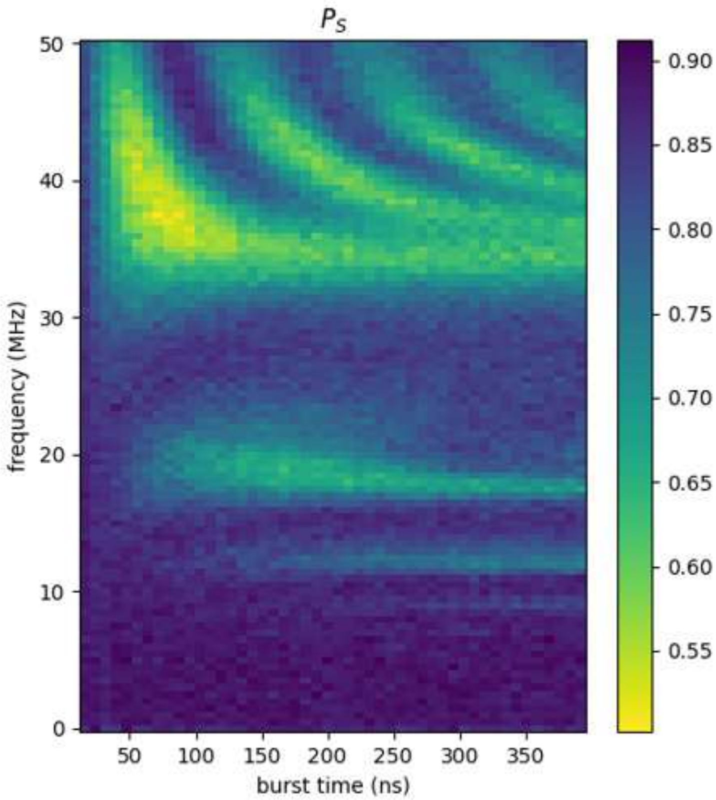
Singlet-triplet (ST) qubits in semiconductor quantum dots have been one of the promising candidates for scalable quantum computation due to their long coherence times and all-electric control. In ST qubits, the difference of Zeeman splitting (ΔB) between two quantum dot serves as a single-qubit control knob as well as a sensor for environmental magnetic field. This ΔB is strongly affected by the Overhauser field generated by surrounding nuclear spins. Therefore, either a micromagnet or a relatively high external magnetic field is typically required for qubit operation to overcome such nuclear spin noise.

In this work, we demonstrate ST oscillations between two electron spins confined in a GaAs double quantum dot without using a micromagnet. GaAs exhibits a large Overhauser field because all naturally occurring isotopes of Ga and As possess nonzero nuclear spin. We operate the system in the low magnetic field regime (100 mT), where the fluctuating nuclear spin field becomes the dominant contribution to ΔB. We apply an oscillatory pulse to the detuning of the double quantum dot and measure the spin state using Pauli spin blockade. The figure presents the singlet probability as a function of driving frequency and burst time. The absence of a clear chevron pattern is due to averaging over ΔB fluctuations. Higher-order resonances features are also observed at lower frequencies, indicating the strong nonlinear energy landscape.

These results demonstrate that coherent resonant ST oscillations are visible under low magnetic fields without the use of micromagnets, even in a condition governed by the random Overhauser field fluctuations. This work provides some insights into the interplay of ST qubit and the surrounding nuclear spin field fluctuation.

Work in progress.

Session: Poster 1.10


P_S
frequency (MHz)
burst time (ns)
0
10
20
30
40
50
50
100
150
200
250
300
350
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55

Simple and fast silicon-based quantum dot/bit simulator for large-scale quantum computing

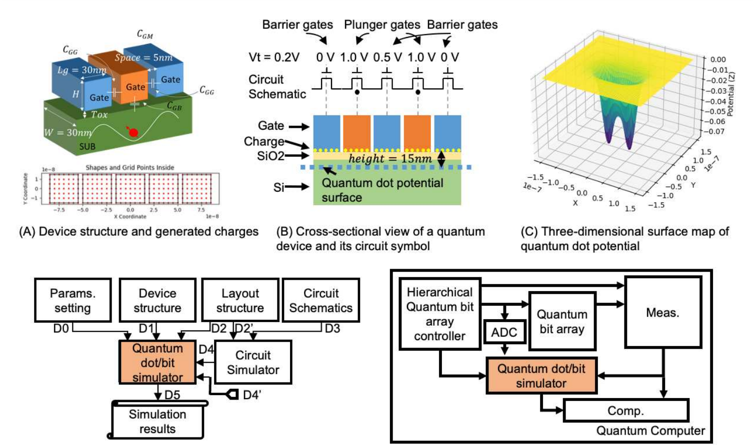
Yusuke Kanno

We have developed simple and fast simulation technology to calculate and visualize the electrostatic potential in silicon-based quantum bit computers. In particular, the electrostatic potential of quantum dots is essential for controlling quantum bit operations. To achieve high-fidelity operations in control system development, it is critical to deeply understand the quantum effects based on the behavior of potential induced by the control signals. Developing the simple and fast quantum dot/bit simulator applicable to the larger scale is indispensable. Based on the fundamental principle of electromagnetism that charge exists where potential exists, we propose a method of calculating the potential of quantum dots by setting virtual point charges at the plunger gates and the barrier gates, and summing up every potentials created by these point charges (calculated as double layer potentials when appropriate, in accordance with the boundary conditions)(Fig.(A), (B)). By appropriately setting the generation interval of point charges according to the distance from the point charge to the 2DEG potential formation surface, it is possible to reduce charge quantization error. The analytical solution for the case of uniform surface charge is known as ref. [1], and our method confirmed that its shape is identical to that of the analytical solution (Fig.(C)). Moreover, our method interfaces existing LSI design tools using minimal methods, enabling efficient collaboration with the development of control technologies based on a deep understanding of quantum bit operations(Fig.(D)). This technology can rapidly simulate the shape of quantum dots and has the potential to become a promising candidate for a quantum dot/bit simulator (digital twin for QC) that can be integrated into actual quantum computers in the future (Fig.(E)).

This work was supported by JST Moonshot R&D Grant Number JPMJMS2065.

[1] J. H. Davies, et al. "Modeling the patterned two-dimensional electron gas: Electrostatics," J. Appl. Phys. 77, 4504–4512 (1995)

Session: Poster 1.11



(A) Device structure and generated charges

(B) Cross-sectional view of a quantum device and its circuit symbol

(C) Three-dimensional surface map of quantum dot potential

(D) Quantum dot/bit simulator can collaborate with other semiconductor tools.

(E) Quantum dot/bit simulator built inline into quantum computers.(Future plan)

Using a Coulomb blockade island as a reservoir for qubit dots

Jakob Walsh, Miriam Schweinböck, Yuji Yamamoto, Felix Reichmann, Lars R. Schreiber and Dominique Bougeard

Driven by scalability efforts, the layout of spin qubit devices more and more develops both towards 1D or 2D arrays of quantum dots hosting spin qubits and towards shuttling approaches, where a spin qubit is moved between functional zones of the qubit processor. Given certain advantages of baseband detection, it is still a popular approach to integrate dedicated charge sensors into such device layouts. An evolution compared to earlier (few-qubit) device layouts resides in the fact that, the charge sensor now frequently covers two functionalities. In addition to charge sensing, it simultaneously also plays the role of a charge carrier reservoir for the adjacent linear chain of spin qubit dots or for a shuttling lane.

In this contribution, we study peculiarities which arise in the tuning and the operation of qubit dots when they are loaded and unloaded via an adjacent charge sensor, which is a Coulomb blockade island. Our device allows to either use the sensor island simultaneously for charge sensing and as the reservoir for an adjacent qubit dot, or to use the sensor island only for charge readout of the adjacent qubit dot. In the latter case, the qubit dot is connected to a separate, extended reservoir. These configurations allow us to compare these two operation modes within the same device, always using the same sensor island and the same qubit dot.

For the case where the sensor island plays both roles – charge sensor and reservoir for the qubit dot – we will particularly discuss unusual charge sensing signatures in the few-electron regime of the qubit dot. It appears that using a sensor island simultaneously as a reservoir increases the sensitivity of the sensor to detect the occasional loss of single electrons out of the qubit dot to its environment.

Session: Poster 1.12

Revealing Correlated Electron Behavior in Silicon Dopant Arrays through Spin-Resolved Transport

Eric D. Switzer and Garnett W. Bryant

Analog quantum simulators based on phosphorus-doped silicon quantum dot arrays have recently been used to investigate extended Fermi-Hubbard models [1]. A key open question is whether transport measurements in such silicon-based two-dimensional nanoscale arrays, when coupled to metallic leads, can provide insight into the underlying many-body physics of the simulated models [2]. In particular, it remains to be determined whether spin-dependent transport properties can reveal signatures of strong on-site and intersite Coulomb interactions. In this work, we numerically examine the spin-resolved transport properties of various two-dimensional quantum dot array geometries under two distinct coupling regimes: (i) weak coupling to ferromagnetic leads, and (ii) strong coupling to similarly polarized leads, which induces spin-dependent renormalization of the array's local density of states. Using the steady-state non-equilibrium Green's function formalism, we analyze both two-terminal and four-terminal configurations to uncover the role of many-body wavefunction interference in determining the transport response. Our results demonstrate that spin-polarized transport measurements in phosphorus dopant-based silicon quantum dot arrays can serve as a diagnostic tool for probing many-body effects in representative extended Fermi-Hubbard models.

[1] X. Wang, E. Khatami, F. Fei, J. Wyrick, P. Namboodiri, R. Kashid, A. F. Rigosi, G. Bryant, and R. Silver, Nat. Commun. 13, 6824 (2022).

[2] M. Gawełczyk, G. W. Bryant, and M. Zieliński, arXiv:2405.05217.

work in progress

Session: Poster 1.13

Advances in control and characterization of six dot HRL SLEDGE devices from the Qubits for Computing Foundry

Joshua J. Lou, Adam R. Mills, Rafal Oszwaldowski, Jonathan J. Marbey, Daniel A. Schug, Justyna P. Zwolak, Edwin Acuna, Matthew D. Reed, Christopher Richardson, Charles Tahan Tahan and Samuel G. Carter

Spin qubits in electrically-defined Si/SiGe quantum dots are attractive for scalable quantum computing, with small qubit sizes, electrical control, promising coherence times, and the silicon material platform. Still, there are significant challenges to address in terms of the complexity of tuning up and controlling multi-dot devices as well as sensitivity of spin qubits to environmental noise. To address these challenges, we are using six-dot Si/SiGe SLEDGE devices from HRL as part of the Qubits for Computing Foundry. These devices have been characterized and are being used to explore the three-dot exchange-only qubit encoding, achieving few μs single-shot readout and 2-axis control at the symmetric operating points (SOPs) (Fig. 1). Preliminary demonstration of full-permutation dynamical decoupling using sequences of N-Z π-pulses has been achieved to extend the coherence time of the qubit. We have begun exploring the effects of gamma radiation and how it shifts charging energies of quantum dots. Additionally, machine learning models have been developed that can assess Pauli Spin Blockade (PSB) window quality and make tuning suggestions, working towards fully automated PSB tuning. Lastly, we are beginning to work with HRL to look into novel qubit encodings that will provide advantages over others such as working in baseband and being insensitive to magnetic field gradients.

Session: Poster 1.14

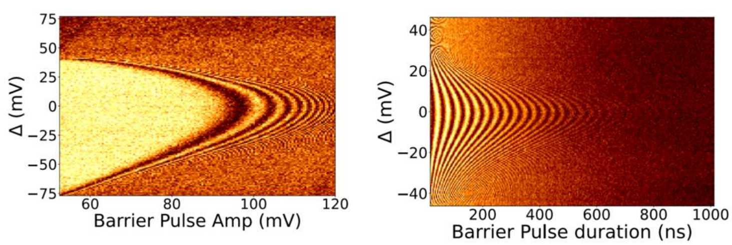


Figure 1: Fingerprint (left) and Rabi Chevron (right) plots showing the symmetric operating point of the n-axis of our 3-dot exchange-only qubit at 0 detuning.

NMOS and PMOS Tunable Quantum Dots Fabricated on FDX-22 Process

Conor Power, Mathieu Moras, Andrii Sokolov, Claude Rohrbacher, Xutong Wu, Sergey Amitonov, Ioanna Kriekouki, Agostino Apra, Panagiotis Giounanlis, Mike Asker, Maurice Harkin, Peter Hanos-Puskai, Pierre Bisiaux, Imran Bashir, David Redmond, Dirk Leipold, Robert Bogdan Staszewski, Brendan Barry, Nodar Samkharadze and Elena Blokhina

We report on the experimental demonstration of quantum dot arrays (QDAs) fabricated using a standard commercial 22 nm Fully Depleted Silicon-On-Insulator (FD-SOI) CMOS process, highlighting their potential for scalable quantum computing. Using industry-compatible fabrication (GlobalFoundries 22FDX™), we form quantum dots electrostatically in transistor-like channels, without modifying the standard photolithographic process. The device features five gate electrodes allowing dynamic control of quantum dot formation, inter-dot coupling, and charge detection.

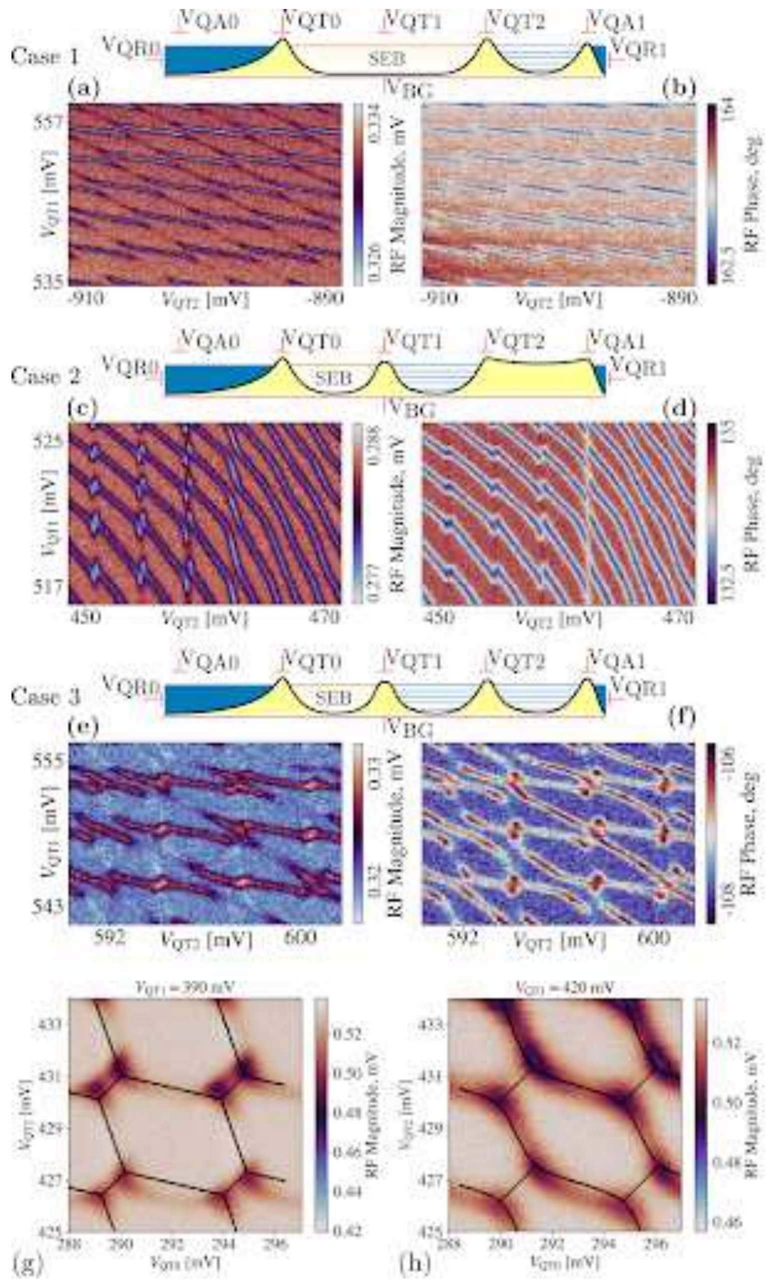
We demonstrate two key quantum functionalities in this CMOS-compatible platform. First, by tuning gate voltages, we achieve well-defined double quantum dot configurations with tunable tunnel barriers, confirmed via bias triangle measurements and charge stability diagrams at cryogenic temperatures (down to 10 mK). This enables precise control over quantum dot coupling, essential for two-qubit gates.

Second, we implement charge sensing using a single-electron box (SEB) located at the edge of the QDA. The SEB, configured from the same gate stack, effectively detects charge transitions in adjacent quantum dots, validating its use as an integrated charge sensor. Various SEB configurations show clear signatures of both single and double quantum dot charge states via radio-frequency reflectometry.

This work marks the first demonstration of charge control and sensing in multi-dot quantum devices fabricated entirely within a commercial CMOS process. It provides strong evidence for the feasibility of large-scale quantum dot-based qubit arrays co-integrated with classical control electronics on the same silicon platform, accelerating the path toward scalable quantum computing.

https://arxiv.org/abs/2412.08422

Session: Poster 1.15


Case 1
Case 2
Case 3
SEB
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
RF Magnitude, mV
RF Phase, deg

Wiring-Efficient Control and Simulation of Silicon Spin Qubit Arrays Driven by Global ESR

Bohdan Khromets, Zach D. Merino, Xinning Wang and Jonathan D. Baugh

Silicon quantum dot arrays driven by a global ESR field rely on small, Stark-shifted g-factor offsets to address individual spins. We introduce an optimal control framework [1] that derives analytic gate voltage trajectories for target quantum operations. The method integrates a first-order system of ODEs to generate closed-form plunger Vi(t) and tunnel gate Wi(t) waveforms that implement single-qubit rotations, SWAPk, and controlled-phase (CZ) gates with unitary fidelity in the ideal limit. Weakly off-resonant qubits are constrained to perform an integer 2π rotation in the rotating frame.

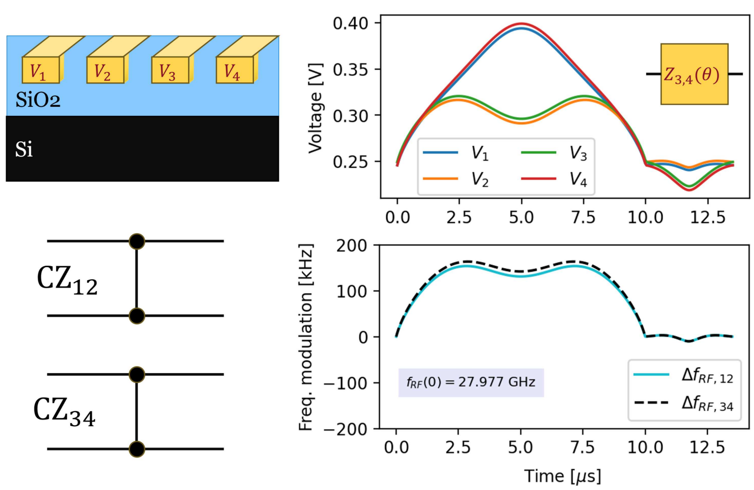
Working in a frequency-modulated frame, we exploit capacitive cross-coupling to eliminate the need for explicit tunnel gate control. For example, Fig. 1 shows simultaneous CZ gates in a four-dot array controlled only by plunger voltages—cutting the number of control lines in half while remaining within the desired charge stability region. The voltage dependences of Stark shifts and pairwise exchange couplings are determined using QuDiPy, a custom in-house Python package that converts 3D electrostatics from realistic device layouts into effective spin Hamiltonians. This enables a full ”layout-to-pulse” workflow entirely in software.

To evaluate algorithm-level impacts of noise and control error, we embed voltage fluctuations and miscalibration directly into time-domain simulations, such as a Variational Quantum Eigensolver for the H2 molecule. Quantum process tomography reveals how the Kraus operator structure evolves with different noise models, providing guidance for error mitigation strategies. Together, the optimal control framework and simulation tools offer a wiring-efficient, physics-grounded approach to high-fidelity control of silicon spin qubit arrays under global ESR excitation.

Reference

[1] B. Khromets, Z. D. Merino, J. Baugh, arXiv:2402.08146 (2024).

Session: Poster 1.16



Robust Automatic Tuning of Silicon Quantum Dots Using CNN-assisted Bayesian Optimization

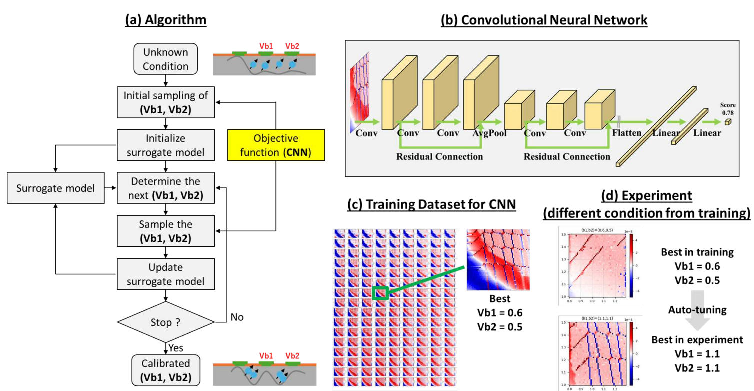
Yuto Kizawa, Atsushi Miyamoto, Ryuji Ukai, Takeru Utsugi, Takashi Takemoto, Takuji Miki, Makoto Nagata and Hiroyuki Mizuno

Automating the tuning process of silicon quantum dot devices has been one of the significant challenges in achieving scalable quantum computers. Conventionally, the gate voltages, especially the barrier voltages, of double quantum dot devices have been tuned manually, relying on expert heuristics for evaluating CSDs.

In this work, we propose an auto-tuning method for barrier gate voltages utilizing Bayesian optimization and machine learning. Bayesian optimization is one of the major algorithms applied to black-box optimization problems, where the internal structure and gradients of its objective function are unknown. In our method, shown in Fig.(a), we consider the barrier gate voltage tuning to be a black-box optimization. The complex relationship between measured CSD and its corresponding score is modeled by the convolutional neural network (Fig.(b)), whose generalization ability enables the evaluation of unknown CSDs, thereby enhancing the robustness of the tuning process. Training datasets are obtained through grid search under a certain condition (Fig.(c)). Once trained, the CNN enables automatic voltage optimization even under different conditions, without any heuristics. We conducted experiments with the parameter settings that changed from the training phase, demonstrating the robustness of our method (Fig. (d)).

Acknowledgement: This work was supported by JST Moonshot R&D Grant Number JPMJMS2065. We appreciate IMEC for providing chips to characterize qubits.

Session: Poster 1.17



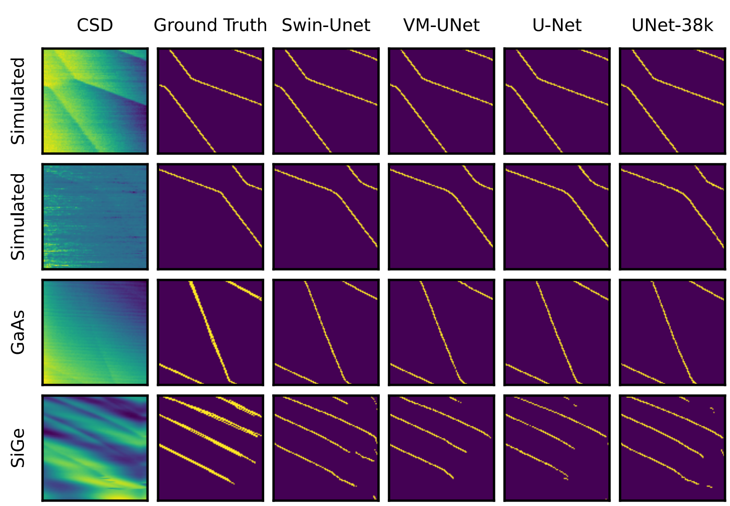
Towards Scalable Cryogenic Charge Transition Detection for Automated Quantum Dot Tuning

Fabian Hader, Fabian Fuchs, Sarah Fleitmann, Karin Havemann, Benedikt Scherer, Jan Vogelbruch, Lotte Geck and Stefan van Waasen

A scalable platform for quantum computing necessitates the automation of the quantum dot tuning process. One crucial step in this process is the capture of the requisite number of electrons within the quantum dots. This is typically accomplished through the analysis of charge stability diagrams (CSDs), wherein the charge transitions manifest as edges. Therefore, it is imperative to automatically recognize these edges with high reliability. To reduce the amount of data transferred to the room-temperature electronics, it is optimal to integrate this detection locally at the cryogenic stage. Machine learning methods for the charge transition detection necessitate substantial amounts of labelled data for training and testing purposes. Therefore, we developed SimCATS [1], a novel approach to the realistic simulation of such data. It enables the simulation of ideal CSD data, complemented by appropriate sensor responses and distortions. The simulated data facilitates the investigation and training of potential charge transition detection methods. Afterward, the trained detection methods are quantitatively and qualitatively evaluated using simulated and experimentally measured data from a GaAs and a SiGe qubit sample. Fig. 1 shows exemplary results of selected approaches. Subsequent exploration of model size reduction revealed a strong correlation with the complexity of the data analysis task, which was mitigated through the implementation of sensor dot compensation. In conjunction with superior measurement quality, this compensation enables robust and scalable ray-based (1D) charge transition detection. Finally, we estimate the cryogenic power requirements for the application of this approach to a fully automated, one-million-qubit system.

work in progress

Session: Poster 1.18



Scalable Autotuning of High-Temperature Quantum Dot Spin Qubits

Tyler J. Kovach, Daniel Schug, M. A. Wolfe, Patrick J. Walsh, Owen M. Eskandari, Jared Benson, Merritt P. Losert, E. R. MacQuarrie, Danielle Middlebrooks, Mark Friesen, M. A. Eriksson and Justyna P. Zwolak

As quantum dot (QD) spin qubits are beginning to deploy in small arrays [1], achieving robust and scalable autotuning—particularly at elevated temperatures—remains a formidable challenge. A major hurdle arises from trapped charges within the oxide layers, which induce random offset voltage shifts on gate electrodes, with magnitudes reaching approximately 650 mV in state-of-the-art devices [1]. While partial mitigation techniques exist, they typically necessitate prior device characterization [2].

In this talk, we introduce a streamlined, five-step physically intuitive framework for initializing and bootstrapping QD devices Fig.1(b) [3]. The most intricate step involves understanding the interaction between screening and finger gates during the independent formation of conduction channels. To dissect this relationship, we employ coupled Schrödinger-Poisson simulations integrated with current continuity analyses, enabling us to identify optimal operating regimes within the device's high-dimensional gate voltage space.

These insights are synthesized into a unified autotuning protocol, represented as a directed acyclic graph (DAG), allowing for fully autonomous calibration and characterization. We demonstrate this methodology experimentally at 1.3 K using an autotuner—BATIS (Bootstrapping Autonomously Testing Initialization System)—to configure a quad-QD Si/SiGe heterostructure device Fig1.(a,c).

We will also discuss our development of an open-source software platform designed to facilitate the deployment and scaling of DAG-based autotuning algorithms. This platform-agnostic approach addresses a critical bottleneck in quantum dot scalability, paving the way for the broader implementation of large QD arrays.

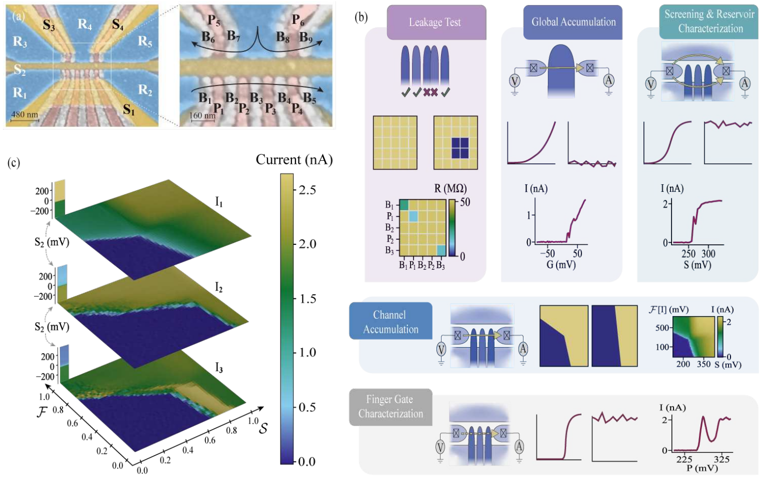
[1] S. Neyens, et. Al., Probing single electrons across 300-mm spin qubit wafers, Nature 629, 80 (2024).

[2] M. Meyer, et. Al., Single-electron occupation in quantum dot arrays at selectable plunger gate voltage, NanoLetters 23, 11593 (2023).

[3] T. Kovach, et. Al., BATIS: Bootstrapping, Autonomous Testing, and Initialization System for Quantum Dot Devices, arxiv: 2412.07676 (2024).

https://doi.org/10.48550/arXiv.2412.07676

Session: Poster 1.19


(a)
(b)
(c)
Leakage Test
Global Accumulation
Screening & Reservoir Characterization
Channel Accumulation
Finger Gate Characterization
Current (nA)
R (MΩ)
I (nA)
G (mV)
S (mV)
P (mV)
S₂ (mV)

Autonomous active monitoring and noise spectroscopy of two-dimensional quantum dot devices

Anantha S. Rao, Barnaby van Straaten, Valentin John, Cécile X. Yu, Stefan D. Oosterhout, Lucas Stehouwer, Giordano Scappucci, Michael Stewart, Menno Veldhorst, Francesco Borsoi and Justyna Zwolak

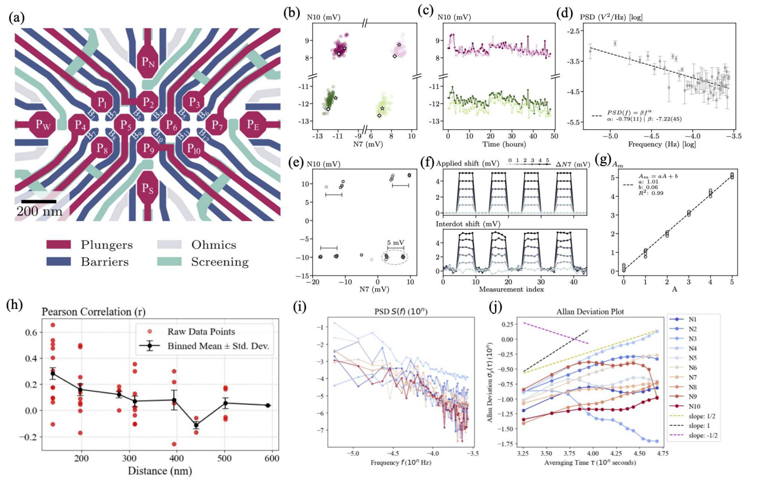
Device inhomogeneity and charge noise remain significant barriers to scaling semiconductor quantum dot arrays, as they require frequent, time-consuming calibrations and a deeper understanding of the underlying noise processes to enable effective mitigation strategies. To address these challenges, we introduce HERON, High-speed Electrostatic Recalibration and On-the-fly Noise-spectroscopy for real-time monitoring, characterization, and correction of noise in large quantum dot systems.

Built upon the modular autonomous virtualization system (MAViS), HERON leverages time-traces of extracted intra- and inter-dot charge transition lines (Fig. c) within double quantum dot stability maps (Fig. b). HERON operates by combining an ensemble of convolutional neural networks, Hough transformations, and physics-informed heuristics, to automatically identify charge transitions defining the relevant charge state and tracks their time evolution, enabling both impromptu corrections for electrostatic drifts and in-situ noise spectroscopy. From the recorded time-traces, we extract the power spectral density (PSD) (Fig. d,i) and perform Allan deviation analysis (Fig i) to characterize the local noise affecting each quantum dot. This allows us to identify noise sources and signatures of two-level fluctuators independent of charge sensor proximity. Cross-correlation analysis further uncovers spatio-temporal noise correlations across the array.

We deploy HERON on a 10-dot hole-based device in planar germanium (Fig 1a), performing continuous autonomous monitoring for over 48 hours. To benchmark sensitivity, we test HERON by introducing artificial voltage pulses, demonstrating reliable detection of electrostatic shifts as small as 0.5 mV (Fig e,f,g). HERON autonomously identifies dominant noise sources for each gate and quantifies their correlations, revealing a noise correlation length of approximately 200 nm (Fig h) in the device. Our methods establish a powerful toolkit for the autonomous stabilization and scalable operation of quantum dot arrays—an essential capability on the path to fault-tolerant quantum computing.

Work in progress

Session: Poster 1.20



Bayesian Optimisation for the Automatic Tune up of RF Sensor Dots for Silicon Quantum Dots

Tara Murphy, Felix -Ekkehard Ritter von Horstig, Di Xu, Helen Sawyor, Henry Moss, Fernando Gonzalez Zalba and David F. Wise

Silicon spin qubits are a promising platform for scalable quantum computing, primarily due to the advantages of CMOS-compatible fabrication and established semiconductor technology. A critical component in these quantum dot array systems is the use of sensor dots, which enable high-fidelity readout of charge states by detecting electron transitions through variations in gate voltages. However, tuning sensor dots remains a challenging and time-consuming task, typically requiring manual adjustment of multiple gate voltages in a high-dimensional parameter space. While several efforts have been made to automate tuning in quantum dot arrays [reference Barnaby], existing approaches have largely been limited to two-dimensional parameter sweeps and have not demonstrated generalizability across devices with varying geometries.

In this work, we present a fully automated method for tuning sensor dots using Bayesian Optimisation (BO), a strategy that actively incorporates feedback from prior measurements to guide future sampling and efficiently explore the gate voltage landscape. This allows the algorithm to identify optimal sensing peaks in terms of transconductance or peak amplitude with minimal experimental overhead. We demonstrate the effectiveness of this method on over 300 sensor dots (SEBs) across multiple devices with varying geometries, achieving reliable tuning by varying both its plunger and barrier gate. Furthermore, we extend our method to higher-dimensional tuning problems, including a demonstration involving five gate voltages. Our results highlight substantial time savings [quantify] and improved scalability, paving the way toward fully automated calibration of large-scale quantum dot arrays.

Session: Poster 1.21

Calibrating the Future: Standardization Challenges and Strategies for Quantum Dot Arrays

Justyna Zwolak

Gate-defined quantum dot (QD) arrays are a leading candidate for realizing scalable, coupled qubit systems and serve as a fundamental building block for quantum computers. Their compatibility with diverse materials and fabrication methods makes them attractive for quantum hardware development. However, present-day QD devices suffer from fabrication-induced disorder and environmental sensitivity, which complicate their characterization, tuning, and operation. These imperfections, combined with the exponential growth in parameter space in larger devices, render manual and heuristic control impractical [1].

At the Quantum Automation & Control Enhancement Lab (Q-ACE), we are developing a modular, autonomous, and platform-agnostic framework to overcome these challenges through fully automated QD device characterization and calibration. Our approach treats tuning as a multi-phase process—from device bootstrapping and virtual gate construction to charge state tuning and optimized readout. Domain-specific algorithms, machine learning, and physics-informed strategies drive this closed-loop system. By integrating physical insight, pattern recognition, and real-time feedback, our tools achieve high success rates across a range of material systems, including GaAs, Si/SiGe, and Ge/SiGe, on both academic and industrial fabrication platforms.

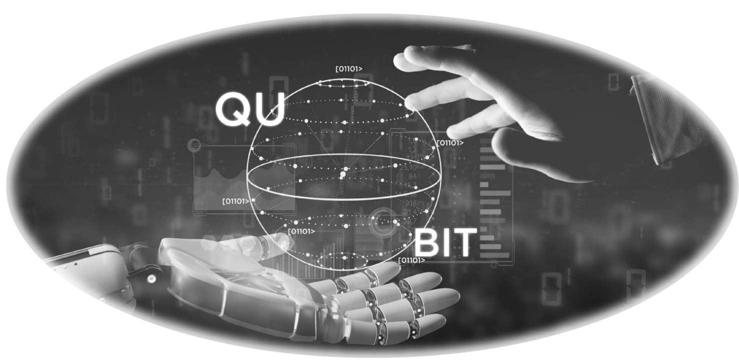
However, despite this progress, achieving truly scalable and reproducible automation remains hindered by a lack of shared datasets, standardization, and benchmarking protocols across the community. A simple but crucial component of success for the field will be to solidify key metrics of performance and key datasets that can be used to assess those metrics. I will discuss findings from the Workshop on Advances in Automation of Quantum Dot Devices Control held in 2023, where stakeholders from industry, academia, and the government discussed methods of collaboration and future roadmap development of methods for tuning large-scale devices, focusing on focus on datasets, benchmarking, and standardization [2].

[1] J.P. Zwolak & J.M. Taylor. Rev. Mod. Phys. 95(1), 011006 (2023).

[2] J.P. Zwolak et al. npj Quantum Inf. 10(1), 105 (2024).

Work in progress (a report from the second Workshop on Advances in Automation of Quantum Dot Devices Control will be prepared after the event).

Session: Poster 1.22



STM-Fabricated Single-Dopant Structures in Silicon for Quantum Photonics and Sensing

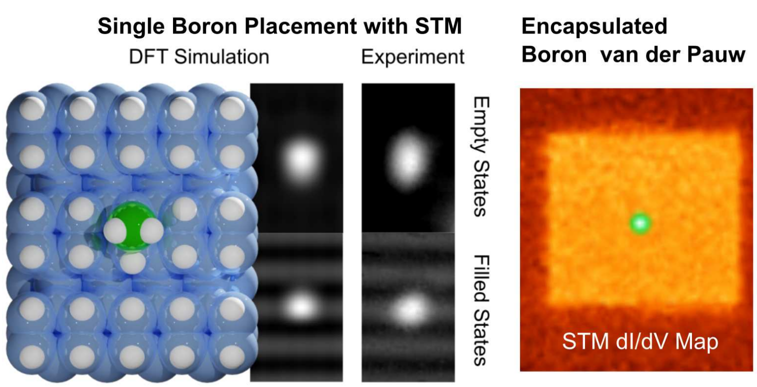
Jonathan Wyrick, Daniel Wines, Kevin Garrity, Maicol Ochoa, Mark-yves Gaunin, Brian Courts, Pradeep Namboodiri, Fan Fei, Vijith Kamalon Pulikodan, Utsav Utsav, Rick Silver, Joshua Pomeroy and Garnett W. Bryant

We present our progress on atomically precise fabrication and theoretical modeling of quantum devices defined by engineered dopant structures in silicon. Using a scanning tunneling microscope (STM), we fabricate device components within a single atomic layer by selectively placing dopant atoms with nanometer precision. Dense dopant regions are used to form conductive wires and electrostatic gates, while isolated or few-atom configurations serve as precisely positioned point defects or artificial molecules with tunable properties.

This effort builds on established capabilities for incorporating phosphorus atoms using phosphine precursors that enable deterministic placement of individual dopants as well as ongoing work to increase fabrication reliability and complexity using automation. Extending these capabilities, we explore fabrication using boron atoms introduced from diborane. We report initial results on the application of single-atom fabrication methods to boron incorporation as well as preliminary demonstration of a larger-scale boron doped region.

In parallel, we are using density functional theory and tight-binding simulations to investigate the electronic and optical properties of phosphorus–boron dopant pairs in silicon. These calculations aim to identify atomic geometries that could enable optically addressable quantum states or photon-mediated interactions, giving us access to key functionalities for quantum sensors and electronic–photonic systems. The results of this effort will be used to guide our fabrication efforts by determining what atomic arrangements will likely exhibit desired quantum behavior.

Session: Poster 1.23



Characterization of single 209-Bi donors in Si nanoelectronic devices

Quim Torrent Nicolau, Mario Cignoni, Amber Heskes, Dennis van der Bovenkamp, Ivana Bošnjak and Floris Zwanenburg

Semiconductor devices have emerged as promising candidates for spin qubits, leveraging well-established CMOS processes. Among the numerous semiconductor qubit hardware platforms, single group-V donors in silicon showcase outstanding properties, including extended coherence times – a crucial requirement for achieving high-fidelity quantum computation, as demonstrated for 31-P implanted devices.

The unique characteristics of group-V donors with nuclear spin I>1/2 – which stem from the rich physics of the nuclear-electron spin interactions – pave the way to new applications. Among group-V donors, the atypical properties – such as strong hyperfine constant and large nuclear spin number – of silicon-bismuth defect systems constitute a strong rationale for studying the encoding of quantum information on single bismuth donors. Indeed, the spin of the electron and nucleus of a single 209-Bi donor can be driven at magnetic field sweet spots – known as Clock Transitions (CTs) – where the qubit is first-order insensitive to magnetic field noise. The presence of ESR CTs has been experimentally reported for Bi clusters. In contrast, CTs for single-atom donors are thus far unexplored. Moving to lower concentration of Bi atoms, coherence times are expected to be further extended due to the reduction of the Bi spin bath, making single atom 209-Bi an excellent platform for realizing highly coherent spin qubits.

In this study, the fabrication and characterization of single 209-Bi-implanted electrostatically gated Si nanodevices are discussed. A central challenge at the fabrication level is the electrical activation of implanted donors. Strategies to assess and optimize the activation yield are proposed and evaluated. The experimental results include charge sensing, manipulation of donor charge states and clear spin signatures at finite magnetic fields, marking a significant step forward towards encoding quantum information in electrons loosely bound to single bismuth donors.

Session: Poster 1.24

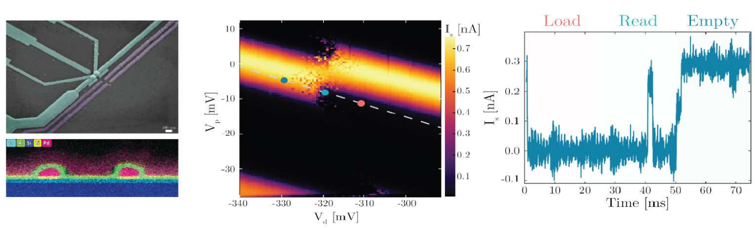


Figure 1. Single-shot spin readout. Left: false-colour SEM and TEM images of the device. Centre: zoom on a charge transition and identification of load, read, empty phases. Right: a single current blip in the read phase denotes a spin-up electron.

Fabrication of arsenic-in-silicon single-electron transistors using scanning tunnelling microscopy hydrogen resist lithography

Kieran Spruce, Raj Ravichandar, David Jonas, Patrick See, Mark Buitelaar, Taylor J. Z. Stock and Neil J. Curson

Silicon devices incorporating single dopant atoms have applications in quantum computing and quantum simulators, where the dopants provide electron or nuclear spin qubits. Scanning tunnelling microscopy hydrogen resist lithography (STM-HRL) enables the fabrication of such devices, traditionally using phosphorus-in-silicon. However, arsenic has shown superior single-atom incorporation precision (97%) [1] and placement accuracy compared to phosphorus (70%) [2], making arsenic-in-silicon more suitable for scaling single-atom devices.

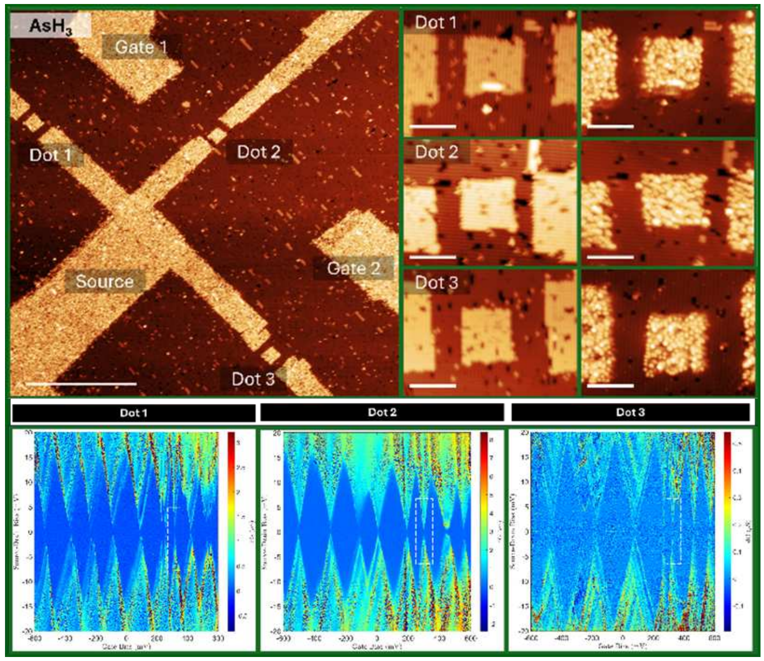
This work demonstrates the first successful fabrication of arsenic-in-silicon quantum dot single-electron transistors (QD SETs) using STM-HRL. We developed a novel three-way SET architecture to compare multiple tunnel junctions with identical fabrication parameters within a single device, providing insights into electron transport characteristics. Electrical characterisation at milli-Kelvin temperatures revealed clear Coulomb blockade behaviour and arsenic SET charging energies of 8-19 meV and lever arms of 0.04, comparable to similar phosphorus devices. Gap resistances varied with junction geometry, ranging from 1 to 40 MΩ. Notably, arsenic-based SETs showed additional Coulomb diamond substructures, indicating electron tunnelling to/from nearby dopants.

The demonstration of arsenic-in-silicon SETs provides a robust foundation for scalable qubits, where each qubit is an SET island with a single atom. This work addresses key challenges in quantum computing hardware development and offers a path to higher-yield, complex device architectures using multiple dopant precursors.

[1] T. J. Z. Stock et al., Advanced Materials, 36 (2024)

[2] J. A. Ivie et al., Phys. Rev. Applied 16, 054037 (2021

Session: Poster 1.25


AsH3
Gate 1
Dot 1
Dot 2
Source
Gate 2
Dot 3
Dot 1
Dot 2
Dot 3
Dot 1
Dot 2
Dot 3

Towards Gallium acceptor qubits in silicon

Ivana Bosnjak, Dennis van der Bovenkamp, Mario Cignoni, Quim Torrent Nicolau, Amber Heskes and Floris A. Zwanenburg

Hole spin qubits have gained interest in recent years due to their potential application in scalable quantum computers, enabled by their anisotropic and tunable g-factor, full electrical control, strong spin-orbit coupling, and the possibility of long-range entanglement.

Among them, group-III acceptor spin qubits in silicon, when operated at so-called sweet spots — specific electric field values — are expected to become first-order insensitive to electric field fluctuations. These sweet spots also correspond to maxima in the EDSR driving strength, making them promising operating points for enhancing coherence times [1].

In this study, the fabrication and characterization of single Ga-implanted, electrostatically gated Si nanodevices are discussed. A key requirement for realizing acceptor-based spin qubits is to induce sufficient heavy hole (HH)–light hole (LH) splitting. Previous work has shown that such splitting can be achieved via strain induced by aluminum electrodes [3]. Building on this approach, we implant gallium atoms in close proximity to an aluminum-gated single-hole transistor, which can be used to read out the hole spin states of a weakly bound hole to a gallium acceptor.

[1] J. Salfi et al (2016), 'Charge-Insensitive Single-Atom Spin-Orbit Qubit in Silicon'

[2] J. Salfi et al (2016), 'Quantum computing with acceptor spins in Silicon'

[3] S. D. Liles et al (2021), 'Electrical control of the g-tensor of the first hole in a silicon MOS quantum dot'

Session: Poster 1.26

Encoded cat qubit in a high spin nucleus in Silicon

Pragati Gupta, Mark R. van Blankenstein, Xi Yu, Danielle Holmes, Benjamin Wilhelm, Arjen Vaartjes, Martin Nurizzo, Fay E. Hudson, Kohei M. Itoh, David Jamieson, Andrew S. Dzurak, Barry C. Sanders and Andrea Morello

The demonstration of Schrödinger cat states on the nuclear spin of an Antimony (Sb) donor in Silicon [1] has opened the door to cat-based quantum error correction codes in spin qudits. In this work we present an encoded cat qubit with a universal logical gate set. Applying correction in post-analysis reduce the gate error rates to below the error correction threshold.

The logical basis states are the spin coherent states of a spin-7/2 nuclear spin pointing along an axis (x) perpendicular to the Zeeman field (z), making an arbitrary logical superposition state a cat state along the spin projection operator Ix. In this basis, we demonstrate a universal single-qubit gate set [2] comprising two operations: the root of the logical bit-flip, a Clifford gate that preserves spin parity, and logical phase shifts, non-Clifford gates that change spin parity. Importantly, both operations are implemented transversally only using covariant SU(2) rotations and virtual phase updates [2].

The dominant errors in this system show up on the Iz operator and, through the nuclear quadrupole moment, on the Iz^2 operator. These introduce rotation and squeezing operations respectively as shown as spin Wigner function plots in figure 1. Upon rotation to the Iz basis both kinds of errors are detectable through an ancillary electron spin qubit and in post-analysis can be corrected, leading to high state - and gate fidelities.

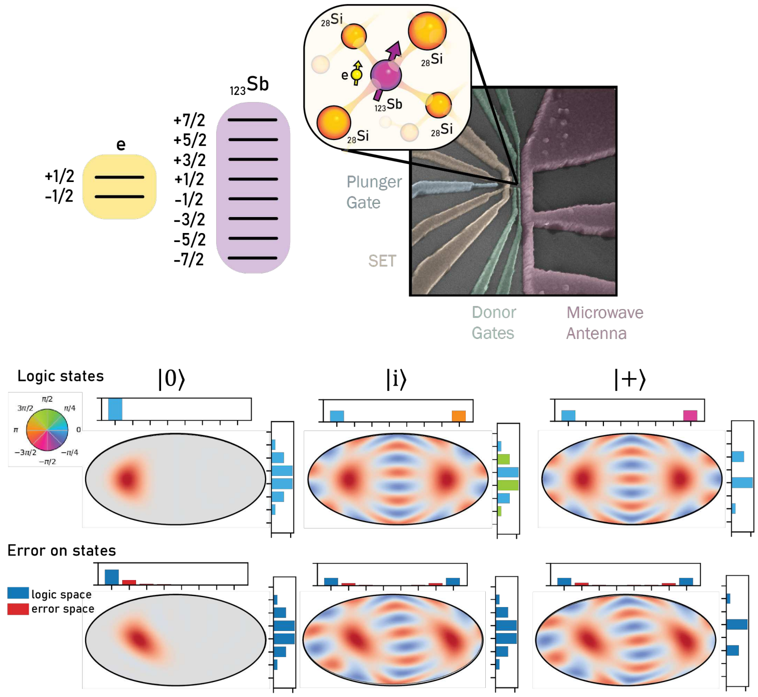
References

[1] Yu, X., Wilhelm, B., Holmes, D. et al Nat. Phys. (2025)

[2] Gupta, P., Morello, A., & Sanders, B. C. (2024) http://arxiv.org/abs/2410.07045

work in progress

Session: Poster 1.27


123Sb
e
+1/2
-1/2
+7/2
+5/2
+3/2
+1/2
-1/2
-3/2
-5/2
-7/2
28Si
123Sb
Plunger Gate
SET
Donor Gates
Microwave Antenna
Logic states
|0⟩
|i⟩
|+⟩
Error on states
logic space
error space

Onsite Bias Effects in Dopant-Based Quantum Dot Arrays for Quantum Simulation

Yan Li and Garnett W. Bryant

Dopant-based semiconductor quantum dot arrays offer a realistic platform for quantum simulation due to their ability to fabricate atomically precise structures with complex geometries and highly controllable parameters. These arrays provide a way to explore many-body physics and quantum phenomena that was not possible before. However, a key challenge in realizing ideal arrays lies in site-to-site variation in onsite energies, either from difference in dopant number or fabrication defects. In this study, we simulate quantum dot systems with varying onsite biases across different geometries. We start from a single site with a positive or negative onsite bias and investigate the resulting changes in the quantum dot array's behavior. Our simulations extend to correlated and random onsite biases on larger arrays and different geometries, including squares and connecting squares which remain invariant under magnetic fields. By examining how these finite systems respond to variations in onsite energies, our results provide insights into the potential of simulating strongly correlated systems, and how the behaviors may evolve from finite to bulk systems. Importantly, the systems and phenomena we simulate can be explored using existing experimental setups, which shows the possibility of using semiconductor quantum dot arrays for complex quantum simulations in near-future quantum technologies.

Session: Poster 1.28

Probing dopant-based quantum simulators: Getting faster than the steady state limit

Garnett W. Bryant, Maicol Ochoa, Daniel Wines, Kevin Garrity and Jonathan Wyrick

Dopant arrays in Si are being used as quantum simulators of interacting electron systems. Extracting information from these simulations raises significant challenges. Transport and reflectometry probe simulators on time scales much slower than any of the dynamics, providing steady-state information about charge occupation but little information about the quantum states of the array. Much faster probing, on the same time scale as hopping in the array or interaction between array spins, is needed. For example, we have shown that fast dynamics reveals the transition from site-to-site hopping to mode filling during transport and the buildup of Coulomb blockade after partial charge occupation. Ferromagnetic states display a wavefunction rigidity that delays transport on short time scales and can be used as a signature for that ferromagnetism. We have carried out dynamical modelling of quantum simulators made with a small dopant array, a source and drain to inject or collect charge from the array and quantum emitters located around the array to probe or modify the fast dynamics. We show that the quantum emitters can stimulate charge transfer into or out of the array, can transfer energy into the array to probe excited states, can modify the potential landscape locally to control the initial quantum state for a simulation. We show how monitoring the quantum emitters allows one to probe and control the array fast dynamics.

This modelling defines the properties of the emitters needed for fast probing. We can precisely place P and are developing precise placement of B. Thus, B-P complexes with shallow acceptor and donor levels could serve as precisely placed quantum emitters operating at near optical frequencies. We discuss our analysis of B-P complexes using tight-binding theory and density function theory to identify complexes that would be useful quantum emitters for fast probing and control.

Session: Poster 1.29

Thermal modelling of on-chip heating in silicon quantum devices

Alicia T. Lieng, Cédric Bohémier and Christopher Escott

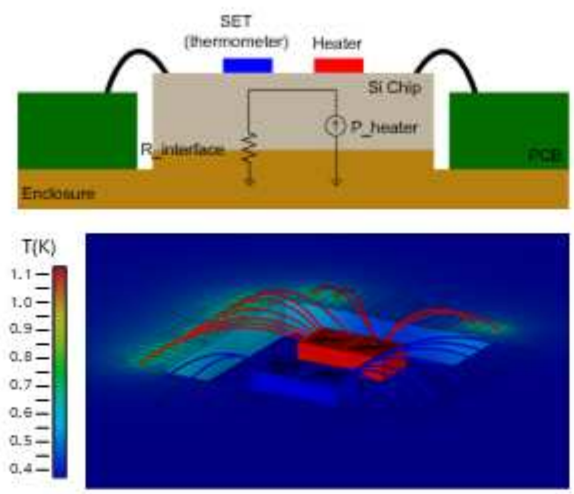
Spin qubits in silicon quantum dots promise large-scale compatibility with industry standard manufacturing processes and cryo-CMOS integration. The power budget for these electronics is set by cryostat cooling capacity and device thermalisation. With larger qubit counts and higher power dissipation, poor thermalisation becomes a limiting factor to device size.

In this work we investigate the use of commercially available thermal modelling softwares to accurately predict heat flow in silicon spin qubit devices. In a standard cryogenic setup, on-chip power dissipation is sunk through the silicon chip base and onto a well-thermalised PCB or enclosure. Simulation results conclude that thermal resistance of this interface is the dominant factor in effective chip temperature.

We use calibrated on-chip SET thermometry to validate these results experimentally. Thermal broadening of SET coulomb peaks is used to measure temperature change from an on-chip heating element. Extracted interface resistances can be fed back into the thermal model for improved accuracy.

work in progress

Session: Poster 1.30



Spin shuttling with gapless scheduling of real-time parametrized pulses

Bilal Kalyoncu, Nicolas Piot, Yigitcan Uzun, Basak Ozcan, David Vos, Gabor Denes, Daniel Weigand, Damaz de Jong, Jules van Oven and Cornelis Bultink

Spin qubits are promising for scalable quantum computation due to their long coherence times, compact footprint, and compatibility with industrial foundries. Increasing connectivity across processors can be achieved by physically relocating qubits. Recent advances have focused on coherent shuttling of spins to enable transport over extended distances, though high fidelity transfer remains challenging.

Conveyor mode shuttling uses a traveling wave potential, demonstrating improved spin coherence. This method is challenging due to the need for precise control over the phase and frequency of multiple signals applied to successive electrodes. Furthermore, dynamic directional control is possible by reversing the signal frequency, which enhances the effectiveness of parameterizing sinusoidal signals. Shuttling is therefore traditionally performed by precalculating these large waveform sequences into memory banks of arbitrary waveform generators. This is not a scalable approach due to memory requirements, and long compilation and upload overhead. We solve this in the Qblox control modules with gapless play of consecutive pulses with instantaneous updating of the frequency parameter in between. This capability is demonstrated for "bucket brigade" and "conveyor-mode" spin shuttling in [1].

We further advance spin qubit research by providing a hardware platform that combines all control and readout tasks. This is operated by a software suite that gives direct access to complex tuning steps like the mitigation of cross-capacitance, microwave crosstalk, and Bias-T signal distortion.

[1] De Smet, M et al. High-fidelity single-spin shuttling in silicon. Nat. Nanotechnol. 20, 866 (2025)

Session: Poster 1.31

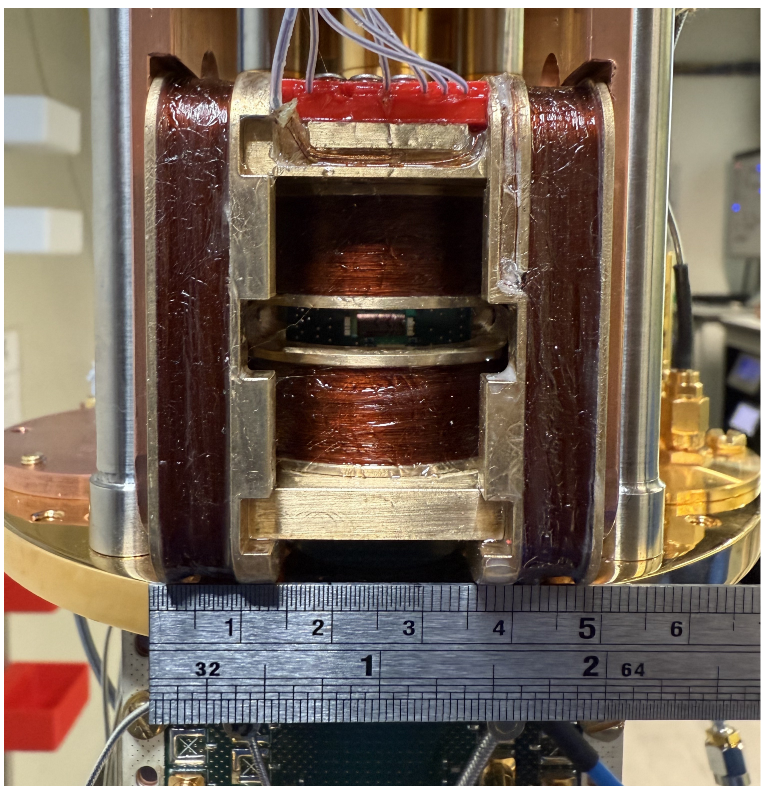
Compact superconducting vector mini-magnet for spin qubit experiments

Di Xu, Jeremy Morgan, Constance Lainé, Mathieu de Kruijf, Dominic Dahinden, Giovanni Oakes, Jonathan Warren, Alexander Waterworth, Sophia Garofeanu, Ross Leon, John Morton and M. Fernando Gonzalez-Zalba

Silicon spin qubits are promising due to their high density and compatibility with classical electronics, but require magnetic fields to lift the spin-state degeneracy. These magnetic fields are typically generated by large and expensive superconducting solenoids that, due to their large mass, increase the cooldown load of typical dilution refrigerator systems.

In this work, we present a three-axis vector mini-magnet, consisting of a principle axis with magnetic field strength up to 700 mT, and two minor axes up to 140 mT, packed in a volume of just 144 cm3. We demonstrate Pauli spin blockade (PSB) readout in a double quantum dot configuration and report on the mini-magnet field stability measured using electron spin resonance (ESR). Furthermore, we demonstrate Rabi oscillations using the compact magnet. The compact nature of the mini-magnet and its low stray field enables installation in most commercial dilution refrigerators. Multiple magnets can be installed in a single refrigerator, allowing for multiple magnetic field experiments at the same time while reducing operational costs.

Session: Poster 1.32



Development of mK CMOS Multiplexer for Increased Quantum Device Test Throughput

Aaron Michael Chronister and HRL Laboratories

Maturing spin-qubit technologies will involve sufficient cryogenic testing to provide the appropriate fabrication and hardware feedback to advance device performance and yield. Recently, cryogenic wafer probing has helped boost test throughput at temperatures from 1 to 2 Kelvin, allowing for characterization of electrostatic performance. To test coherent spin-physics and qubit performance, however, requires operation at temperatures below 100mK. To address this, HRL has developed a CMOS-based multiplexer (MUX) operating at milli-Kelvin temperatures with sufficient bandwidth for qubit manipulation. This MUX increases test throughput by enabling characterization of multiple devices in a single cool-down. This poster will present characterization of the MUX and resulting qubit measurements.

Session: Poster 1.33

Fabrication and measurement of Ge quantum dot devices with low noise, fast readout, and simple fabrication

Tien-Ho Chang, Guan-Yu Yang, Jian-Chang Zheng, Chia-Hao Wei, Rui-Xuan Jiang, Chi-Wei Lee, Jo-Yu Wang, Ying-Quan Lai, Guang-Li Luo, Ta-Chun Cho and Tzu-Kang Hsiao

Due to several advantages such as long coherence time, strong spin orbit coupling, and low effective mass, Germanium hole-spin qubits have become a promising platform for quantum computing and quantum simulation. In this poster I will demonstrate our measurements of a germanium double quantum dot device, measured in a 10mK environment. Our device is fabricated in house on a locally grown germanium quantum well heterostructure with a single aluminum fine gate layer defining three quantum dots that are covered by a global accumulation gate which allows for easier alignment in fabrication. The device is loaded on a custom-made sample PCB and measured via RF reflectometry.

Our device contains metal gates that allow for the formation of three quantum dots, with one acting as a SET charge sensor, and the other two intended for a singlet-triplet qubit. We have successfully measured the charge stability diagram for the two quantum dots via the sensor dot, indicating the successful formation of all three gate-defined quantum dots as well as the ability to control charge occupation and RF readout of charge states. Additionally, I will also report on the current progress in spin readout and control, charge noise characterization of our device, and also fabrication related processes such as superconductivity of PtSiGe that we use as our ohmic contacts. The simplified device design of Ge quantum dot with RF-compatibility will be beneficial for material characterization and Ge-based quantum device development.

work in progress

Session: Poster 1.34

On the Trade-Off Between Qubit Homogeneity and Efficient Electrical Control of Hole Spin Qubits in Germanium

Biel Martinez i Diaz and Yann-Michel Niquet

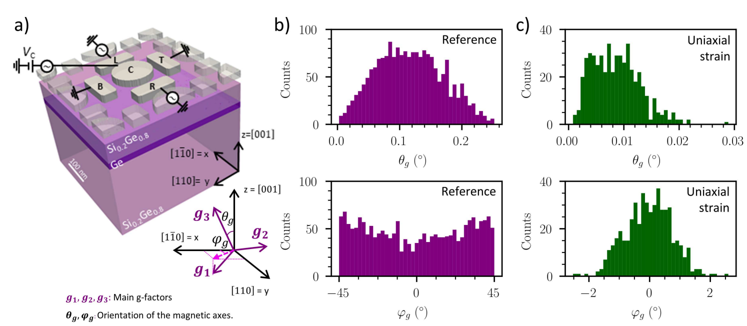
The scalability of hole spin qubits in semiconductor quantum computing may be limited by strong variability arising from their intrinsic spin-orbit coupling (SOC), which makes spins highly sensitive to their electrical environment. Ge/SiGe heterostructures have recently emerged as a promising platform for hole spin qubits. These epitaxial systems are expected to offer reduced disorder due to the epitaxial character of the Ge/SiGe interface and the separation of the qubits from defective oxides. Nonetheless, all existing multi-qubit experiments show fingerprints of a significantly different spin properties between qubits [1,2]. While this variability is often seen as a challenge, it has also been harnessed for spin manipulation by shuttling thanks to differences in precession axes between neighboring dots [2].

In this simulation work, we present a systematic analysis of the impact of electrical disorder—originating from charge traps in the amorphous oxides—on the charge and spin properties of Ge spin qubits. We quantify the induced variability and discuss its implications for scalability [3]. We also review recent strategies to mitigate variability, including optimized gate designs [4], strain engineering [5], and the use of unstrained, bulk Ge substrates [6]. We compare the variability figures (see Fig. a) and operational trade-offs of different spin manipulation techniques, such as electric-dipole spin resonance (EDSR) versus spin shuttling (see Fig. b,c). Our findings provide a comprehensive summary for understanding and addressing variability in Ge spin qubits, and a guide for future technological choices.

[1] Nature 591, 580–585 (2021).
[2] Science 385,447-452 (2024).
[3] arXiv:2507.04953 (2025).
[4] Phys. Rev. Applied 22, 024030 (2024).
[5] Phys. Rev. Applied 23, 024057 (2025).
[6] arXiv:2506.04977 (2025).

arXiv:2507.04953 (2025).

Session: Poster 1.35



First-Principles Band Alignment in Strained Si/$Si_{1-x}Ge_x$ and Ge/$Si_{1-x}Ge_x$ Heterostructures

Nathaniel M. Vegh, Pericles Philippopoulos, Raphaël J. Prentki, Wanting Zhang, Félix Beaudoin, Hong Guo and Yu Zhu

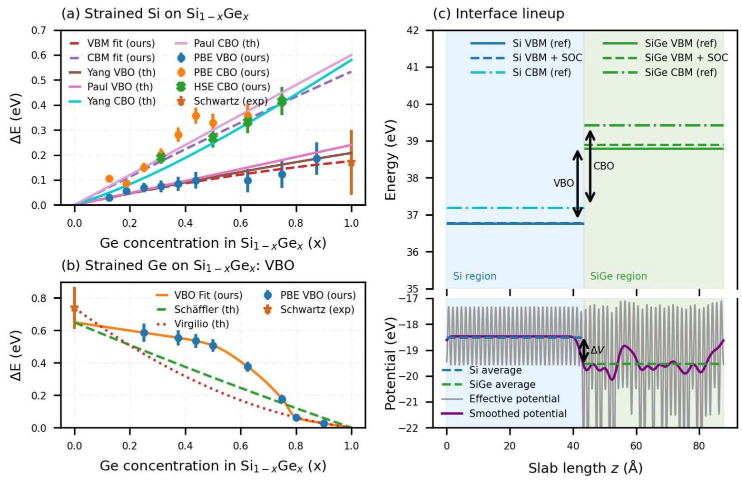
Silicon–germanium alloys and their strained-layer heterostructures are crucial to both electron- and hole-based spin-qubit and quantum-well devices. However, their reported band offsets can differ by over 100 meV across experimental techniques. Semi-empirical models, typically fitted at a few compositions, differ by similar magnitudes and omit nonlinear corrections. We filled this gap in the scientific literature with a first-principles density-functional-theory (DFT) workflow that computes valence-band offsets (VBOs) and conduction-band offsets (CBOs) for strained Si/Si1−xGex and strained Ge/Si1−xGex across $0 \leq x \leq 1$.

All DFT calculations used the RESCU solver. We fitted Perdew–Burke–Ernzerhof (PBE) equation-of-state curves on special-quasirandom-structures (SQS) to determine composition-dependent in-plane lattice constants. These SQS cells were optimized to emulate random-alloy disorder in small supercells. We then imposed the associated biaxial strains on pure-Si and pure-Ge epilayers and relaxed their out-of-plane lattice constants. Band-edge energies were first extracted from PBE, then corrected using the Heyd–Scuseria–Ernzerhof (HSE) screened hybrid functional to address PBE's band-gap underestimation. To capture the interface potential lineup, we averaged the electrostatic potential across 512-atom SQS heterojunction slabs to average out finite-size noise and capture alloy disorder.

The figure shows our first-principles data (circles with error bars), compared to experiments (brown stars with error bars) and theoretical models (solid/dashed lines). In Panel (a), we present strained Si on Si1−xGex with PBE & HSE band edges; CBO fit uses HSE (PBE illustrates underestimation). Panel (b) displays strained Ge on Si1−xGex VBOs with benchmarks. Panel (c) provides an example interface lineup at x=0.3125, including plane-averaged potential, ΔV, spin-orbit-coupling (SOC) shifted edges, and VBO/CBO.

Our workflow inherently captures nonlinear bowing, yielding band offsets with 10 meV uncertainties—better than semi-empirical k·p or tight-binding methods. It has excellent agreement with experimental values and predicts beyond measured regimes, providing an accurate database for device models to accelerate Si/SiGe quantum-well and spin-qubit design.

Session: Poster 1.36



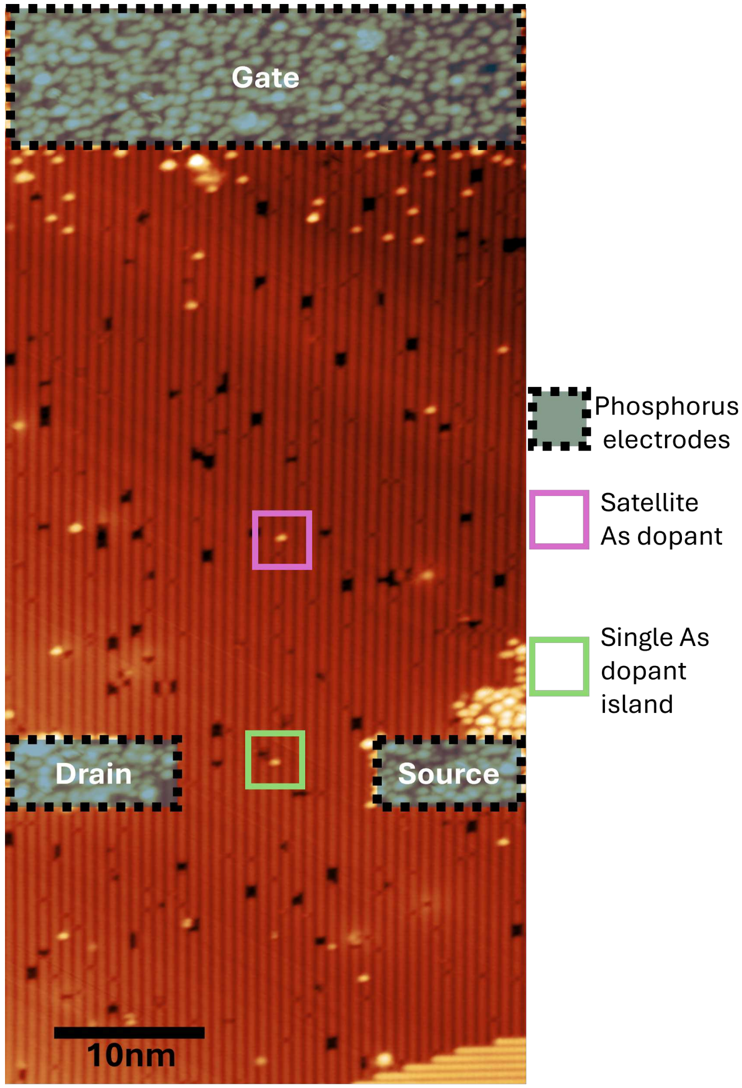
(a) Strained Si on $Si_{1-x}Ge_x$
VBM fit (ours)
CBM fit (ours)
Yang VBO (th)
Paul VBO (th)
Yang CBO (th)
Paul CBO (th)
PBE VBO (ours)
PBE CBO (ours)
HSE CBO (ours)
Schwartz (exp)
ΔE (eV)
Ge concentration in $Si_{1-x}Ge_x$ (x)
(b) Strained Ge on $Si_{1-x}Ge_x$: VBO
VBO Fit (ours)
Schäffler (th)
Virgilio (th)
PBE VBO (ours)
Schwartz (exp)
ΔE (eV)
Ge concentration in $Si_{1-x}Ge_x$ (x)
(c) Interface lineup
Si VBM (ref)
Si VBM + SOC
Si CBM (ref)
SiGe VBM (ref)
SiGe VBM + SOC
SiGe CBM (ref)
VBO
CBO
Si region
SiGe region
Energy (eV)
ΔV
Si average
SiGe average
Effective potential
Smoothed potential
Potential (eV)
Slab length z (Å)

Machine Learning Guided Fabrication of Single-Atom Devices in Hydrogen Resist Lithography with Arsenic Dopants

Nick Kolev, Kieran Spruce, Timothy Brown, Neil Curson and Taylor Stock

Scanning tunneling microscopy hydrogen resist lithography (STM-HRL) is a fabrication technique capable of producing electronic devices in silicon with true atomic precision, and could in principle be used to fabricate a solid-state universal quantum computer. In this technique, the probe of an STM is used to pattern a single atomic layer of hydrogen on an atomically perfect silicon surface. This forms a chemically resistant mask for the atomically precise positioning of substitutional dopant atoms, delivered via gas phase molecular precursors. Currently, device fabrication relies on skilled STM operators who handcraft individual devices, one at a time, in a labour-intensive process and it has only been used successfully on the sub-nanometre scale for phosphorus dopants. Arsenic has recently been demonstrated to be a favourable alternative dopant to phosphorus in the STM-HRL procedure, due to its increased reproducibility and precision in creating single dopant structures. Efforts are currently underway to exploit the unique chemistry of arsine adsorption at specific types of dangling bond sites to control the distribution of single arsenic dopants in the silicon surface. Here we present a method to use machine learning image recognition as a means to identify and map distributions of dopant arsenic atoms and atomic-scale defects and to align these features within STM-HRL fabricated device structures. By mapping large surface areas, similar dopant patterns can be found and subsequently converted to identical devices. Alternatively, a series of devices can be fabricated where a single parameter is changed (e.g. inter-dopant distances) to explore effect of that parameter on device performance. We illustrate the utility of this method by carrying out the lithography steps that would be needed for the fabrication of multiple single atom single electron transistors (SETs) that have a nearby satellite dopant. One such SET is shown in the figure.

Session: Poster 1.37


Gate
Drain
Source
10nm
Phosphorus electrodes
Satellite As dopant
Single As dopant island

Single electron transistors made using a single gate with varying width

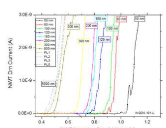
Joshua Pomeroy, Pradeep Namboodiri, Nikki Ebadollahi, Runze Li, Christian Pederson and Michael Stewart

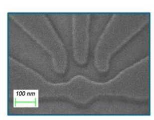
A single gate structure is demonstrated as a means of generating the electrostatic profile needed to form a single electron transistor by utilizing gate width variations, which affects whether the silicon is inverted beneath the gate at a given voltage. Shape variation in gates used for quantum devices is an infrequently exploited variable that can enable greater complexity with fewer gates. Another promising opportunity is to utilize single gate SETs (single electron transistors) as test structures during processing that could reveal process deviations with single electron sensitivity. Generating a SET with a single gate leverages the increased voltage required to invert as gates get very narrow, particularly at the dimensions used for quantum devices.

In this work, we have mapped out the gate width dependence for a Ti/Pd gate stack on 20 nm of thermal silicon oxide using a series of nano-wire transistor from 30 nm – 1000 nm in width and 10 μm in length. The gate voltage dependence of each transistor was measured at 10 mV of bias to reveal substantial shifts in the threshold voltages, e.g., 0.5 V over the range, as shown in the figure at left. The gate voltage required to reach 1 nA of channel current is linear in the inverse of the gate width, suggesting a scaling proportional to the total depletion volume around the gate. From this, a "bubble" gate, e.g., the lower gate in the figure at right, was be designed and we present Coulomb diamond data demonstrating the formation of a reservoir-barrier-dot-barrier-reservoir electron gas profile and discuss the successes and limitations either for primary qubit formation or quantum test structure devices.

Work in progress - publication being prepared

Session: Poster 1.38





Qubits for Computing Foundry at HRL

Edwin Acuna

Significant progress has been made recently in silicon spin qubit demonstrations, showcasing the potential of silicon-based quantum computing. However, reliably fabricating these devices remains a formidable challenge for academic research groups. HRL Laboratories, in collaboration with the Laboratory of Physical Sciences' Qubit Collaboratory, is addressing the challenges faced by the research community by providing devices through the Qubits for Computing Foundry (QCF). We make devices based on the single-layer etch-defined gate electrode (SLEDGE) technology, which constitutes a scalable and flexible platform for spin-based quantum computing. We offer a set of standard device designs, which include linear six-quantum-dot arrays capable of supporting two exchange-only qubits as well as other qubit control modalities when integrated with a Co micromagnet. We also support collaborators in designing their own devices compatible with our SLEDGE process. Here, we provide examples of standard device designs available, detail the flexibility available to users for designing custom devices, and discuss the performance of a custom device design fabricated through the QCF.

Session: Poster 1.39

Automating the STM Fabrication of Silicon Based Quantum Devices Using Machine Learning and Computer Vision

Mark-yves Gaunin, Fan Fei, Connor Lin, Fnu Utsav, Brian R. Courts, Vijith Kamalon Pulikodan, Pradeep Namboodiri, Rick Silver and Jonathan Wyrick

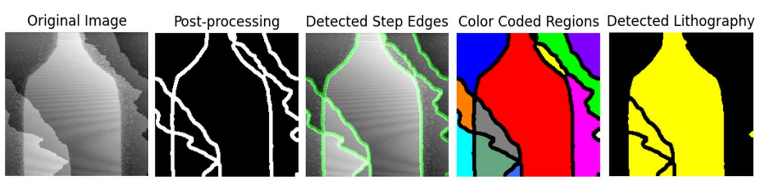
A scanning tunnelling microscope (STM) enables atomically precise hydrogen depassivation lithography (HDL) on a silicon surface. The fabrication of analog quantum simulators and dopant-based qubits have already been demonstrated using such methods. The main challenge arising from scanning probe lithography is that the tip can change quality throughout the fabrication process. A user must operate and manually verify that patterns have been written correctly. A high-quality device may take a week, sometimes up to a month, to manually pattern.

Automation is needed to increase throughput and scalability of the lithography process. We detail here our progress towards automation. A convolutional neural network has been trained to determine the sharpness/dullness of an STM tip based on detected dangling bonds from a silicon surface image. Computer vision algorithms are utilized to differentiate between natural silicon step edges and patterned lithography edges (see image). Another trained model provides a deep learning approach for determining the necessary parameters used in the computer vision algorithms to detect the lithography regions with highest accuracy. The detected lithography is compared to a GDSII file containing the desired device pattern to verify the accuracy of a patterned region.

We are developing the first open-source software platform for automatically imaging, patterning, and verifying hydrogen depassivation lithography on a silicon surface in an effort to make fabrication of silicon-based quantum devices more robust and reproducible. This streamlines the fabrication process to be more in line with standardized electron beam lithography (EBL) and photo-lithography processes, where a user uploads a GDSII file with the desired pattern, calibrates and sets initial parameters, and then allows the automated program to finish the writing process.

work in progress

Session: Poster 1.40



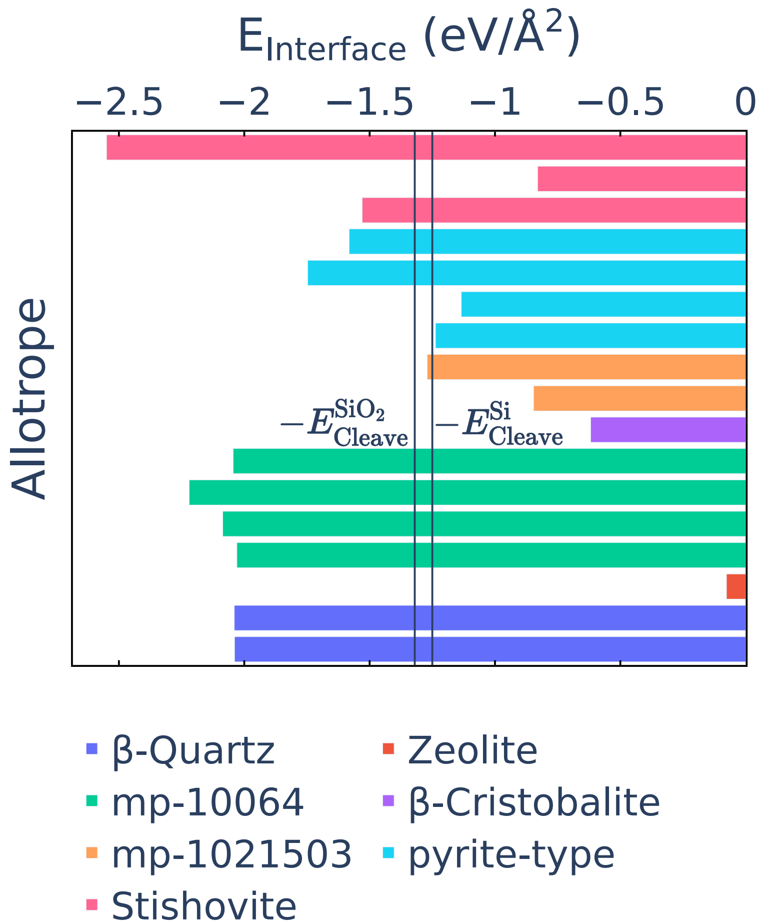
Predicting The Identity of Intermediate Range Order at The Si:SiO2 Interface via Interfacial Energies

Preston Valiant, Quinn Campbell and Shashank Misra

The structure of the Si:SiO2 interface is a key ingredient to understand charge noise in metal oxide semiconductor (MOS) spin qubits, as it is host to different point defects, and provides the dielectric and mechanical interface directly adjacent to the qubits themselves.

This poses a challenge for modeling, however, as the SiO2 at these interfaces is widely taken to be amorphous and non-periodic. Recent 4D-STEM analysis of the Si:SiO2 interface, however, has revealed significant nanoscale symmetric ordering in the SiO2 near the interface, which has yet to be positively identified as specific SiO2 phases. We provide predictions for possible interfacial structures in these ordered domains via the minimum interfacial energy, derived from density functional theory calculations. From this analysis, we find that of the SiO2 allotropes tested, Stishovite (110) is likely a dominant SiO2 phase at the interface. Thus, we intend to model different electrical noise sources using Si(001):Stishovite as the representative atomic structure.

Session: Poster 1.41



$E_{Interface}$ (eV/Å^2)
−2.5
−2
−1.5
−1
−0.5
0
Allotrope
$-E^{SiO_2}_{Cleave}$
$-E^{Si}_{Cleave}$
β-Quartz
mp-10064
mp-1021503
Stishovite
Zeolite
β-Cristobalite
pyrite-type

Impact of electrostatic crosstalk on spin qubits in dense CMOS quantum dot arrays

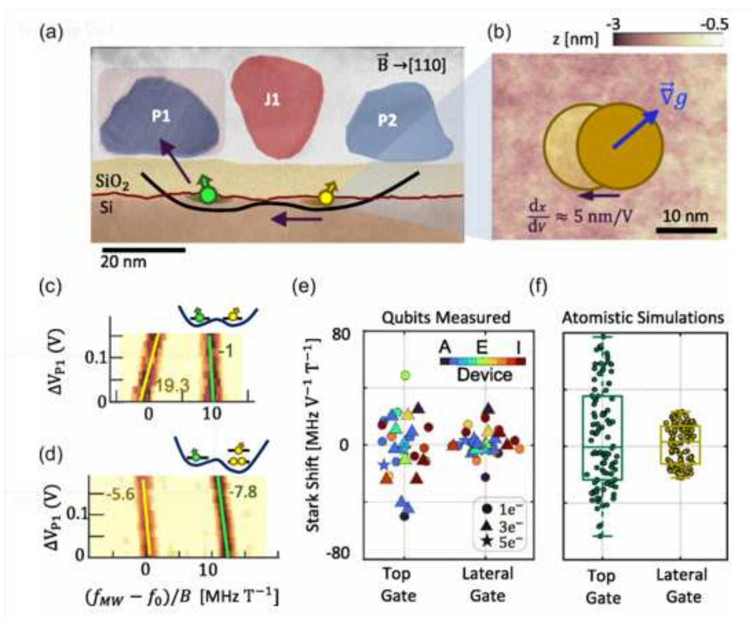
Jesus Cifuentes, Andre Saraiva, Paul Steinacker, Tuomo Tanttu and Andrew Dzurak

Current complementary metal-oxide semiconductor (CMOS) quantum processors employ dense gate arrays to define quantum dots, making them susceptible to crosstalk from capacitive coupling between the dots and the neighboring gates. Small but sizable spin-orbit interactions can transfer this electrostatic crosstalk to the spin g factors, creating a dependence of the Larmor frequency on the electric field generated by gate electrodes positioned tens of nanometers apart. We study the Stark shift from tens of CMOS spin qubits measured in nine devices and develop a theoretical framework that explains how electric fields couple to the spin of the electrons in increasingly complex arrays. This includes electric fluctuations that limit qubit coherence times T2*.

J.Cifuentes, et al , Phys. Rev. B 110, 125414 – Published 10 September, 2024

J.Cifuentes, et al , Phys. Rev. B 110, 125414 – Published 10 September, 2024

Session: Poster 1.42



A superinductor in a deep sub-micron integrated circuit

Gorka Aizpurua, Tom H. Swift, Fabio Olivieri, James Kirkman, Grayson M. Noah, Mathieu de Kruijf, Felix-Ekkehard von Horstig, Alberto Gomez-Saiz, John L. Morton and M. Fernando Gonzalez-Zalba

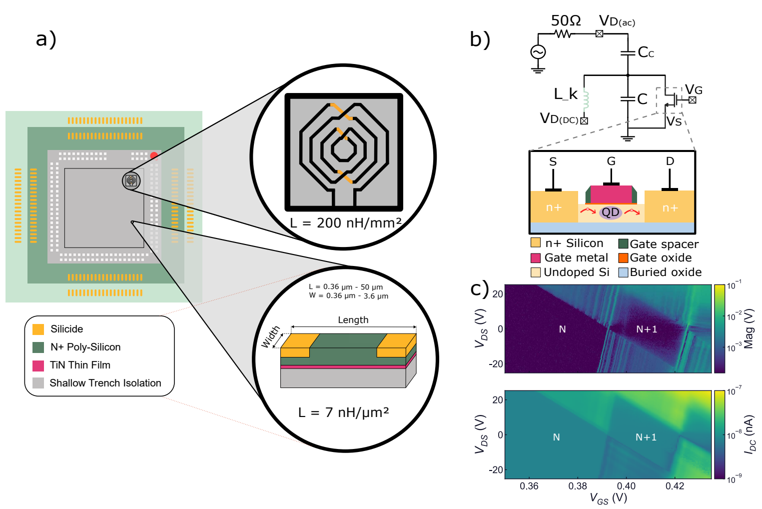
Superinductors are electronic components that possess an intrinsic impedance higher than the superconducting resistance quantum (Rq = 6.45 kΩ). These elements have already demonstrated applications ranging from metrology and sensing to quantum computing. Particularly, superinductors have served as fundamental building blocks for quantum computing architectures and have also enabled applications such as near-quantum-limited cryogenic amplifiers. Moreover, these applications are not exclusively beneficial for superconducting-based architectures; other platforms, such as silicon spin qubits, can also take advantage of them.

Superinductors are typically fabricated using exotic materials with a high kinetic inductance density such as Joshepson junction arrays or layered 2d materials, which present challenges for integration within standard CMOS fabrication processes.

In this work, we present a superinductor based on TiN thin films integrated into the 22-nm FDSOI integrated circuit manufacturing process. We characterize the kinetic inductance properties of these thin films and demonstrate their application in quantum computing through measurements of a radiofrequency single-electron transistor and single-electron box. With this implementation, we achieve a charge readout sensitivity of 1 ps, an improvement of more than two orders of magnitude compared to the state-of-the-art (625 ps) [1]. This is accomplished while reducing the footprint area by four orders of magnitude, two key aspects for scalability in silicon spin qubit platforms.

[1] D, K. et al., 2019. Single-Shot Spin Readout in Semiconductors Near the Shot-Noise Sensitivity Limit. Phys. Rev. X, p. 041003.

Session: Poster 1.43



Beyond Dopant Placement: Bringing the Precision of STM Lithography to other Si Quantum Devices

James H. G. Owen, Ehud Fuchs and John Randall

STM Lithography has been used with great success by UNSW and others to fabricate quantum devices, using the single-atom precision to place single P, As, B, et al. to form qubits or quantum dots. However, this is a very low-throughput process, and is limited in the materials which can be patterned in this way.

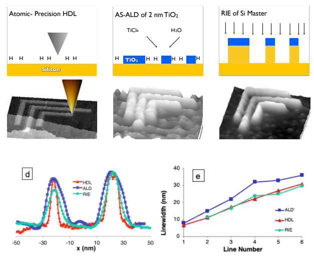
Single-nm precision is also crucial for other implementations of qubits, such as quantum dot qubits. Variations in the physical dimensions of the top gates create significant variations in the size of the electrostatic confinement and therefore the energy levels in the qubit. Previous work suggested that a variation of 2 nm in the gate dimensions was enough to double or halve the tunnel splitting, or a factor of 4 in Exchange Interactions. The variation in gate and other dimensions complicates the design of multi qubit systems and the required tuning of the biases on the gates for multiple qubits becomes so complex that machine learning is employed.

We are developing a pathway from atomically-precise STM patterns to Nanoimprint templates, by selective growth of a hard mask in the STM patterns, followed by reactive ion etching or Cl-based Atomic Layer Etching, to create ultraprecise templates, with a minimum linewidth of 5 nm, well below that feasible with e-beam or photolithography. While the atomic precision of the initial STM pattern will be reduced in the final template, the precision of templates thus produced, combined with the precision and throughput of Jet and Flash Nanoimprint lithography will produce far more uniform top gates with a scalable manufacturing technique which can be integrated into mainstream CMOS processes, and thus broaden the applicability of STM patterning to the wider Si quantum device community.

J. B. Ballard et al., ”Pattern transfer of hydrogen depassivation lithography patterns into silicon with atomically traceable placement and size control,” J. Vac. Sci. Technol. B, vol. 32, no. 4, p. 041804, Jul. 2014.

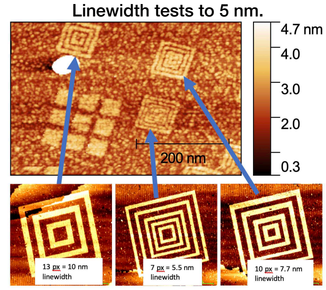
Session: Poster 1.44

STM to Nanoimprint



In searching for the minimum linewidth achievable with this method, we found that ALD tends to broaden the pattern, while RIE returns it to the original dimensions.

Linewidth tests to 5 nm.



Hole spin qubits in unstrained Germanium layers

Esteban A. Rodriguez-Mena, Lorenzo Mauro, Mauricio Rodriguez and Yann-Michel Niquet

Hole spin qubits in Ge/GeSi heterostructures have made outstanding progress recently. They can be efficiently manipulated with electric fields owing to the strong spin-orbit interaction in the valence bands of germanium [1, 2].

This progress has largely relied on Ge/GeSi heterostructures grown on a thick GeSi buffer that biaxially strains the Ge well and opens the heavy-hole/light-hole bandgap. As a consequence, the confined carriers are almost pure heavy-holes with a strongly anisotropic gyromagnetic response [3], which hinders the optimization of the magnetic field orientation: the figures of merit (Rabi frequencies, lifetimes...) can indeed vary by an order of magnitude within a few degrees around the heterostructure plane [3, 4].

We propose to address this issue by confining the holes at the interface of an unstrained, bulk Ge substrate or thick buffer. We model such structures and show that the gyromagnetic anisotropy is considerably reduced, effectively extending the range of operation of the qubits [5]. The increased heavy-hole/light-hole mixing enhances the Rabi frequencies but decreases the spin lifetimes; yet the quality factors of unstrained Ge qubits are significantly larger than those of conventional, strained heterostructures, making such devices are ideally suited to fast and resilient spin qubits with low Larmor frequencies.

This theoretical proposal is backed by the recent demonstration of the growth of such an unstrained Ge structure, and the formation of a high-mobility 2D hole gas [6]. It highlights the prospects for quantum dots [6].

[1] N. W. Hendrickx et al., Nature 591, 580 (2021).
[2] C.-A. Wang et al., Science 385, 447 (2024).
[3] V. John et al., arXiv:2412.16044 (2025).
[4] L. Mauro et al., Physical Review B 109, 155406 (2024).
[5] L. Mauro et al., arXiv: 2506.04977 (2025)
[6] D. Costa et al., arXiv: 2506.04724 (2025).

L. Mauro et al., Hole spin qubits in unstrained Germanium layers, arXiv: 2506.04977 (2025)

Session: Poster 1.45

Proximity-induced superconductivity in GeSi/Ge heterostructures with in situ-grown aluminum

Pauline Drexler, Marcus Wyss, Alexander Vogel and Dominique Bougeard

Two-dimensional hole gases (2DHG) in germanium have been identified as a promising platform for the realization of planar superconducting qubit concepts. A key ingredient of this functionality relies on the proximity effect between a superconductor and a 2DHG induced in an adjacent germanium quantum well (QW). Planar Josephson junctions can then be fabricated by connecting a segment of the proximitized 2DHG to superconducting reservoirs. As an additional advantage, the 2DHG carrier density is gate-tunable via the electric field effect in such planar junctions.

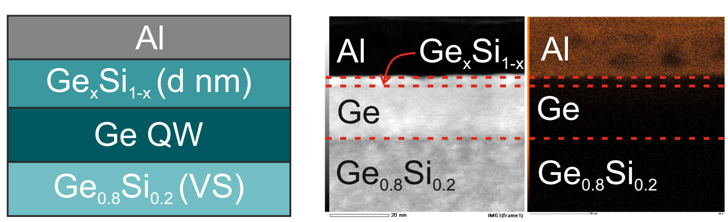
Currently, superconducting contacts are mostly formed ex situ, either through solid-state interdiffusion or by etching and depositing the superconductor directly onto the semiconductor. Here, we present an alternative approach, where the superconducting thin film is grown in situ onto the QW heterostructure, which may enhance the proximity effect.

Our semiconductor and superconductor layers are grown in separate solid-source molecular beam epitaxy (MBE) chambers. In situ growth of thin aluminium films onto pristine GexSi1-x/Ge/Ge0.8Si0.2 QW heterostructures ($0.8<x<0.95$) is enabled through ultrahigh vacuum-connection of the chambers.

Structural and chemical analysis demonstrate sharp interfaces in the hybrid Al/QW heterostructures. We will show transport characterization of the superconducting thin films and discuss the gate-tunability of the 2DHG in these surface-near GeSi/Ge QWs.

Optimizing the proximity effect in the Al/QW hybrid heterostructure involves finding a trade-off between hosting the 2DHG as closely as possible to the interface with the Al, while maintaining a sufficiently high mobility. To address this optimization, we systematically vary two parameters of our Al/GexSi1-x/Ge/Ge0.8Si0.2hybrid heterostructures: The thicknesses of the GexSi1-x barrier between the Al and the 2DHG range from 5nm to 20nm. Additionally, we tune the height of this GexSi1-x QW barrier, by growing heterostructures with Ge concentrations $0.8<x<0.95$.

Session: Poster 1.46



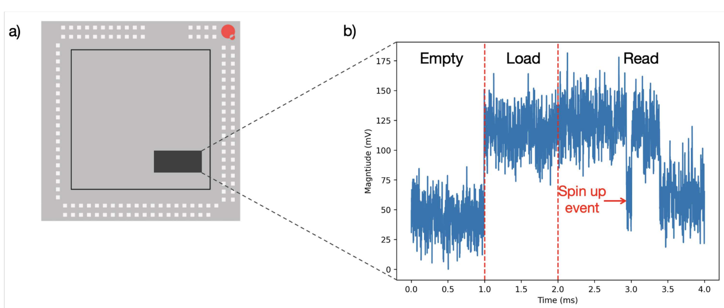
Spin readout and integrated superinductors in 22nm FDSOI

Isobel Clarke, Thomas Swift, Virginia Ciriano-Tejel, Fabio Olivieri, Gorka Aizpurua-Iraola, James Kirkman, Grayson Noah, Mathieu de Kruijf, Felix-Ekkehard von Horstig, David Ibberson, Mark Johnson, Alberto Gomez-Saiz, John J. L. Morton and M. Fernando Gonzalez Zalba

Here we present results towards the implementation of electron spin qubits on an industry-standard process: 22nm fully-depleted silicon-on-insulator (FDSOI) from Global Foundries, a speciality technology used over the past 10 years to manufacture ICs for IoT and 5G devices and as a low-power alternative to FinFETs. We present results from our latest Hoxton chip manufactured on 22nm FDSOI (Figure 1a), which includes an addressable array of 1024 quantum dot devices embedded in transistors with a high-frequency multiplexer, operating below 1K. Rapid radio-frequency reflectometry measurements and parameter extraction of these dots were undertaken to determine the best dimensions for forming quantum dots. We then demonstrate spin readout measurements in this technology (Figure 1b), using a ramped Elzerman readout technique, reproducible on other devices, and fast charge sensing via a radio-frequency single electron transistor (rfSET). We characterise a spin lifetime of T_1 = 26ms at B = 2T, and find a magnetic field dependence consistent with Johnson and phonon noise. Finally, we demonstrate how the tank circuit of the rfSET can be integrated on chip with a sensitivity improvement of more than two orders of magnitude over the state-of-the-art, combined with a 10,000-fold area reduction. Overall, our results demonstrate the substantial promise of 22nm FDSOI technology as a platform for building a scalable quantum computer, with the potential to instantly scale up a qubit unit cell into larger structures once an optimal design is achieved.

work in progress

Session: Poster 1.47



Investigating the effects of eddy currents in quantum devices for global qubit control

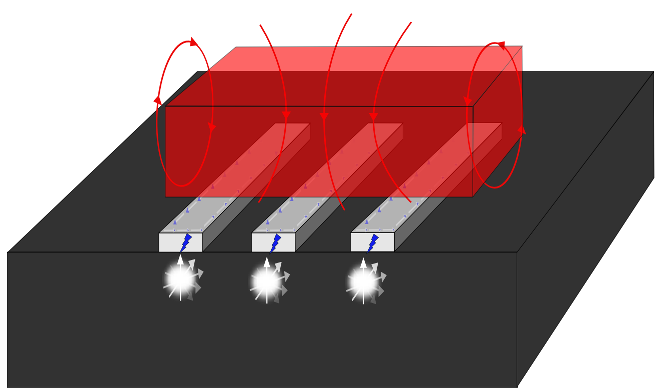
Savi' Apicella, Ensar Vahapoglu, Andrew Dzurak, Arne Laucht and Jarryd Pla

In recent years, spin qubits have achieved remarkable progress, surpassing 99% fidelity in both single- and two-qubit operations for the first time. Despite these advancements, several challenges remain critical to the successful development of this technology. One such challenge involves engineering a global drive capable of addressing potentially millions of spin qubits, while meeting stringent requirements for field uniformity and minimizing induced electric noise. A proposed solution in the literature involves utilizing an off-chip dielectric resonator made of potassium tantalate ($KTaO_3$) to deliver the global drive to spin qubit devices. This approach effectively reduces the device's footprint and mitigates heating concerns.

Tuning and controlling the fields generated by the resonator are vital components of this setup, essential to achieve precise quantum gates and optimise qubits coherence. However, particularly in metal-oxide-semiconductor (MOS)-based quantum devices, a phenomenon whose impact on qubit performance has not been estimated is the formation of eddy currents within the gate nanostructure. In this study, we investigate the effect of eddy currents induced by the resonator's field. Our findings indicate that this phenomenon acts as a source of magnetic and electric field, opening new potential pathways for qubits driving. We quantitatively estimate the amplitude of this effect with respect to the resonator field and develop a qualitative the model to explain the origin of the current and identify relevant parameters. Finally, we propose mitigation strategies to reduce the impact of eddy currents, by analysing gate materials and discussing alternative simplified gate structures. Being qubit homogeneity and long coherence paramount requirements for future spin qubit devices, understanding and mitigating this effect might prove vital for scaling up this technology.

Work in progress

Session: Poster 1.48

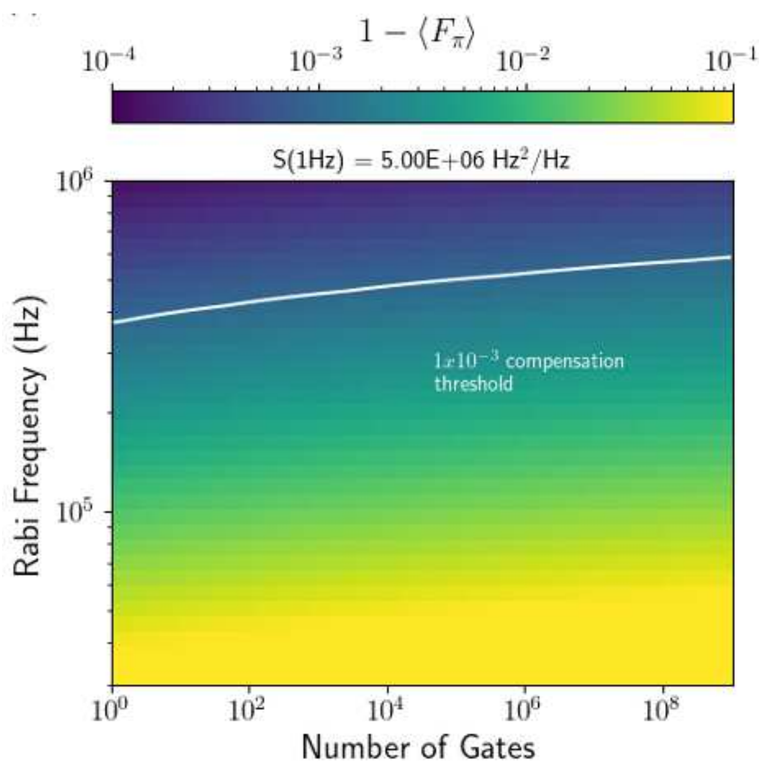


Noise and Drift Budgets for Scaling Quantum Devices

Michael Stewart, Tommy O. Boykin II, Michael Gullans and Pooja Yadav

Noise and drift present a stubborn obstacle in achieving the full potential of quantum devices across applications. In qubits, noise and drift reduce the fidelity of operations and cost valuable measurement time by forcing periodic device retuning. To combat loss in fidelity, qubit retuning routines are often run at regular intervals or in an ad-hoc fashion when the effect of the drift is clear in the data. This has the desired effect: to remove the reduction in fidelity in the middle of time-consuming measurements. Consequently, however, it is possible that two types of devices yield equivalent fidelities while one was retuned many more times and took much longer to measure. In metrology, where there is an effort to parallelize single-electron devices to realize the Ampere, noise limits the achievable uncertainty and current by limiting the measurement time, and the number of devices which can be operated simultaneously. Retuning routines in electrical metrology are not an option as their use would essentially obviate the utility of the standard. We present a simple analysis of noise which characterizes drift and can be used to predict the available measurement time before compensation. We compare this statistic with others and discuss its use. Specifically, we use detuning frequency noise for a single qubit to estimate the infidelity of a π gate as a function of the number of gates run and the Rabi frequency. We also estimate the number of qubits which can be run simultaneously, qubit readout fidelity as a function of time, and the measurement time available when realizing the Ampere.

Session: Poster 1.49



$1-\langle F_\pi \rangle$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
S(1Hz) = 5.00E+06 Hz^2/Hz
10^6
10^5
Rabi Frequency (Hz)
$1x10^{-3}$ compensation threshold
10^0
10^2
10^4
10^6
10^8
Number of Gates

Correlated offset charge jumps in Si/SiGe quantum dots

Brighton X. Coe, Michael A. Wolfe, Owen M. Eskandari, Jared Benson, Tyler Kovach, John Reily, Alysa Rogers, Gabriel J. Bernhardt, Mark Friesen, Shimon Kolkowitz and Mark A. Eriksson

Here we report correlated jumps in the offset charge between very closely spaced SiGe quantum dots. To observe correlations, we utilize a fiber optic connection in a 3K cryogenic refrigerator to deposit energy from multiple 1.6 eV photon impacts on the back side of the host silicon substrate. These photon bursts simulate the effects of environmental radiation depositing energy in the substrate, which have recently been found to cause correlated errors in superconducting qubits on silicon substrates [1,2]. It is of great interest to know if Si/SiGe quantum dot qubits, which are also fabricated on silicon substrates, are similarly sensitive to radiation.

One key difference between superconducting and Si/SiGe qubits is that Si/SiGe heterostructures have additional interfaces between the bulk silicon substrate and the qubit region. These interfaces are of interest for two reasons: first, they are locations at which charge can be trapped, which can induce qubit errors. Second, in principle, they can block charge migration. We show here that such interfaces do not preclude charge migration to the qubit region.

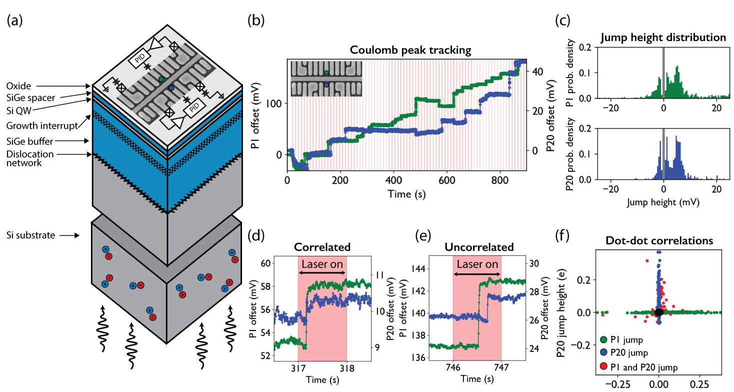
We track multiple offset charge shifts from a series of photon bursts by using active feedback to sit on the side of a Coulomb blockade peak on two dots simultaneously. Using this technique, we find that small photon bursts result in a repeatable offset charge shift, indicating that charge is trapped at a nearby interface, with a small percentage of these trapping events resulting in shifts on both dots simultaneously. A Poisson solver is used to find a vertical location for this charge to be trapped that is consistent with experimentally observed shifts.

[1] Vepsäläinen, A. P. et al. Nature 584, 551–556 (2020).

[2] Wilen, C.D., Abdullah, S., Kurinsky, N.A. et al. Nature 594, 369–373 (2021).

work in progress

Session: Poster 1.50

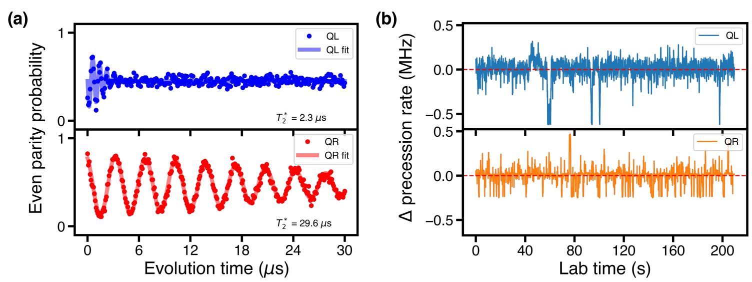


Probing position-dependent noise spectrum of silicon spin qubits near vanishing decoherence gradient

Hanseo Sohn, Shinwoo Lee, Jaemin Park, Hyeongyu Jang, Jonginn Yun, Jun Yoneda, Lucas E. A. Stehouwer, Gavide Degli Esposti, Giordano Scappucci and Dohun Kim

Semiconductor spin qubits offer high controllability and scalability, enabling micromagnet-based fast spin manipulation and individual addressability at the nanoscale. However, micromagnet-induced decoherence gradients can limit qubit coherence time, depending on the micromagnet design and the qubit position. In this work, we investigate the noise spectrum of two qubits in isotopically purified silicon: one located near vanishing decoherence gradients exhibiting a long coherence time (inhomogeneous coherence time T2* ∼ 30 μs) and a neighbouring qubit strongly affected by excess field gradients (T2* ∼ 2 μs). By simultaneously tracking the qubit precession rates, we analyze the noise characteristics, including cross-correlation between the two qubits. These results quantify the spatial noise correlations between qubits subject to different decoherence effects, highlighting their relevance for designing scalable, high-density quantum processors.

Session: Poster 1.51



Developing metrics to accelerate ab initio defects studies in quantum devices

Minh Nguyen, Misra Shashank and Quinn Campbell

Silicon based quantum devices are still significantly charge noise limited, and a leading candidate to produce fluctuating electric fields are point defects. Ab initio methods such as density functional theory (DFT) can describe the electronic properties of these defects, providing a way to identify which point defects are the most problematic. A challenge in computationally studying these devices is the large number of possible defects. We believe some point defects, such as vacancies of the same element at silicon-silica interfaces, have electronic structures that are similar, but which experimental techniques like deep-level transient spectroscopy cannot distinguish between. The ability to a priori predict when two defect structures have similar electronic properties can significantly reduce the search space for both ab initio and experimental studies. This benefit becomes even more impactful when extended to studying defect complexes such as vacancy pairs. In this work, we aim to systematically characterize features of interfacial defects, such as the configuration of neighboring atoms and their distance from the interfacial plane, to develop metrics for quantifying the similarity of electronic structures between point defects. We analyze the local density of states and formation energies of point defects at silicon-silica interfaces. Preliminary results indicate that vacancy pairs adjacent to the same atoms exhibit greater electronic similarity. In addition, silicon vacancies in bulk silicon tend to exhibit more similarity further into the bulk phase as their distance from the interfacial plane increases.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

Session: Poster 1.52

Efficient Quantum Dot Tuning with Ray-Based Algorithms

Han Na We and Paul Surrey

Efficient and reproducible control of quantum dots is a critical challenge for scaling silicon-based quantum processors. We present automated ray-based tuning algorithms integrated into our Tuning Toolkit Framework (TTF), developed to reliably and efficiently form and control single- and double-quantum-dot configurations. Within TTF, ray-based tuners autonomously initialize QuBus devices from the depleted state to the first electron transition in the single-quantum-dot (SQD) regime, achieving success rates above 75% within 30 minutes. On these devices, ray-based tuners require substantially fewer measurements than two-dimensional approaches, reducing total runtime — including acquisition and analysis—by at least a factor of two. Bootstrapping tuners for accumulation and sensor coarse tuning have been benchmarked on the Cryogenic Wafer Prober (CWP), achieving success rates of approximately 90%. A dedicated fine-tuner further stabilized sensor response, transforming disordered signals into clean Coulomb oscillations within half an hour. These results establish automated ray-based tuning as a scalable and resource-efficient pathway toward robust control of silicon quantum dot arrays, supporting progress toward large-scale quantum computing.

Session: Poster 1.53

Single electron transport and stray dopant signatures in arsenic-doped silicon devices probed by direct current and radio-frequency reflectometry measurements

David Jonas, Rajath Ravichandar, Kieran Spruce, Timothy Brown, Taylor J. Z. Stock, Neil J. Curson and Mark R. Buitelaar

Devices consisting of atomically-precise phosphorous dopants in silicon, fabricated via scanning tunnelling microscopy hydrogen resist lithography, have driven semiconductor-based quantum computing for more than two decades. However, qubits formed from arsenic dopants remain unexplored, despite offering a four-dimensional Hilbert space for quantum memory, purely electrical nuclear spin control due to a finite quadrupolar moment, and a higher incorporation yield than phosphorous [1].

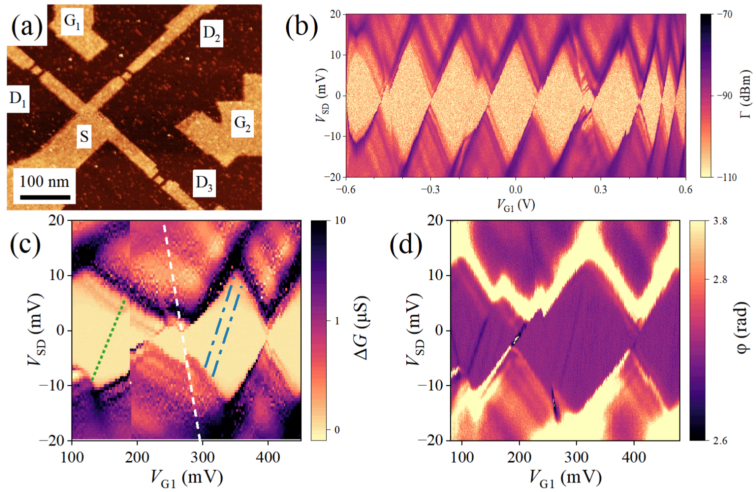
In this work, single electron transistors (SETs) composed of arsenic arranged in a novel three-way architecture were characterised using direct current and radio-frequency (RF) reflectometry measurements at 6 mK. Coulomb diamonds are observed in both measurements up to substrate breakdown. Compared to a complimentary phosphorous device which was also fabricated, arsenic SETs exhibit higher resistances, larger charging energies, and weaker gate couplings, consistent with a more strongly bound electron wavefunction.

Utilising an RF readout setup with a capacitance sensitivity of 0.04 aF Hz-1/2, which includes SrTiO3 varactors for impedance matching and frequency tuning, and a Josephson parametric amplifier with a noise temperature of 0.1 K [2], additional transport features are observed. These include transport lines superimposed on the SET lines from stray arsenic dopants near the RF lead, discontinuities in the SET lines from dopants close to the SET, and charge jumps from dopants acting as fluctuators. These results demonstrate the viability of arsenic-in-silicon atom-based qubits and their potential for scalable quantum technologies.

[1] Stock et al., Adv. Mater. 36, 2312282 (2024). [2] Apostolidis et al., Nat. Electron. 7, 760-767 (2024).

Figure 1. (a) STM micrograph of three arsenic SETs, as well as source (S), drain (D1,D2,D3), and gate (G1,G2) electrodes. (b) Single electron transport for dot 1 observed from RF reflectometry. (c-d) Comparing DC and RF measurements distinguishes stray dopants near the SET (white dashed line), the RF lead (blue dot-dashed lines), and both the RF lead and SET (green dotted line).

Session: Poster 1.54


(a)
G1
D2
D1
S
G2
D3
100 nm
(b)
VSD (mV)
VG1 (V)
Γ (dBm)
(c)
VSD (mV)
VG1 (mV)
ΔG (μS)
(d)
VSD (mV)
VG1 (mV)
φ (rad)

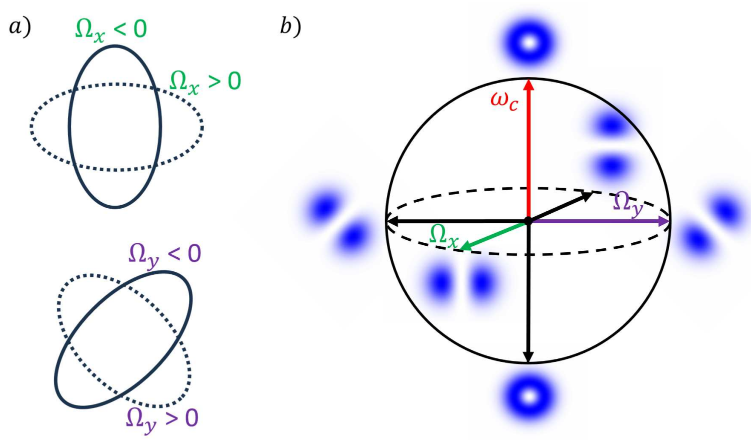
Proposed Five-Electron Charge Quadrupole Qubit

John Caporaletti and Jason P. Kestner

A charge qubit couples to environmental electric field fluctuations through its dipole moment, resulting in fast decoherence. We propose the p-orbital (pO) qubit, formed by the single-electron, p-like valence states of a five-electron Si quantum dot, which couples to charge noise through the quadrupole moment. We demonstrate that the pO qubit offers distinct advantages in quality factor, gate speed, readout, and size. We use a phenomenological, dipole two-level-fluctuator charge noise model to estimate a T2*~80 ns. In conjunction with Rabi frequencies of order 10 GHz, an order of magnitude improvement in qubit quality factor is expected relative to state-of-the-art semiconductor spin qubits. The pO qubit features all-electrical control via modulating the dot's eccentricity. We also show how to perform two-qubit gates via the $1/r^5$ quadrupole-quadrupole interaction. We find a universal gate set using gradient ascent-based control pulse optimization, subject to 10 GHz maximum allowable bandwidth and 1 ns pulse times.

PRL: https://doi.org/10.1103/l1x2-n2w9

Session: Poster 1.55



Gate-Tunable Light Hole Spin-Orbit Interactions in Group IV Planar Systems

Frédéric Quenneville, Patrick Del Vecchio, Nicolas Rotaru, Patrick Daoust and Oussama Moutanabbir

Hole spin qubits in germanium (Ge) have been the subject of intensive research towards the implementation of reliable and robust quantum processors. The strong spin-orbit interaction (SOI) peculiar to holes provides an additional degree of freedom allowing for effective all-electrical spin manipulation schemes, such as qubit driving through electric dipole spin resonance (EDSR). However, common planar systems with heavy hole (HH) ground states are limited by their weak linear-in-k contributions to Rashba SOI (RSOI). Herein, we introduce light hole (LH) systems as an alternative to address this limitation. $k \cdot p$ theory is used to explore RSOI of LH-like ground states in tensile-strained MOS-like group IV planar systems. The results show strong linear-in-k EDSR-relevant contributions to RSOI attributed to the LH-like ground state. The inherent asymmetry of the systems also provides full tunability of RSOI through gate fields, which are shown to act as switches that can turn ON/OFF RSOI and configure hole spin qubits to be either sensitive to or protected from EDSR.

Session: Poster 1.56

Optimal transport-based unfolding of qubit readout noise

Benjamin Faktor, Katy Craig and Benjamin Nachman

Readout noise remains a significant source of error in the current era of noisy intermediate-scale quantum computing. The task of unfolding readout noise has been studied extensively, but current techniques suffer from poor handling of transportational noise and information loss due to binning.

We consider an unfolding inverse problem with optimal transport cost. That is, given a measurement and noise model, we seek the predicted true distribution whose simulation under applied noise is closest to the observed measurement in the sense of the 2-Wasserstein metric.

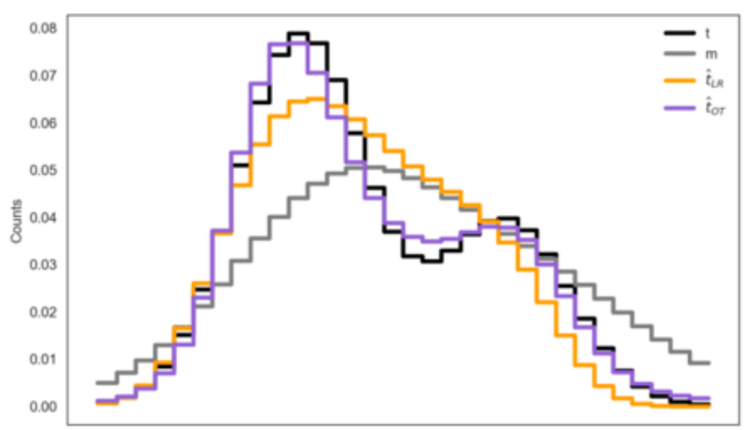
At the continuum level, we prove the unfolding problem to be well-posed under minimal finiteness and continuity assumptions on the measurement and noise model. At the discrete level the entropy-regularization of the unfolding problem is shown to be solvable by iterated Kullback-Liebler projections, which–by leveraging the Euler-Lagrange equations–are furthermore proven to be equivalent to Sinkhorn-type iterations. For a system with n qubits this corresponds to a reduction in iteration-wise computational complexity from O(4n) to O(2n).

We employ this approach for unfolding readout noise from IBMQ Johannesburg and demonstrate improved performance compared to the current state-of-the-art approach. The primary benefits of the optimal transport cost arise when the noise model encodes non-negligible transport over the underlying state space, in which case the Wasserstein distance more appropriately reflects distributional divergence than other metrics. Moreover, since optimal transport does not require absolute continuity of probability measures, our method entirely avoids binning of the measurement and is especially suitable for scenarios involving low-resolution noise models.

In the figure below, the measured distribution (m) is obtained from the (generally unknown) true distribution (t) via a non-negligibly shift-inducing noise model. Our optimal transport-based unfolding method (tOT) more closely approximates (t) than Lucy-Richardson (tLR).

work in progress

Session: Poster 2.1



Toward noise correlation-based uninterrupted feedback of a silicon quantum dot

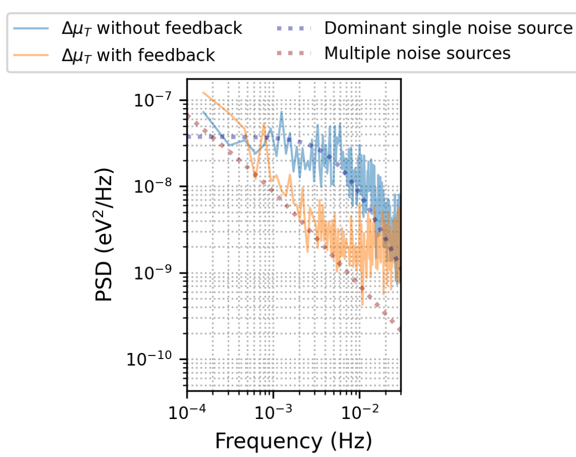
Tatsuya Matsuda, Tetsuo Kodera and Jun Yoneda

Noise correlation between qubits affects the efficiency of quantum error correction, a warranted issue for large-scale silicon spin qubits. In this study, we explore the possibility of turning the strong spatial noise correlation to our advantage to realize feedback without direct monitoring. If noise is perfectly spatially correlated across adjacent dots, one can stabilize a quantum dot electrostatically by keeping track of the potential fluctuation of a neighboring dot. As a proof-of-concept experiment, we use a system of a Si-MOS quantum dot in proximity with a charge sensing dot and perform feedback on the electrochemical potential of the dot ΔμT solely based on the fluctuations in the charge sensor ΔμM. ΔμM and ΔμT are assessed by analyzing the charge sensor signal near the charge transition conditions of the respective dots. We evaluate the feedback performance based on the time-domain traces and power spectral densities of ΔμT when we emulate noise with different correlation strengths via external gate voltage signals. While parts of noise can be amplified when there are multiple noise sources with different couplings to the dots, ΔμT is shown to be stabilized when noise is dominated by a single noise source and sufficiently correlated (figure).

Part of this work was financially supported by JST Moonshot R&D Grant Number JPMJMS2065, and KAKENHI (JP23H05455, JP23H01790, and JP23K17327). We acknowledge imec and Hitachi for providing the Si-MOS quantum dots used in this study.

work in progress

Session: Poster 2.2



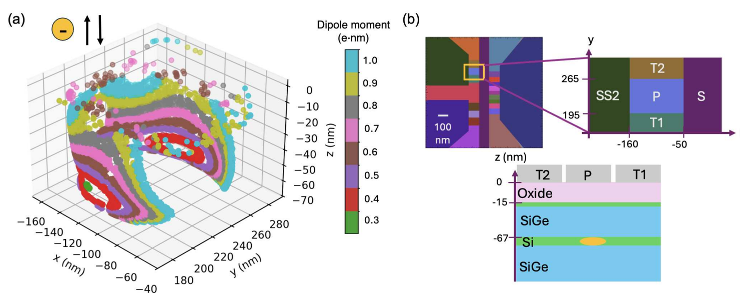
Spatial Triangulation of Two-Level Fluctuators in Si/SiGe Quantum Dot Devices

Leah Tom

Charge noise has been shown to be a primary limiting factor in the fidelities of gate operations in silicon spin qubits in Si/SiGe quantum dot devices. This charge noise has been demonstrated to arise from an ensemble of Two Level Fluctuators (TLFs) particular to each quantum dot. In this work, we develop a general method that takes in experimental input on simulated measurements of the chemical potential changes induced by the TLF and simulated measurements of the change in the TLF's detuning in response to modulations of nearby gates. By varying the location, spatial orientation and electric dipole moment of the simulated TLF in the vicinity of the most strongly coupled gates as shown in Fig (b), we demonstrate that it is possible to identify the location of a TLF with high likelihood. In this study, we demonstrate the utility of this method by determining that the TLF measured in the study, F. Ye Phys. Rev. B 110 (23) 235305 , is located near the Si/SiGe interface, as shown in Fig (a) if we consider electric dipole moments closest to experimental measures. This method can be extended to similar datasets to perform spatial triangulation.

work in progress

Session: Poster 2.3



Surface Morphology Assisted Trapping of Strongly Coupled Electron-on-Neon Charge States

Kaiwen Zheng, Xingrui Song, Sidharth Duthaluru and Kater W. Murch

Single electrons confined to a free neon surface and manipulated through the circuit quantum electrodynamics (circuit QED) architecture is a promising novel quantum computing platform. Understanding the exact physical nature of the electron-on-neon (eNe) charge states is important for realizing this platform's potential for quantum technologies. We investigate how resonator trench depth and substrate surface properties influence the formation of eNe charge states and their coupling to microwave resonators. Through experimental observation supported by modeling, we find that shallow-depth etching of the resonator features maximizes coupling strength. By comparing the trapping statistics and surface morphology of devices with altered trench roughness, our work reveals the role of fabrication-induced surface features in the formation of strongly coupled eNe states.

K Zheng, X Song, KW Murch, arXiv:2503.01847, 2025

Session: Poster 2.4

Temporal Coarse Graining for Classical Stochastic Noise in Quantum Systems

Tameem Albash, Steve Young and Noah Tobias Jacobson

Simulations of quantum systems with Hamiltonian classical stochastic noise can be challenging when the noise exhibits temporal correlations over a multitude of time scales, such as for 1/f noise in solid-state quantum information processors. High frequency components of the noise necessitate a small time step to avoid aliasing, whereas low-frequency components that are crucial to capture drift in such systems require long simulation times to observe. This broad range of relevant timescales results in high simulation cost. Here we present an approach for simulating Hamiltonian classical stochastic noise that performs temporal coarse-graining by effectively integrating out the high-frequency components of the noise. This is achieved by generating a realization of the stochastic process on a coarse time grid, expressing the conditioned stochastic process in terms of a bridge process, and performing the ensemble average over the bridge process. We focus on the case where the noise can be expressed as a sum of Ornstein-Uhlenbeck processes, where correlators of the bridge processes can be expressed analytically. This combination of noise trajectories on a coarse time grid and ensemble averaging over bridge processes has practical advantages that we highlight with numerical examples.

arXiv:2502.12296

Session: Poster 2.5

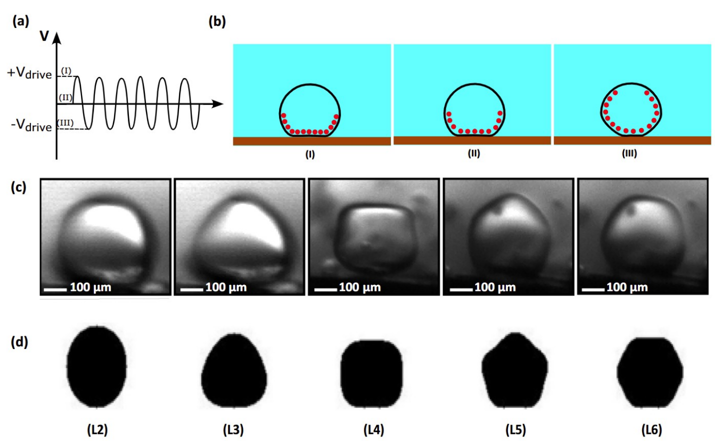
Imaging Wigner crystallization on flat and curved charged helium surfaces under electrical excitation

Ambarish Ghosh and Shriganesh Neeramoole

Classical phase transition (Wigner crystallization) of the 2D layer of electrons was first observed on the surface of liquid helium in 1979, where the phase boundary was detected by resonances in the coupled plasmon-ripplon modes, which were observed in the crystal phase but not for the fluid phase. Subsequent experiments involving the detection of phase transition by measuring the changes in the transport properties further confirmed the results of Grimes and Adams.

We report a new approach of detecting Wigner crystallization on flat charged helium surface by direct visualization and imaging of the charged surface using high speed camera to detect changes in the electron ripplon coupling. Our experiments involved electrical excitation of the charged surface which generates ripplons. The different ripplon modes excited at the liquid surface were detected using Fourier analysis. The 2DES charge distribution for a given field configuration was determined using numerical simulations. Because the electron-ripplon coupling is dependent on the phase of the 2DES on the surface, the phase boundary is determined by detecting the change in the ripplon modes excited. This is the first direct observation of Wigner crystallization on liquid helium and the technique can be used to further study the transverse electron-ripplon modes. We extend the same technique to Multi Electron Bubbles (MEBs) as well.

Session: Poster 2.6



Toward Coupling Electrons on Helium to Superconducting Qubit Systems

Austin J. Schleusner, Camryn Undershute, Camille A. Mikolas, Alex N. Carrothers and Johannes Pollanen

The spins of electrons offer a high-coherence platform for hybrid systems based quantum memory applications, in particular for superconducting qubit processors. Among the various physical systems that host accessible electronic spin states, electrons trapped above the surface of superfluid helium are particularly compelling due to their extremely long predicted coherence times [1], spatial control, and integration with circuit quantum electrodynamic architectures. In this work, we investigate integrating electrons on helium with superconducting qubit systems as a high-coherence quantum memory platform.

[1] S.A. Lyon, Phys. Rev. A. 74, 052338 (2006)

Session: Poster 2.7

Germanium Nuclear Spin Coupled to SiMOS Quantum Dots

Gauri Goenka, Paul Steinacker, Andrew Dzurak and Andrea Morello

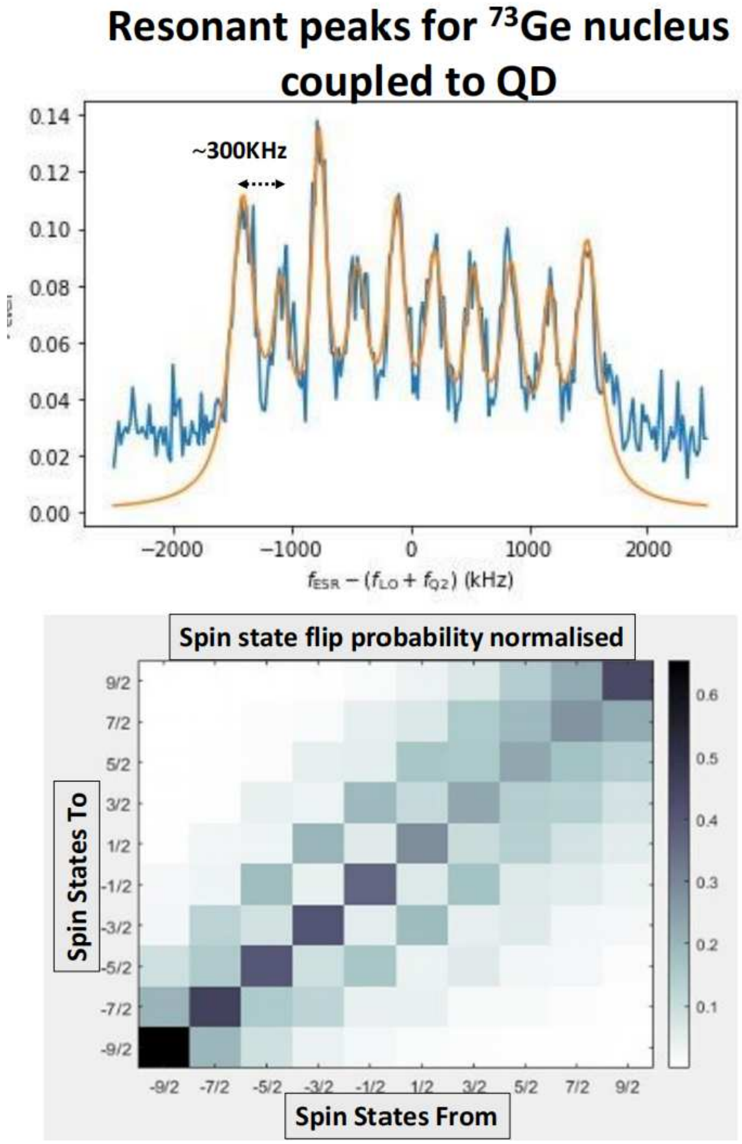
Background – With several contenders to realize qubits for quantum computation, SiMOS quantum dots are one of the leading qubit platforms. With their nanoscale size and CMOS compatibility, they possess the promise of being scaled to billions of physical qubits. Nuclear spins are often considered a noise source in SiMOS quantum dot qubit platforms, but they can also act as excellent quantum computation platform with extremely high coherence times at the order of many milliseconds. Studying nuclear spins, and in particular high-dimensional nuclear spins, as ancillas for quantum computation, will help scale down the size of quantum processors further and also pave the way forward for encoding error-corrected quantum information. Nuclear spin qubits/qudits (10-level systems) have been studied as donor-based platforms for quantum computation in silicon, but high-spin nuclei coupled to quantum dots remain understudied.

Objectives – To realize quantum computation based on a high spin nucleus, we aim to couple a single 73Ge nucleus to a SiMOS quantum dot, establishing initialization, readout, and coherent control of 73Ge, with the final goal to encode error-corrected quantum information into the 73Ge Hilbert space.

Methods – We have realized qubits at millikelvin and coupled a single quantum dot to a 73Ge nucleus.

Results & Conclusions – We recognize the presence of a single 73Ge spin coupling to a single quantum dot by monitoring the Electron Spin Resonance (ESR) frequency for a prolonged time. We detect 10 equally spaced resonance peaks (300 kHz spacing), that correspond to the 10 levels of the 73Ge Hilbert space. The resolvable hyperfine coupling of 300 kHz makes it promising to address the 73Ge Hilbert space, as being able to invert the electron spin at a particular frequency constitutes readout of the nuclear spin.

Session: Poster 2.8


Resonant peaks for 73Ge nucleus coupled to QD
~300KHz
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
−2000
−1000
0
1000
2000
fESR − (fLO + fQ2) (kHz)
Spin state flip probability normalised
Spin States To
Spin States From
9/2
7/2
5/2
3/2
1/2
-1/2
-3/2
-5/2
-7/2
-9/2
0.6
0.5
0.4
0.3
0.2
0.1

Measuring Electron Spins on Solid Neon for Quantum Technology

Shan Zou, Yutian Wen, Alec Dinerstein, Evgenii Zaitsev and Dafei Jin

We have achieved a novel solid-state qubit platform by trapping and manipulating single electrons on the surface of solid neon (eNe). Relaxation time (T1) and dephasing time (T2) both reach approximately 0.1 milliseconds, marking a significant advancement. To enable long-term scalability and extended coherence, we propose a charge–spin hybrid qubit architecture. A first step in realizing spin qubits within this system is the measurement of ensemble electron spin resonance (ESR)—an experiment that, due to historical circumstances, has not yet been performed. To address this, we will utilize a pyramid resonator engineered for both DC tunability and a high filling factor, allowing precise control over spin density and enhanced ensemble cooperativity. This effort aims to lay the groundwork hybrid qubit integration in this solid neon platform.

work in progress

Session: Poster 2.9

Resolving Andreev spin qubits in germanium-based Josephson junctions

Silas Hoffman and Charles Tahan

Andreev spin qubits (ASQs) are a promising platform for quantum information processing which benefit from both the small footprint of semiconducting spin qubits and the long range connectivity of superconducting qubits. While state-of-the-art experiments have developed ASQs in InAs nanowires, these realizations are coherence-time limited by nuclear magnetic noise which cannot be removed by isotopic purification. In Ge-based Josephson junctions, which can be isotopically purified, Andreev states have been experimentally observed but spin-resolved Andreev states remain elusive. Here, we theoretically demonstrate that the geometry of the Josephson junction can limit the qubit frequency to values below typical experimental temperatures and render the ASQ effectively invisible. ASQs could be experimentally resolved by judiciously choosing the geometry of the junction and filling of the underlying Ge. Our comprehensive study of ASQ frequency on in situ and ex situ experimentally controllable parameters provides design guidance of Ge-based Josephson junctions and paves the way towards realization of high-coherence ASQs.

arXiv:2506.13988

Session: Poster 2.10

Decoherence of Majorana Qubits by 1/f Noise

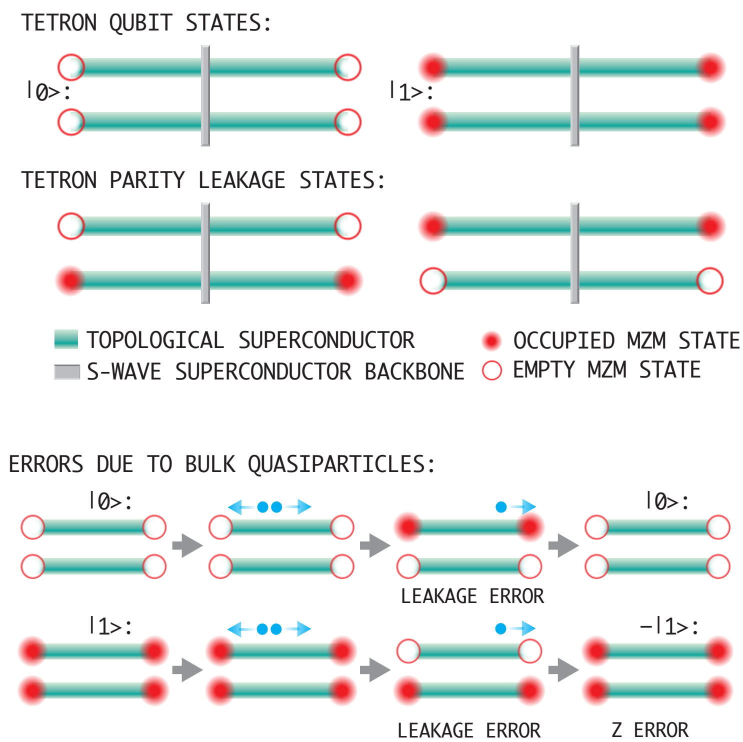
Marcus C. Goffage, Abhijeet Alase, Maja C. Cassidy and Susan N. Coppersmith

Qubits based on Majorana Zero Modes (MZMs) in superconductor-semiconductor nanowires have attracted intense interest as a platform for utility-scale quantum computing. These qubits have been predicted to show extremely low error rates due to the topological protection of the MZMs, where decoherence processes have been thought to be exponentially suppressed by either the nanowire length or the temperature. However, here we show that 1/f noise, which is ubiquitous in semiconductors, gives rise to a previously unexplored mechanism for Majorana qubit decoherence. The high frequency components of this noise cause quasiparticle excitations in the bulk of the topological superconductor, which in turn result in qubit errors that increase with the length of the nanowire. The attached figure illustrates this fundamental error mechanism in a tetron qubit which is comprised of two nanowires. We calculate the probability of quasiparticle excitation for a disorder-free nanowire in the presence of 1/f noise and show that this mechanism limits the decoherence times of the MZM qubits currently being developed [1] to less than a microsecond even for perfectly uniform nanowires with no disorder. This decoherence time is significantly shorter than the time to implement quantum gates using this technology and is also shorter than the decoherence times of qubits in other leading solid-state architectures.

[1] M. Aghaee et al. (Microsoft Azure Quantum), Nature 638, 651 (2025).

[1] A. Alase, M. C. Goffage, M. C. Cassidy, and S. N. Coppersmith, arXiv preprint, arXiv:2506.22394

Session: Poster 2.11


TETRON QUBIT STATES:
|0>:
|1>:
TETRON PARITY LEAKAGE STATES:
TOPOLOGICAL SUPERCONDUCTOR
S-WAVE SUPERCONDUCTOR BACKBONE
OCCUPIED MZM STATE
EMPTY MZM STATE
ERRORS DUE TO BULK QUASIPARTICLES:
|0>:
|0>:
LEAKAGE ERROR
|1>:
-|1>:
LEAKAGE ERROR
Z ERROR

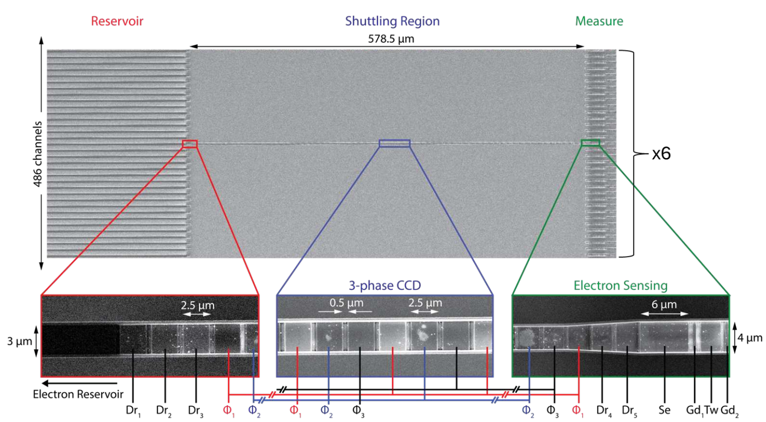
Efficient, long-range shuttling of electrons bound to liquid helium

Gordian Fuchs, Mayer M. Feldman, Tiffany Liu, Luke A. D'Imperio, Michael D. Henry, Eric A. Shaner and Stephen A. Lyon

Electrons floating on superfluid helium are a promising physical system for quantum computing due to their high electron mobilities, long spin coherence and negligible spin-orbit coupling. In particular, charge coupled devices (CCDs) have previously been shown to enable efficient electron transport along both horizontal and vertical gate-defined channels filled with superfluid helium. This provides a highly scalable, all-to-all connected architecture that has the potential to enable fast and coherent qubit transfer. We demonstrate charge transfer of a total of 2 electrons across 6 parallel, around 600 µm long gate-defined helium-filled channels using a 3-phase CCD. The CCD was fabricated utilizing a complementary metal-oxide-silicon (CMOS) back end of line (BEOL) metallization process at the Sandia National Laboratories MESA fab. The uppermost metal layers were post-processed by reactive ion etching to define the helium channels and apply voltage biases to move the electrons. In addition, we outline a path towards demonstrating single electron transfer along parallel and perpendicular helium-filled channels on the same CCD device. The electron sensing technique currently operates at 102 kHz, without the need for tuned RF resonators. Shifting the measurement frequency to a few MHz, improving the noise environment, and optimizing our home-built cryogenic amplifier circuit is expected to enable single electron sensitivity.

Feldman, M.M., Fuchs, G., Liu, T. et al. Sensing Few Electrons Floating on Helium with High-Electron-Mobility Transistors. J Low Temp Phys 219, 242–251 (2025). https://doi.org/10.1007/s10909-024-03256-1

Session: Poster 2.12



Cooling Electrons Bound to Superfluid Helium with Resistive Metallic Gates

Matthew Schulz and Stephen A. Lyon

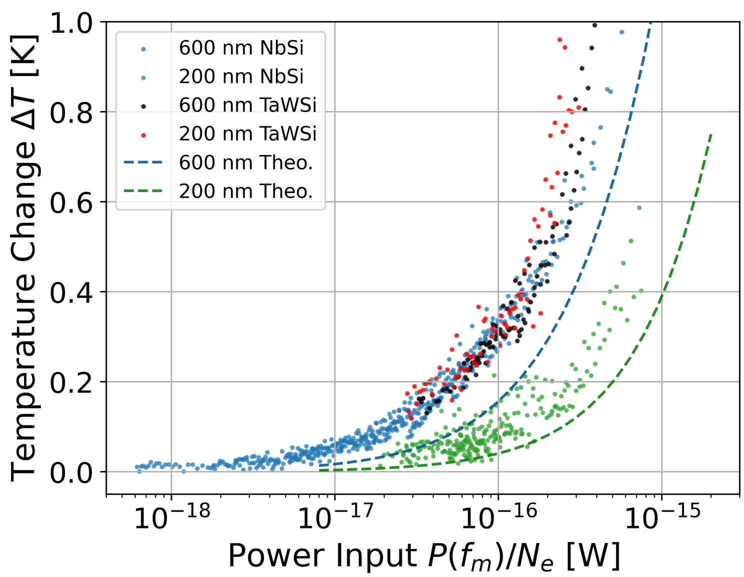
Electron thermalization is important for maintaining fidelity in readout and preserving quantum states during operations. Nonpolar materials for electron platforms, such as silicon and liquid helium, have a particularly difficult time coupling to electrons to cool them. In addition, the phononic density of states falls off as energy squared at low temperatures, leading to the well-known cubic temperature dependence of electron thermalization via phonon-electron interactions. To aid in electron thermalization, the lagging image charges in the metal electrodes beneath the 2DEG have been predicted to create a dipole with the 2DEG and dissipate kinetic energy of the electrons, cooling the 2DEG [1]. With a high resistivity metal, the Johnson noise from the electrodes will not decohere the spins. This image charge dipole interaction also preserves mobility as much as possible, given that it acts as viscous drag rather than backscattering. Here, we investigate the ability of the lagging image charges to cool a 2DEG using a thermopower-based temperature measurement [2]. We report evidence of cooling at distances from the resistive metal of 600 nm and lower that is not present with superconducting electrodes.

Supported by the US DOE, BES under DE-SC0020136 and by NQIS C2QA Center under DE-SC0012704.

[1] J. S. Shier. Am. J. Phys. 36, 245 (1968).
[2] E. I. Kleinbaum and S. A. Lyon, Phys. Rev. Lett. 121, 236801 (2018).

work in progress

Session: Poster 2.13



Delta axis spectroscopy: a method to measure excited state tunnel couplings

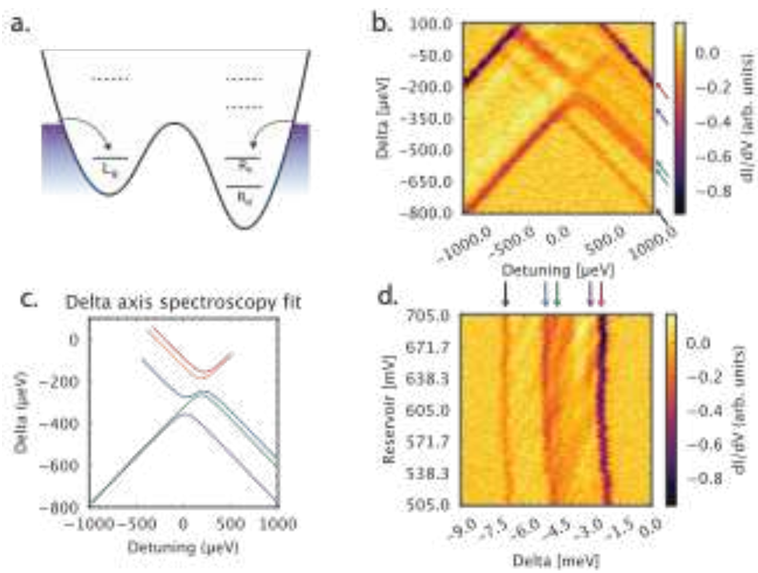
John Reily, Daniel J. King, Jonathan Marcks, Michael A. Wolfe, Piotr Marciniec, Tyler J. Kovach, Brighton X. Coe, Matthew J. Curry, Joelle Corrigan, Nathaniel C. Bishop, Gabriel J. Bernhardt, Mark Friesen, Benjamin D. Woods and Mark Eriksson

We propose and experimentally implement a new method to measure excited state tunnel couplings in quantum dot qubits: delta axis spectroscopy (DAXS). In this method, pulsed gate voltages shift the energy levels of a double quantum dot (Panel a.) perpendicular to the detuning axis on the stability diagram. This method is similar to pulsed-gate spectroscopy but instead utilizes access to reservoirs on both sides of a double quantum dot, which enables the extraction of interdot tunnel couplings between both ground and excited states, in addition to energy levels. Figure panel b. shows an example of DAXS where tunnel couplings are visible as avoided crossings and energy levels are visible as diagonal lines. Panel c. shows the DAXS fit, from which energy spacings and tunnel couplings are quantitatively extracted by fitting simultaneously to all relevant levels of the double quantum dot. Relevant levels of the double dot can be differentiated from resonances in the leads, as shown in Figure panel d., where lead resonances appear diagonally due to lead control while dot states are vertical. These states are identified and matched to states in DAXS with colored arrows. We demonstrate this method on a 3-qubit Tunnel Falls device [1].

[1] S. Neyens, et al., Nature 629, 80-85 (2024).

Work in progress

Session: Poster 2.14



Spin Coherence Calculations for Mobile Electrons Bound to Superfluid Helium

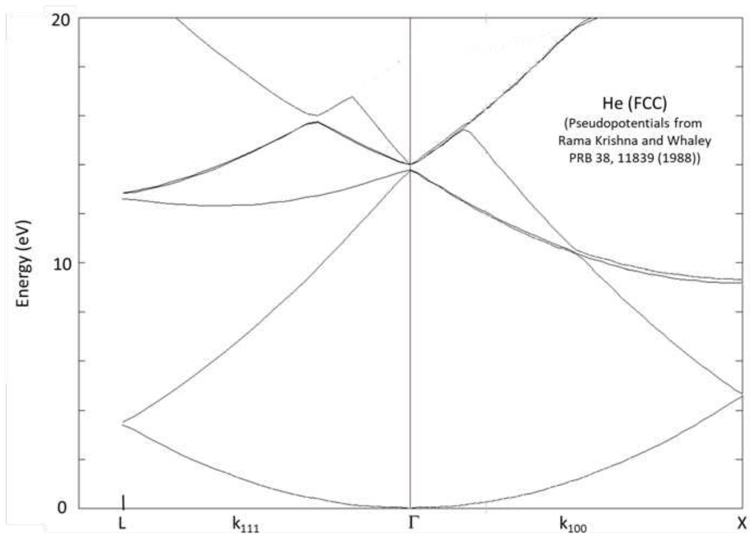
Stephen A. Lyon

It has been suggested that electrons bound to the surface of superfluid helium will have very long spin coherence, even when mobile, due to helium's low spin-orbit interaction and the fact that it can be isotopically enriched to no more than few parts in 10^{13} of 3He. This situation can be contrasted with electrons in silicon, where electron spin coherence of at least 10 seconds is measured for bound electrons, but the Rashba spin-orbit term limits the coherence of mobile electrons to the microsecond range. However, while estimates of the decoherence have been made for electrons bound to helium, calculations of the Rashba term have not previously been made. From detailed calculations of the Rashba term and the dielectric discontinuity at the helium vacuum interface, we find that spin decoherence is very small for mobile electrons on helium.

The Rashba coefficient is obtained from calculations of an electron above crystalline solid helium. This approach assumes that the Rashba term only weakly depends on the crystallinity and will be similar for the liquid phase. A close-packed (fcc) structure is assumed, with lattice constant matching the density of liquid helium. Empirical atomic helium pseudopotentials are used with 113 plane waves to calculate the helium band structure (see Figure). Different published pseudopotentials all lead to a spin-orbit interaction that does not meaningfully limit the spin coherence of mobile electrons on helium.

In addition, the dielectric discontinuity at the helium surface gives rise to an image charge. For electrons bound to helium there will be an effective magnetic field acting on a moving electron which is just given by that of the moving image. Spin decoherence can then be described as a Dyakonov-Perel process. This mechanism leads to faster decoherence, but again long enough to be of little importance for quantum devices.

Session: Poster 2.15



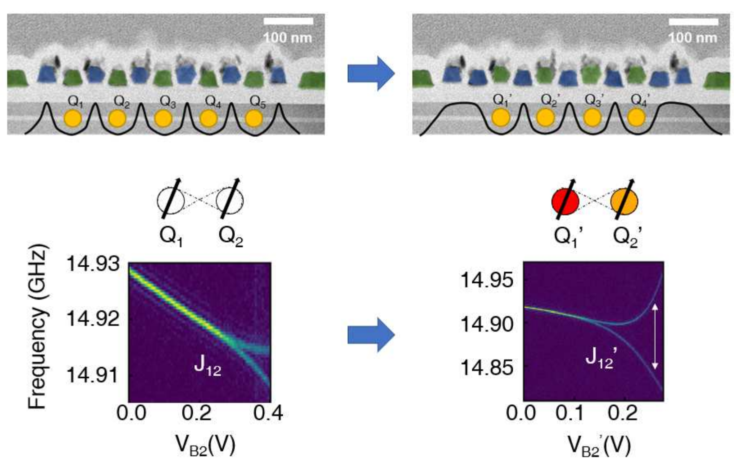
Investigating Qubit Operation under Switched Gate Roles

Jaemin Park, Hyeongyu Jang, Hanseo Sohn, Younguk Song, Lucas E. A. Stehouwer, Davide Degli Esposti, Giordano Scappucci and Dohun Kim

Quantum computing is expected to achieve supremacy over classical computing in various fields such as cryptography, quantum simulation and optimization. Among the candidate physical systems, spin qubits based on semiconductor quantum dots are considered promising for dense and large-scale quantum processors, owing to their compatibility with industrial Complementary-Metal-Oxide-Semiconductor (CMOS) technology. The trend in gate design has shifted from making the effective width of plunger gates slightly wider than that of barrier gates — which led to significant wavefunction overlap — to using gates of equal width, enabling long-range shuttling, dynamic barrier control and multi-qubit entanglement. In this work, we study a tuning method involving switched gate roles, where plunger gates are placed in the third layer and barrier gates in the second layer, contrary to the conventional tuning. We successfully access the single-electron and four-electron regimes required for Pauli-Spin-Blockade (PSB)-based parity readout with this configuration. Despite the outermost quantum dots being located farther from the sensing dots than in the conventional tuning, the signal-to-noise ratio of the readout signal remains sufficient to resolve spin parity, enabling successful single-qubit operation and readout. Furthermore, the tunability of the exchange coupling is significantly enhanced, with the largest increase reaching nearly four orders of magnitude, corresponding to 11.1 dec/V. We compare the experimental data with the simulated data and analyze where the improvement mainly arises. These results demonstrate that spin qubits can be reliably reconfigured and operated under any nano-gate in situ, which in turn serves as a powerful tool for studying noise characteristics arising from spatially localized two-level fluctuators or sensing dots.

work in progress

Session: Poster 2.16



RF Reflectometry Modelling for Admittance Extraction in Quantum Dot Arrays

Conor Power, Mathieu Moras, Andrii Sokolov, Robert Bogdan Staszewski and Elena Blokhina

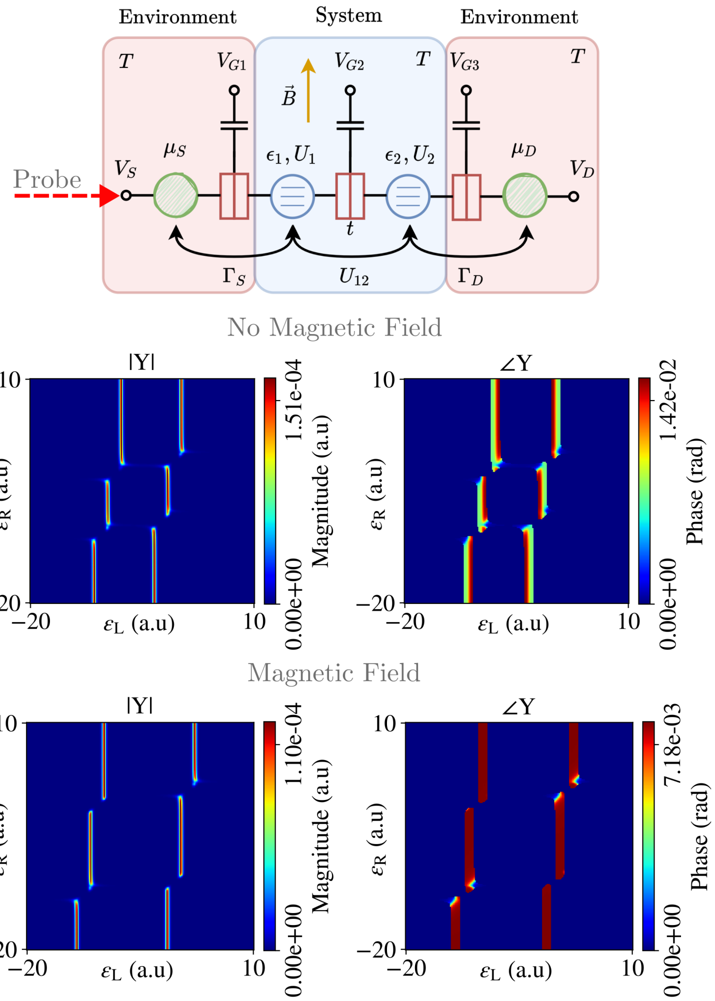
In this work we report the modelling and simulation of quantum dot arrays subject to adiabatic RF perturbations in an effort to numerically extract their admittance. Reflectometry readout of quantum dot arrays is a routine operation in the lab but there remains a gap in the literature discussing how different physical transport phenomena such as Pauli-Spin Blockade etc. are manifest in the magnitude and phase variations of a reflectometry (time-dependent) signal in a charge stability plot. We also compare the variation in admittance as detected through reservoir reflectometry or through gate reflectometry.

The complex admittance of the quantum dot array is defined here in terms of the ratio of the current in response to the time-dependent probing voltage. Currently the Von-Neumann equation is solved to second order in the hybridisation (weak-coupling) resulting in populations via the Pauli Master Equation (PME). Current is then found via sequential tunnelling. Multiple reservoirs can be connected or disconnected as needed, allowing for transport-like reflectometry or single-electron box reflectometry as required. The quantum dot array itself is modelled using the extended Hubbard Hamiltonian. PME is appropriate for the DC/low frequency probing of the interacting quantum dot system and provides a low computational cost as compared to a Lindblad or NEGF approach.

Current results focus on the simulation of the quantum dot array as probed through a weakly-coupled reservoir in a single-electron box mode, showing a distinctive phase variation over the charge stability diagram without PSB and with PSB, see figures. Future work will continue to calibrate the model for specific fabrication processes, perform gate based reflectometry, and include a Lindblad extension to model higher order coupling and more exotic noise processes. We also plan to extend the reflectometry sensing of capacitively coupled charge sensors to quantum dot arrays.

work in progress

Session: Poster 2.17


Environment
System
Environment
Probe
V_S
μ_S
V_{G1}
V_{G2}
V_{G3}
$\vec{B}$
T
ϵ_1, U_1
ϵ_2, U_2
t
μ_D
V_D
Γ_S
U_{12}
Γ_D
No Magnetic Field
|Y|
∠Y
ε_R (a.u)
ε_L (a.u)
Magnitude (a.u)
Phase (rad)
1.51e-04
1.42e-02
0.00e+00
Magnetic Field
1.10e-04
7.18e-03

Observing quantum chaotic kicked top dynamics on a high-spin nuclear in Silicon

Sean Hsu, Xi Yu, Rocky Yue Su, Danielle Holmes, Fay E. Hudson, Kohei M. Itoh, David N. Jamieson, Andrew S. Dzurak and Andrea Morello

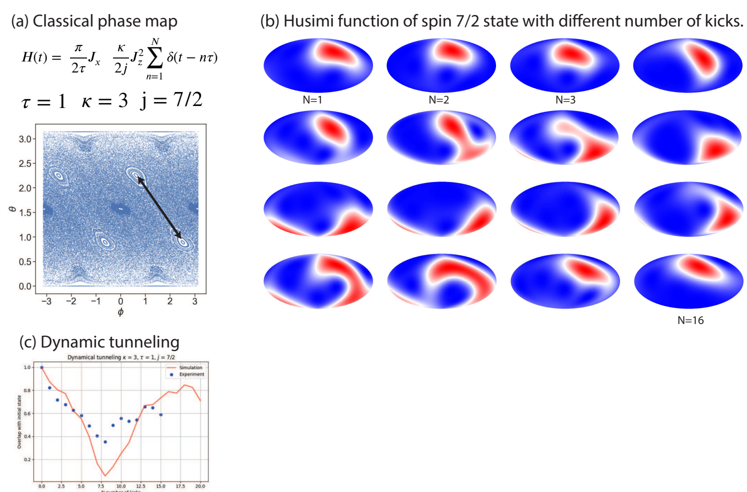
Chaotic dynamics plays a role in many fields of science as most Hamiltonians of interest are non-integrable. In quantum mechanics, due to the Heisenberg uncertainty principle, states are probabilistically distributed in phase space, resulting in the correspondence between classical and quantum chaos to break down. This work aims to observe quantum chaos based on the Quantum Kicked Top (QKT) model on a high-spin antimony (^{123} Sb) nucleus.

Sb is a high spin nuclear with J=7/2, which spans an 8-dimensional Hilbert space. Navigation of the full Hilbert space has been demonstrated [1] using standard ESR and NMR techniques. More recently, our group has also demonstrated SU(2) global rotation and selective number arbitrary phase (SNAP) operations [2]. Implemented by instantaneous clock frame rotation virtually, the errorless SNAP gate in our system is ideal to provide delta-function-like kicking to the system.

This work, for the first time, observes the chaotic dynamics on a J=7/2 nuclear spin based on the QKT Hamiltonian. We observed experimental evidence of the quantum dynamical tunneling, which is classically forbidden. What's more, the result in smaller subspaces shows that the frequency of the tunneling depends on the size of the spin, which agrees with the classical limit (j⟶∞) in theory. This work lays a good foundation for exploring trotter errors and performing digital quantum simulations.

[1] Fernández de Fuentes, I., Botzem, T., Johnson, M.A.I. et al. Navigating the 16-dimensional Hilbert space of a high-spin donor qudit with electric and magnetic fields. Nat Commun 15, 1380 (2024).
https://doi.org/10.1038/s41467-024-45368-y

Session: Poster 2.18

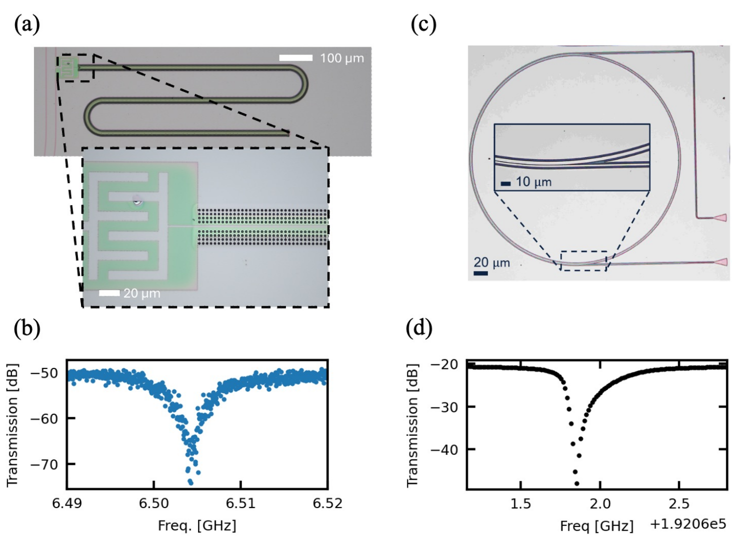


Progress on microwave-optical photon conversion with silicon color centers

Phillip Suwan Kirwin, Mohammad Khalifa, Eloïse Baril, Arjun Sen, Sheri Jahan Chowdhury, Jaden Ingleton, Lukas Chrostowski, Jeff F. Young and Joseph Salfi

Microwave-optical conversion could be an enabler of scalable quantum networks, but a device that meets all performance requirements has not yet been demonstrated. We present recent experimental progress towards an integrated microwave-optical converter based on color centers in silicon. Such a device is comprised of an optical resonator, a microwave resonator, and an ensemble of spin-bearing color centers. Here we present a characterization of both cavities required for this device that can be integrated together into a single chip. Namely, we fabricated coplanar waveguide-based superconducting microwave resonators suspended on silicon-on-insulator substrates with quality factors of 1e4, measured at 10 mK and single-photon powers (Fig. 1(a, b)), and silicon photonic microring resonators on silicon on-insulator substrates with quality factors of 1e6 (Fig. 1(c, d)). These resonators are of sufficiently high quality to experimentally realize a high-efficiency converter. Finally, we show our progress towards cryogenic packaging of hybrid photonic-superconducting integrated circuits.

Session: Poster 2.19



Engineering Solid-Neon Growth for Coherent Electron Qubits

Yueheng Shi, Brennan Dizdar, Chris Wang and David Schuster

Recent studies of electron-based qubits levitated on solid neon (eNe) have renewed interest in optimizing growth conditions of cryogenic noble gas substrates. In this emerging platform, electrons are electrostatically trapped above a thin solid neon layer and manipulated with planar electrodes. The lowest energy quantized lateral motional modes of these electrons are utilized as charge qubit states. Compared to semiconductor-based electron qubits, eNe charge qubits demonstrate significantly enhanced charge coherence times. Solid neon offers an exceptionally clean electromagnetic environment due to the absence of nearby substrate background charges and the ability to isotopically purify neon to remove nuclear spins, thus presenting promising opportunities for spin-orbit interaction-based qubits.

However, well-controlled growth of smooth noble gas solids remains to be demonstrated, and the nanoscale roughness of neon surfaces studied thus far likely limits qubit performance. Here, we report progress in characterizing solid neon growth using a planar high-critical temperature superconducting microwave resonator, particularly targeting layer thicknesses from 30 nm to 1 μm. While the triple-point (de)wetting of neon in the 24-27K temperature range typically inhibits the growth of thin layers beyond several nanometers, we monitor the liquid-to-solid transition in real-time to explore the nanolayer to bulk solid transition. In addition to dielectric and electron gas sensing, leveraging a microwave resonator with integrated planar DC bias electrodes makes standard cavity QED experiments accessible at mK temperatures with this study. This allows us to study properties of electron ensembles on neon surfaces, including surface mobility and lateral motional mode properties, under varying neon growth conditions, making strides towards improving control and coherence of future eNe qubits.

Session: Poster 2.20

Quantum dot as a perceptron for future learning machines

Jose Nicolas Alvez, Sonali Goel, Parth Girdhar, Federico Fedele and Natalia Ares

Artificial neural networks rely on nonlinear activation functions to enable efficient learning. In this work, we propose a physical implementation of a perceptron using a quantum dot as the nonlinear element. The sharp electronic transition of the quantum dot naturally emulates an activation function, and we show that the steepness of this transition directly governs the gradient available for learning. Too shallow a transition reduces sensitivity, while excessive sharpness limits the effective parameter space; thus, an optimal sharpness emerges that maximizes learning speed. This balance enables efficient gradient-based training in hardware, without relying solely on digital simulation. Furthermore, we discuss how arrays of such quantum-dot-based perceptrons can be scaled to construct physical learning machines, where machine learning is performed intrinsically by the material system rather than by external computation. This approach opens a pathway toward compact, energy-efficient neuromorphic architectures, bridging condensed matter physics and artificial intelligence.

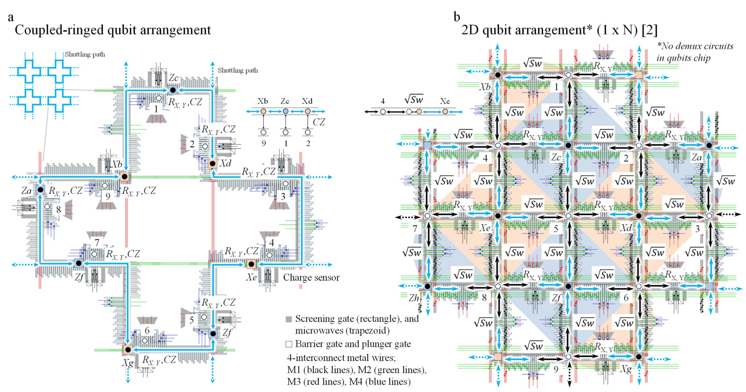
Session: Poster 2.21

Coupled-ringed Qubit Array Arrangement for Scalable Fault-tolerant Quantum Computer

Satoru Akiyama, Takashi Takemoto, Tatsuya Tomaru, Yusuke Wachi, Takayasu Norimatsu, Noriyuki Lee and Hiroyuki Mizuno

One of the main challenges concerning scalable fault tolerant quantum computers is achieving quantum coupling between logical qubits [1] and fabricating physical qubit structures that are highly compatible with conventional semiconductor processes. To address these issues, this paper proposes a coupled-ring qubit arrangement consisting of a 1 x N structure, in which ancilla qubits form an outer ring and data qubits are arranged inside the ring to make two-qubit operations possible. The top-left side of figure a shows four coupled logical qubits, where physical qubits mutually shuttle through the paths depicted with dotted lines, making the architecture scalable. When the logical qubit is surface-coded with the distance three, eight ancilla qubits are placed along the ringed 1 x N structure and nine data qubits are arranged inside the ring. Only ancilla qubits are shuttled along the outer ring to perform CZ operations with data qubits; the number of shuttling operations is half compared to using root SWAP operations (figure b, [2]). Although not shown in figure a, staggered arrangement of local magnets is designed at each operation region to generate gradient magnetic fields for electric dipole spin resonance. The qubit device structure is designed using three gate electrode layers: screening, barrier, and plunger gates. The control voltages for these three-layer gates are provided via four-layer metal wiring, following standard semiconductor processes. The numerous control wires required for qubit manipulation are electrically connected to the control electronics by applying hybrid bonding technology [3]. This work was supported by JST Moonshot R&D Grant Number JPMJMS2065.

Session: Poster 2.22



Omnidirectional shuttling to avoid valley excitations in Si/SiGe quantum wells

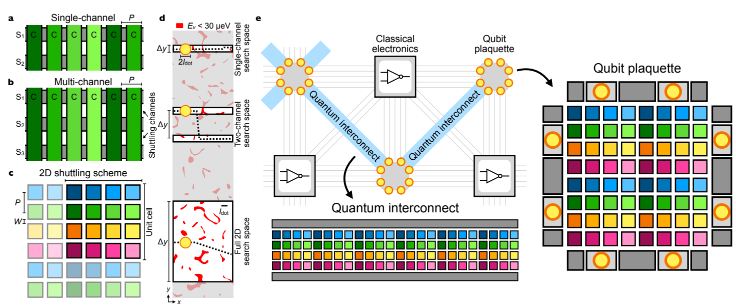
Owen M. Eskandari, Róbert Németh, Vatsal K. Bandaru, Pedro Alves, Emma Brann, Hudaiba Soomro, Avani Vivrekar, Mark Eriksson, Merritt Losert and Mark Friesen

Conveyor-mode shuttling is a key approach for implementing intermediate-range coupling between electron-spin qubits in quantum dots. Initial implementations are encouraging; however, long shuttling trajectories along a single channel (Fig a) composed of clavier (C) gates are guaranteed to encounter regions of low conduction-band valley energy splittings (Fig d), due to the presence of random-alloy disorder in Si/SiGe quantum wells. Here, we theoretically explore two schemes for avoiding valley-state excitations at these valley-splitting minima, by allowing the electrons to detour around them. The first is a multichannel shuttling scheme (Fig b), which allows electrons to tunnel between parallel channels to avoid regions of low valley splittings. The second is a two-dimensional (2D) shuttler (Fig c) composed of pixel-like clavette gates formed into a 2D unit cell, which provides full omnidirectional control and does not rely on electron tunneling to avoid regions of low valley splittings. Using simulations, we estimate shuttling fidelities in these two schemes, obtaining a clear preference for the 2D shuttler.

Based on such encouraging results, we propose a full qubit architecture structured around 2D shuttling (Fig e), which incorporates three distinct technologies: qubit plaquettes (comprised of qubits, readout and control electronics, arranged around the periphery of a 2D shuttler), quantum interconnects (also comprised of 2D shuttlers), and classical control electronics interspersed between the qubit plaquettes. This architecture enables all-to-all connectivity within qubit plaquettes and high-fidelity communication between different plaquettes.

https://arxiv.org/abs/2412.09574

Session: Poster 2.23

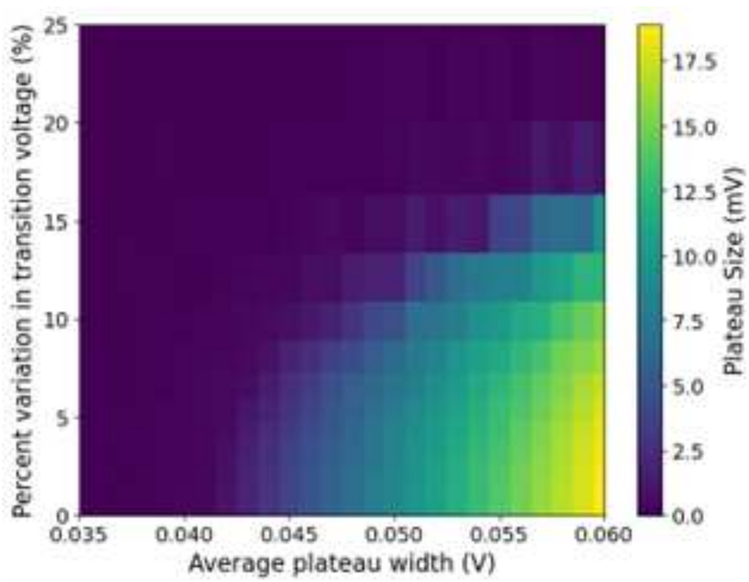


Variability in Device Parameters for Parallel Operation of Single Electron Pumps

Pooja Yadav, Tommy O. Boykin, Masaya Kataoka, Eite Tiesinga and Michael Stewart

Single electron charge pumps (SEPs) have the potential to serve as a practical realization of the Ampere if the generated currents can be increased from 100 pA to 1-10 nA while maintaining a relative uncertainty below 10-7. The pumped current is given by, I = nef, where n is the number of pumps operated in parallel, and f is the operating frequency. Since increasing the frequency beyond a certain point give rise to larger uncertainties through, for instance, non-adiabatic excitations, there is a strong push in the community to parallelize devices. Significant challenges in parallel device operation arise from device-to-device variability in, for instance, the position and size of the plateaus and the voltage width of transition between plateaus. These variations can result in non-overlapping current plateaus and an inability to parallelize. There are two strategies for overcoming these variations. The first involves making many devices and post-selecting only those with sufficient overlap. The second strategy supplies separate compensating gate voltages to each device to bring them into alignment. With the goal of identifying acceptable levels, we study the effects variations in the system parameters have on the summed current and its deviation from I = nef within the decay cascade model.

Session: Poster 2.24

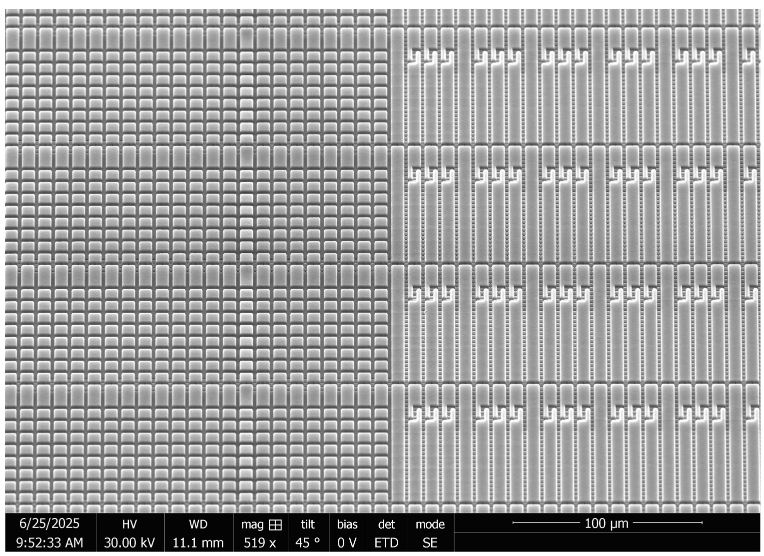


Efficient shuttling of electrons on helium using a CCD-like architecture.

Heejun Byeon, Kyle E. Castoria, Niyaz R. Beysengulov, Elena O. Glen, Michael Sammon, Jenna Theis, Stephen A. Lyon, Johannes Pollanen and David G. Rees

Electrons floating on the surface of superfluid helium have emerged as promising mobile spin qubits due to their theoretically long spin coherence times. To precisely control their position and transport, we have developed and fabricated a CCD-like array, which has been integrated into a silicon chip using CMOS technology. Electrons are moved in groups ranging from several tens down to single electrons along liquid helium-filled CCD channel regions. We employ conveyor-like transport within 128 microchannels, each serving as a pathway between electron reservoir areas and detection regions in a two-dimensional plane. This transport process can be repeated over one million times, allowing electrons to travel approximately 100 meters with no measurable loss. This scheme's outstanding transfer fidelity supports its potential as a scalable spin-qubit platform based on electrons floating on helium.

Session: Poster 2.25



Interplay of Zeeman Splitting and Tunnel Coupling in Coherent Spin Qubit Shuttling

Ssu-Chih Lin, Paul Steinacker, Meng Ke Feng, Ajit Dash, Santiago Serrano, Wee Han Lim, Kohei M. Itoh, Fay E. Hudson, Tuomo Tanttu, Andre Saraiva, Arne Laucht, Andrew Dzurak, Hsi-Sheng Goan and Chih-Hwan Henry Yang

Among candidates for realizing quantum computation, Si-based quantum dots (QDs) is an attractive platform due to the potential of scaling up. The high-fidelity single- and two-qubit gates satisfying surface code requirements are demonstrated [1]. However, the conventional two-qubit gates rely on the exchange coupling of the adjacent spins and hence restrict the arrangement of qubits. A promising solution is the spin shuttling protocol [2], where the spins are moved together when needed.

In this work, we demonstrate high-fidelity bucket-brigade (BB) spin shuttling in a silicon MOS device, utilizing Pauli Spin Blockade (PSB) readout. We achieve an average shuttling fidelity of 99.8%. The residual shuttling error is highly sensitive to the ratio between interdot tunnel coupling and Zeeman splitting, with tuning of these parameters enabling up to a twenty-fold variation in error rate. An appropriate four-level Hamiltonian model supports our findings [3]. These results provide valuable insights for optimizing high-performance spin shuttling systems in future quantum architectures.

Reference:

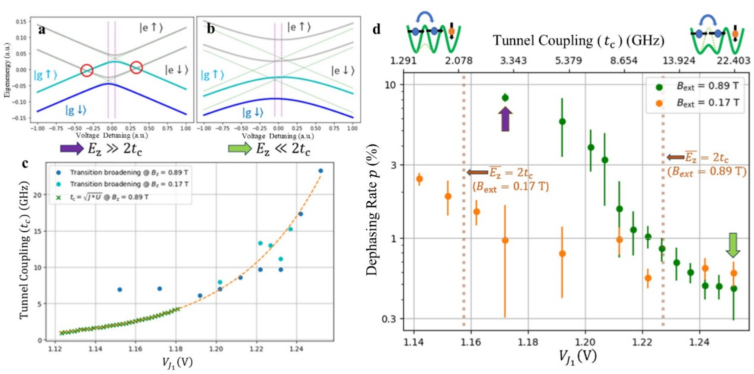
[1] Steinacker, P.et al. A 300 mm foundry silicon spin qubit unit cell exceeding 99 % fidelity in all operations. arXiv: 2410.15590 (2024)

[2] Boter, J. M. et al. Spiderweb Array: A Sparse Spin-Qubit Array. Phys. Rev. Appl. 18, 024053 (2022)

[3] Feng, M.K. Control of dephasing in spin qubits during coherent transport in silicon. Phys. Rev. B 107, 085427 (2023)

https://doi.org/10.48550/arXiv.2507.15554

Session: Poster 2.26



Optimizing Spin Qubit High Velocity Shuttling in Si/SiGe Simulation Including Random Alloy Disorder

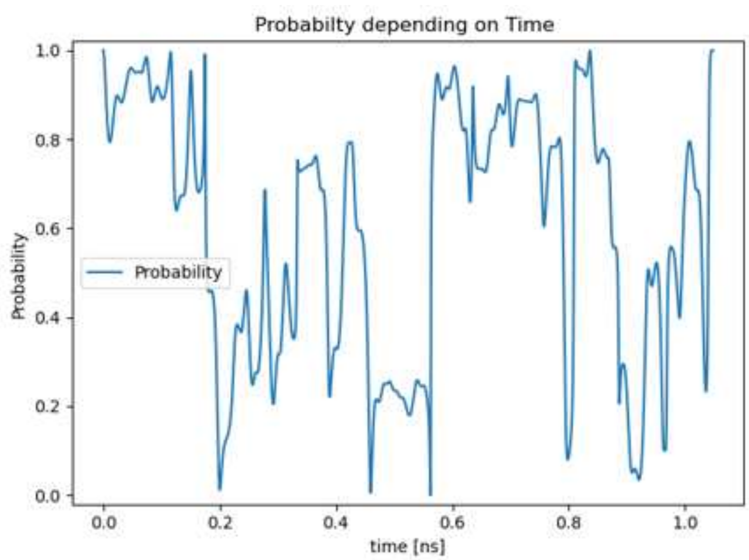
Kenichiro Senda, Hideaki Yuta, Tatsuo Tsuzuki, Kotaro Taga, Rio Fukai, Akira Oiwa and Takafumi Fujita

Spin shuttling is a promising strategy for mitigating the wiring density problem in large-scale semiconductor quantum computers. Si/SiGe-based spin qubits are particularly well-suited for such architectures, as evidenced by the demonstration of high-fidelity single- and two-qubit gate operations exceeding 99.9%. However, spatial inhomogeneity in the valley splitting of Si/SiGe heterostructures presents a significant challenge to achieving high-fidelity spin transport. In particular, in regions where the valley splitting is locally small, higher shuttling velocity enhances the probability of Landau-Zener transitions, resulting in leakage from the computational subspace. Conversely, lower shuttling velocity increases the susceptibility of the system to decoherence arising from Overhauser fields, 1/f charge noise, and valley-spin coupling.

In this study, we numerically investigate the feasibility of high-fidelity spin shuttling at velocities approaching 1000 m/s. Unlike previous studies that suppress valley excitations by reducing velocity in critical regions, we propose an alternative strategy: (1) ensure the spin returns to the valley ground state at the end of the transport, (2) suppress probabilistic occupation of both valley ground and excited states to avoid irreversible valley-spin entanglement, and (3) minimize the residence time comparing to period of rotation frequency in valley superposition states if they arise. To identify optimal velocity and electric field profiles under these constraints, we employ Bayesian optimization, which efficiently handles high-cost, non-differentiable objective functions and avoids convergence to poor local optima.

Our results demonstrate that, by carefully controlling the temporal and spatial profile of the shuttling protocol, high-speed and high-fidelity spin transport can be achieved even in the presence of valley splitting inhomogeneity.

Session: Poster 2.27



Unifying Floquet Theory of Longitudinal and Dispersive Readout

Alessandro Chessari, Esteban Rodriguez Mena, José Carlos Abadillo-Uriel, Victor Champain, Simon Zihlmann, Romain Maurand, Yann Michel Niquet and Michele Filippone

In the context of circuit quantum electrodynamics (cQED), fast qubit measurements rely on the mechanism of dispersive readout : a transverse interaction between the two lowest levels of a superconducting artificial atom and a resonator shifts the frequency of the resonator, enabling quantum non-demolition (QND) measurements. Recently, a longitudinal interaction had been proposed as a way to perform faster-than-dispersive measurements in superconducting qubits. However, mechanisms to achieve such interaction are nowadays hard to connect, as they stem from distinct theoretical frames, adopting different approximations. Such a situation calls for a unified description, embracing different devices and regimes.

We devise a Floquet theory to establish a universal connection between AC Stark shift, longitudinal coupling and dispersive readout in cQED. We find that when a qubit transversally coupled to a resonator is driven at the resonator frequency, the resonator probes the Floquet spectrum of the qubit at the drive amplitude. An effective longitudinal interaction then arises from the slope of the Floquet spectrum while a dispersive shift arises from the curvature. We derive semi-analytical results supported by exact numerical calculations, which we apply to superconducting and spin cQED settings, providing a unifying, seamless and simple description of longitudinal and dispersive readout in generic cQED systems. Our approach unifies the adiabatic limit, where the cavity dynamics is so slow that the longitudinal coupling results from the static spectrum curvature, with the diabatic one, where the static spectrum plays no role. We find that resonances between different replicas in the Floquet spectrum lead to a degradation of the readout in the adiabatic regime and to the ionization of the qubit. On the other hand, diabatic readout is equally effective, with the advantage to avoid higher replica processes.

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.134.037003

Session: Poster 2.28

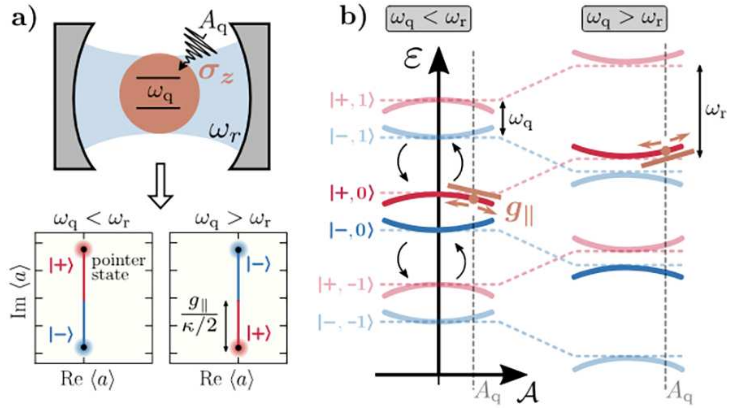


Figure 1. Longitudinal readout of qubits. a) The qubit is driven at the resonator frequency ω_r, which experiences an effective σ_z-dependent drive. In the case of pure longitudinal coupling (1), the cavity pointer states move in opposite direction depending on the qubit state $|\pm\rangle$. b) The transverse drive to the qubit couples different replicas (labeled by integers) of the Floquet quasi-energy spectrum, leading to an AC Stark shift. The emergent longitudinal qubit-photon coupling $g_\parallel$ is given by the slope of the AC Stark shift at the driving strength A_q. The sign of $g_\parallel$ depends on whether $\omega_r \gtrless \omega_q$.

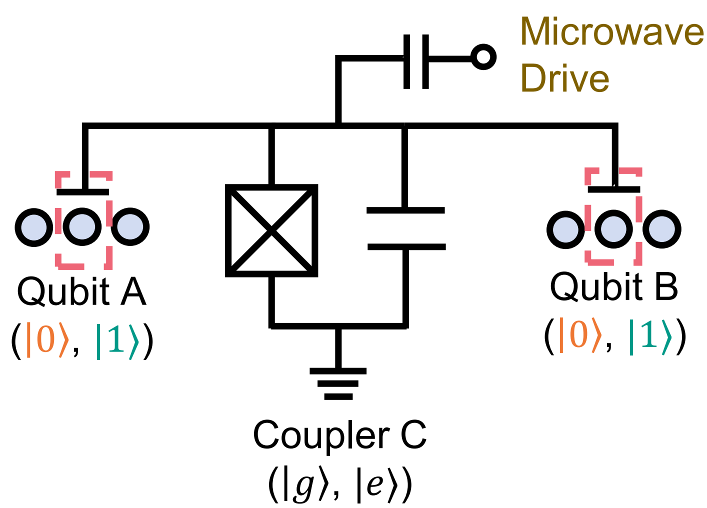
Remote entangling gates for spin qubits in quantum dots using a charge-sensitive superconducting coupler

Harry Hanlim Kang, Holly G. Stemp, Ilan T. Rosen, Max Hays, Frederike Brockmeyer, Gabriel Cutter, Mathis Moes, Réouven Assouly, Aranya Goswami, Farid Hassani Bijarbooneh, Jeffrey A. Grover and William D. Oliver

We propose a method to realize microwave-activated cz gates between two remote spin qubits in quantum dots using a charge-sensitive superconducting coupler. The qubits are longitudinally coupled to the coupler, such that the transition frequency of the coupler depends on the logical qubit states; a capacitive network model using first-quantized charge operators is developed to illustrate this. Driving the coupler transition then implements a conditional phase shift on the qubits. Two pulsing schemes are investigated: a rapid, off-resonant pulse with constant amplitude, and a pulse with envelope engineering that incorporates dynamical decoupling to mitigate charge noise. We develop non-Markovian time-domain simulations to accurately model gate performance in the presence of $1/f^{\beta}$ charge noise. Simulation results indicate that a cz gate fidelity exceeding 90% is possible with realistic parameters and noise models. Finally, we design a hybrid system for combining superconducting couplers and quantum dots, addressing hardware challenges such as microwave hygiene and dense signal routing within a vector-magnet bore.

Phys. Rev. Applied 23, 044055

Session: Poster 2.29



Simulations of spin-spin dispersive coupling mediated by a superconducting resonator in terms of the Jaynes-Cummings ladder model

Andrii Semenov, Brian Malone and Elena Blokhina

In this work, we analyse spin-spin coupling mediated by a superconducting resonator in terms of the Jaynes-Cummings ladder model [1]. The model consists of two flopping-mode qubits coupled to a resonator. The micromagnets for each flopping-mode qubit are placed such that the transversal/longitudinal gradients of the magnetic field are the same, while the constant longitudinal components are different, which facilitates different resonance frequencies for the qubits.

We study the effects of different orientations of micromagnets and different strengths of the outer magnetic field on resonant and dispersive spin-spin coupling, as well as the effects of the number of photons in the resonator. We simulate these regimes together with iSWAP/CZ oscillations at different configurations with the pump tone on/off. We also analyse the effects of noise on the oscillations.

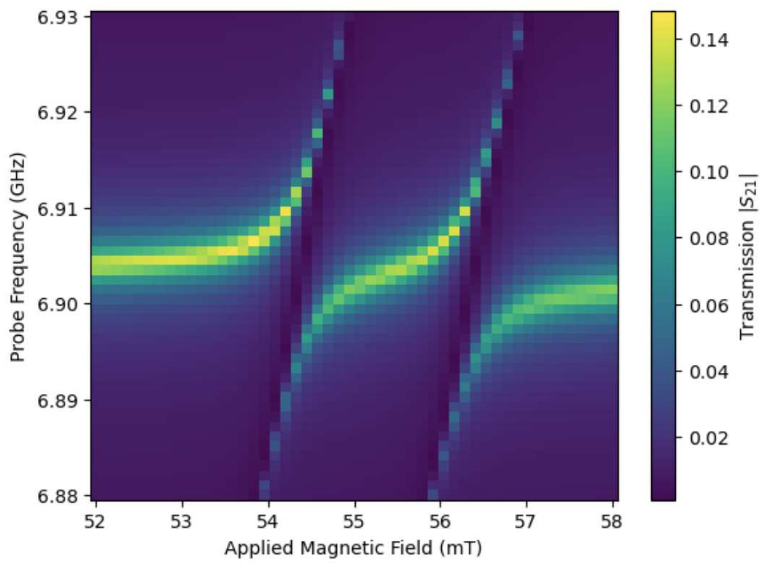
While this model has already been proposed and studied in the literature in the transversal coupling regime [2,3], to study the dispersive coupling regime, a standard perturbation approach has been assumed. In this work, we do not use perturbation theory and take into account the effects of the whole model. This approach allows us to better understand and predict configurations for future device fabrication.

[1] Tobias Bonsen, Patrick Harvey-Collard, Maximilian Russ, Jurgen Dijkema, Amir Sammak, Giordano Scappucci, and Lieven M. K. Vandersypen. Probing the Jaynes-Cummings ladder with spin circuit quantum electrodynamics. Phys. Rev. Lett., 130:137001, 2023.

[2] Patrick Harvey-Collard, Jurgen Dijkema, Guoji Zheng, Amir Sammak, Giordano Scappucci, and Lieven M. K. Vandersypen. Coherent Spin-Spin Coupling Mediated by Virtual Microwave Photons. Phys. Rev. X, 12(2):021026, 2022.

[3] Jurgen Dijkema, Xiao Xue, Patrick Harvey-Collard, Maximilian Rimbach-Russ, Sander L. de Snoo, Guoji Zheng, Amir Sammak, Giordano Scappucci, and Lieven M. K. Vandersypen. Cavity-mediated iSWAP oscillations between distant spins. Nature Physics, 21:168–174, 2025.

Session: Poster 2.30


6.93
6.92
6.91
6.90
6.89
6.88
Probe Frequency (GHz)
52
53
54
55
56
57
58
Applied Magnetic Field (mT)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
Transmission $|S_{21}|$

A co-designed control and measurement architecture for hybrid superconductor-semiconductor qubit systems

Holly G. Stemp, Harry Hanlim Kang, Frederike Brockmeyer, Gabriel Cutter, Mathis Moes, Ilan Rosen, Max Hays, Réouven Assouly, Aranya Goswami, Farid Hassani Bijarbooneh, Jeffrey Grover and William Oliver

Electron spins confined in quantum dots offer a scalable and compact platform for quantum computing. Their small footprint enables the integration of many qubits on a single chip, but this high qubit density introduces significant challenges for routing on-chip classical control electronics; an essential component for scalable operation. To address this, long-range spin coupling mechanisms are needed to connect spatially sparse arrays of spin qubits. While previous approaches have explored spin shuttling and high-impedance superconducting resonators for this purpose, both present their own advantages and challenges. In this work, we propose an alternative scheme that uses a superconducting qubit as a coherent coupling element between distant triple quantum dot qubits. To support simultaneous, high-fidelity operation of both spin and superconducting qubits, we co-designed a hybrid control and measurement architecture, addressing hardware-specific challenges such as microwave hygiene and dense routing within a vector-magnet bore. Our approach aims to establish engineering best practices for operating scalable, hybrid superconductor-semiconductor quantum processors.

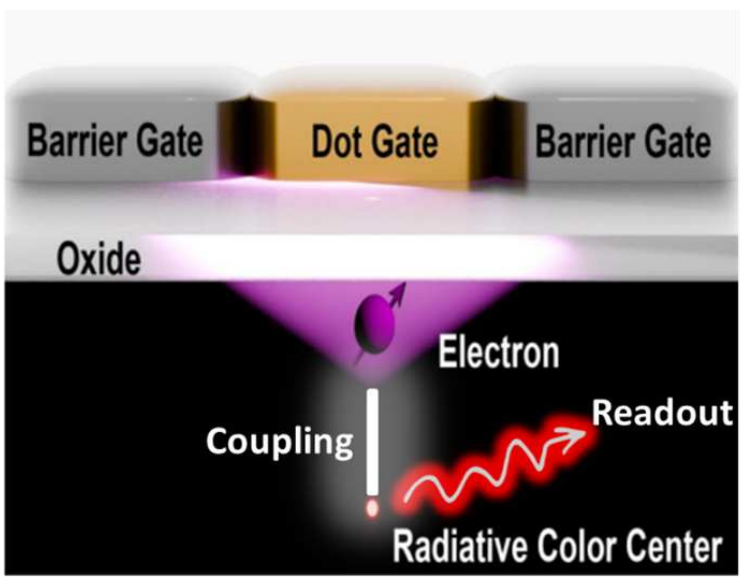
Session: Poster 2.31

A Photonic Approach to Spin Qubit Readout

Nikki Ebadollahi, Christian Pederson, Saumya Choudhary, Vijin K. Veetil, Marcelo I. Davanco, Kartik A. Srinivasan, Pradeep N. Namboodiri, Aaron M. Katzenmeyer, Matthew Pelton and Joshua Pomeroy

Silicon color centers (CCs) are promising candidates for quantum light sources and for optical spin-to-charge conversion through Stark induced spectral shifts. Optical qubit readout could dramatically reduce power demands, improve signal-to-noise ratio, and reduce crosstalk, while also establishing a path toward quantum information transfer, if strong coupling with photonic cavities is achieved. To develop this potential, we have fabricated silicon p-i-n junctions embedded with W- and G-type CCs, systematically investigating how device architecture influences electro-optic efficiency. These devices provide a framework for understanding color center synthesis, process integration with microelectronics, and a preliminary platform for integrating electronic and photonic components. We find that by tuning the intrinsic region width, implantation area, and the dimensions of the p- and n-type leads, trends to improve light emission efficiency can be identified. Building on this foundation, we explore a transition to a metal-oxide-semiconductor (MOS) CC p-i-n architecture, thereby enabling independent control over electron and hole injection and reducing parasitic recombination. This work will showcase electroluminescence spectra from p-i-n devices with embedded CCs, comparative analyses of device geometries, and recent advancements in MOS-based CC p-i-n diodes. We will also discuss pathways towards integrating efficient, telecom-band single-photon sources into scalable quantum photonic platforms, advancing spin readout capabilities and photon-mediated qubit interactions.

Session: Poster 2.32



Multiphoton State Transitions in a Multilevel Quantum Spin System

Sabastian Atwood, Manoj Subramanya, Tomas Orlando and Stephen Hill

The lanthanide ion gadolinium doped in crystalline yttrium orthovanadate (Gd3+:YVO4) is an air-stable, spin S = 7/2 paramagnet with magnetic field-tunable spin energy levels due to its crystal field interactions. These properties make it a promising test ground for multilevel quantum state operations via electron paramagnetic resonance (EPR) spectroscopy. In particular, its high spin and tunable anharmonicity favor the implementation of multiphoton state initialization, as proposed by Leuenberger and Loss [Nature 410, 789 (2001)]. Looking toward a demonstration of Leuenberger and Loss's proposal, we report continuous wave and pulsed EPR studies of Gd3+:YVO4 identifying multiphoton resonances and comparing their signatures to theoretical predictions.

Work in progress

Session: Poster 2.33

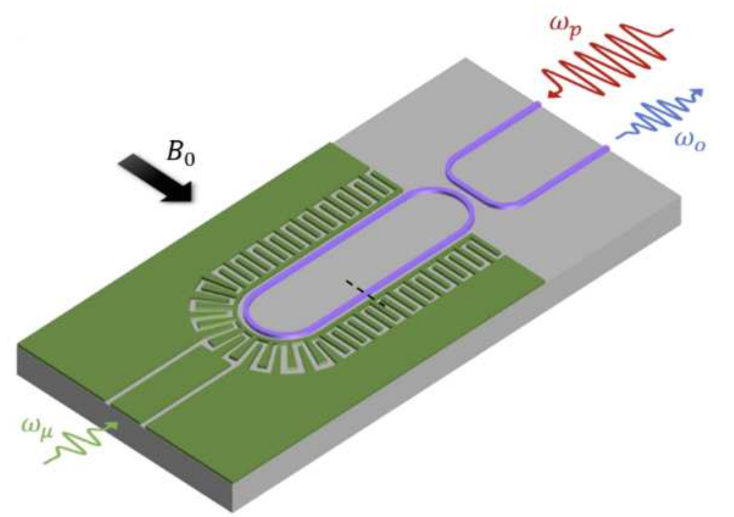
Robust microwave-optical photon conversion using cavity modes strongly hybridized with a color center ensemble

Mohammad Khalifa, Phillip S. Kirwin, Jeff F. Young and Joe Salfi

A microwave-optical converter with high efficiency (>50%) and low added noise (≪1 photon) could enable the creation of scalable optical quantum networks. However, integrated converters demonstrated to date are too lossy or weakly non-linear to provide this performance. Here we develop a theory of microwave-optical conversion employing an ensemble of spin-bearing color centers strongly coupled to a photonic resonator and/or a superconducting microwave resonator. We find a counterintuitive operating point where microwave and optical photons are tuned to bare center/cavity resonances, which, compared to the weak-coupling limit, has much stronger non-linearity, offering high efficiency with reduced pump- and center-induced losses, and that is robust to inhomogeneous broadening. Considering a novel converter design that comprises a silicon-photonic racetrack cavity surrounded by an interdigitated superconducting resonator, as shown in the figure, and taking color center and optical pump-induced losses into account, we predict 95% efficiency and added noise ≪ 1 quanta at low (μW) pump powers for both Er- and T-centers in Si. Our results open new pathways to build quantum networks.

Khalifa, M., Kirwin, P. S., Young, J. F., and Salfi, J. ”Robust microwave-optical photon conversion using cavity modes strongly hybridized with a color center ensemble” Nature Partner Journals: Quantum Information 11 (2025).

Session: Poster 2.34



Development of a fiber-based optical system for quantum state transfer from single photon polarization to single hole spin

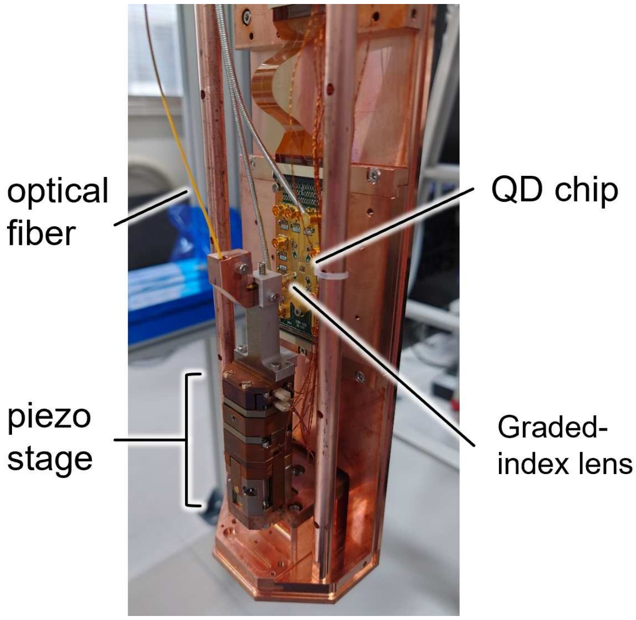
Rio Fukai, Hikaru Sugiyama, Kotaro Taga, Takafumi Fujita, Guy Austing and Akira Oiwa

Quantum state transfer from single photon polarization to single carrier spin is a fundamental technology for realizing quantum repeaters in long-distance quantum communications, and distributed quantum computation implemented by optically connected quantum processors. This transfer, based on angular momentum conservation, can be achieved by illuminating a quantum dot (QD) with polarized photons in a magnetic field, and has been demonstrated in GaAs QD. Ge QD is potentially suitable platform for this transfer because of its excellent properties as spin qubit and a direct transition energy corresponds to an O-band telecom wavelength.

Here, we present a fiber-based optical system combined with a dilution refrigerator designed to illuminate Ge QDs. In this system, we can control the wavelength, polarization and power of the incident light, and pick single optical pulses using room-temperature optics. The conditioned light is delivered to the mixing chamber plate in a dilution refrigerator via optical fibers. Finally, the light is focused on a QD chip by an optical fiber equipped with two graded-index lenses for collimation and focusing. These lenses are mounted on a three-axis piezo stage operating in a magnetic field at a cryogenic temperature. This enables us to adjust the beam spot position and beam spot focusing on a QD chip with sub-nm resolution while keeping the refrigerator cool. This feature reduces the time required for alignment and beam spot size compared to our conventional free-space system.

Using this unique setup, which has fine-alignment optics in addition to a standard spin qubit measurement system, we will work on detecting single photogenerated holes in a Ge QD as a first step toward the quantum state transfer.

Session: Poster 2.35


optical
fiber
QD chip
piezo
stage
Graded-
index lens

Fast readout of a hopping Ge-hole spin qubit via dynamical longitudinal coupling to a superconducting resonator

Rusko Ruskov (Hristov) and Charles Tahan

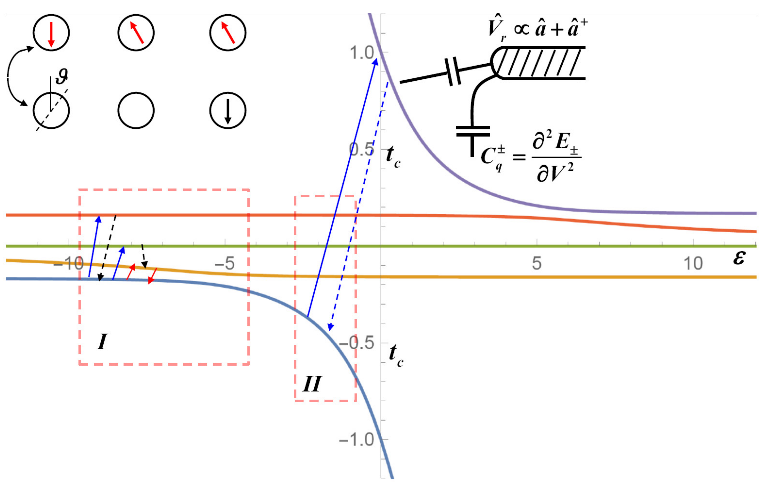
We study a possibility for a fast quantum readout of a Ge-hole quantum dot (QD) spin qubit based on recently proposed semiconductor hopping spins [1]. While a single-QD spin is not feasible to measure directly, the single-QD spin state can be mapped to an intermediary singlet-triplet qubit that is measured via the dynamical longitudinal coupling in a dispersive regime [2]. Using an on-chip superconducting resonator for the readout (compare to Ref. [3]), the corresponding quantum measurement rate can be made much faster, by one-two orders of magnitude, than the usual dispersive rate, allowing to overcome typical dephasing mechanisms such as a charge noise, phonon relaxation, and coupling to TLS fluctuators. Readout optimization at various quantum dots' detunings bearing in mind the strong spin-orbit effects is further discussed.

[1] Chien-An Wang et al., Operating semiconductor quantum processors with hopping spins, Science 385, 447-452 (2024)

[2] R. Ruskov, C. Tahan, Longitudinal (curvature) couplings of an N-level qudit to a superconducting resonator at the adiabatic limit and beyond, Phys. Rev. B 109, 245303 (2024)

[3] Guoji Zheng et al., Rapid gate-based spin readout in silicon using an on-chip resonator, Nature Nanotechnology 14, 742-746 (2019)

Session: Poster 2.36



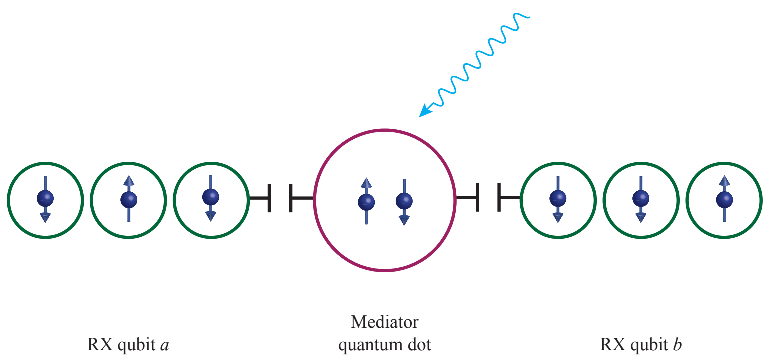
Enabling Modularity for Spin Qubits via Drive-Tunable Entanglement

Vanita Srinivasa

Modularity represents a promising approach to scaling spin-based quantum processors but requires the integration of coherent and tunable entanglement of spin qubits across a wide range of distances. While the exchange interaction enables rapid gates and coherence-protected qubit encodings with all-electrical control in this platform, the inherently short range of the interaction imposes constraints on scalability. Additionally, exchange-based two-qubit gates can lead to leakage for multielectron spin qubits. Our recent work addresses the challenge of tunable long-range coupling by developing a detailed theoretical framework for cavity photon-mediated entangling gates between parametrically driven spin qubits, in which the sidebands generated by the driving fields enable tunability and spectral flexibility [V. Srinivasa, J. M. Taylor, and J. R. Petta, PRX Quantum 5, 020339 (2024)].

Achieving full modularity within a quantum processing platform requires combining long-range entanglement with compatible local entanglement. We present an approach for entangling spin qubits within individual qubit modules based on capacitive coupling mediated by an ac-driven multielectron mediator quantum dot. We illustrate this method by considering the case of resonant exchange (RX) qubits, which are exchange-only qubits defined in three-electron triple quantum dots that are additionally characterized by intrinsic spin-charge coupling. The method can also be applied to other types of spin qubits that can be coupled capacitively. We show that this approach leads to an entangling gate for RX qubits that does not require the extensive sequence of pulses typically needed for implementing tunneling-based two-qubit gates between exchange-only qubits. We also describe how the drive-based tunability of this intramodular entangling approach allows for integration with the sideband-activated long-range approach for cavity-mediated entangling gates in order to enable modularity.

Session: Poster 2.37



Coherent spin operation in strained germanium double quantum well devices

Dario Denora, Michael Chan, Marion Bassi, Hanifa Tidjani, Setareh Kazemzadeh, Lukas Stehouwer, Giordano Scappucci and Menno Veldhorst

Quantum dot-based spin qubits have made rapid developments in device complexity. Approaches towards scaling up spin qubits are primarily based on one- or two-dimensional planar arrays. In the case of Ge/SiGe heterostructures, by introducing an additional quantum well, vertically coupled quantum dots can be formed.

We demonstrate the formation of QDs in different quantum wells spaced by a few nm using transport measurements across a single hole transistor (SHT) [1]. The single-hole regime in a vertical double quantum dot was realized by measuring using RF-SHT sensors [2]. These works are promising for novel approaches for qubit operation and readout schemes based on the engineering and controlling and stacking vertically double quantum dots (DQDs).

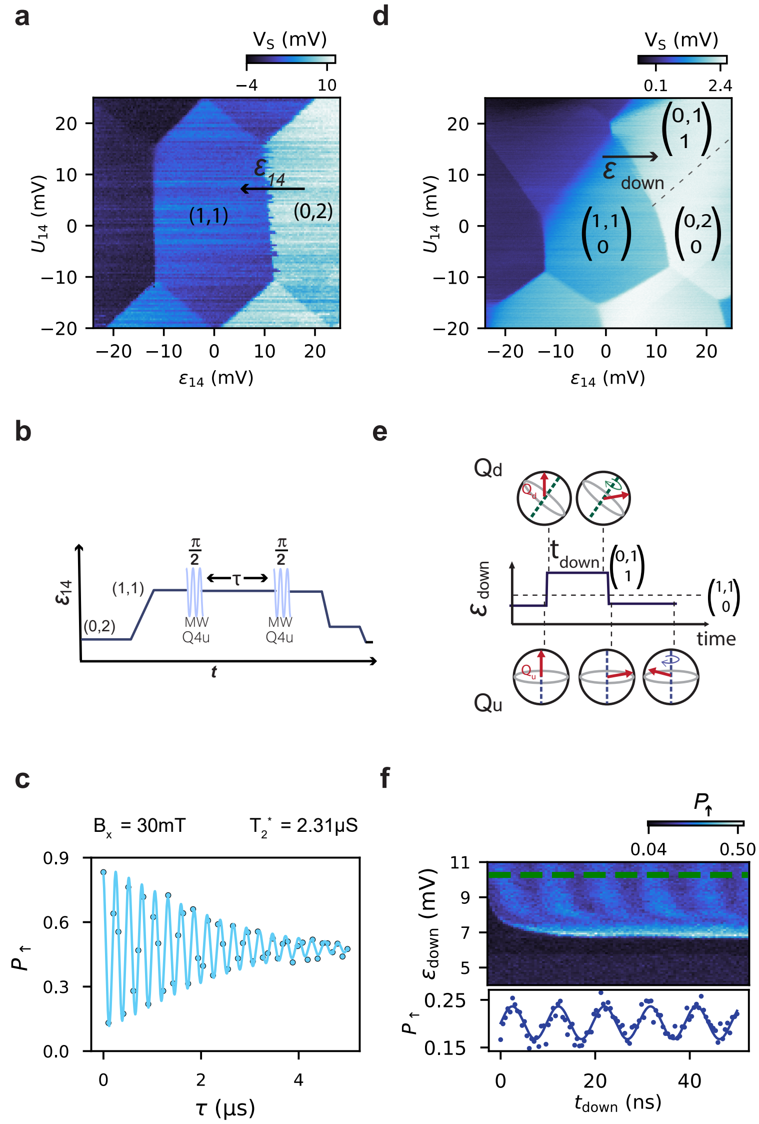
Here, we demonstrate the feasibility of defining quantum dots in two wells using gate-defined plunger and barrier gates. We show this capability by exploiting the different gate-to-dot capacitances that arise from the separation of the quantum wells in the vertical (z) direction [3]. We also explore the spin degree of freedom in this platform. We find that spin coherence can be maintained in multi-quantum well structures, suggesting that the increase in layers do not contribute to an increase in noise [Figure a-c]. The difference in the g-tensor between holes residing in the two wells can be used to perform single-qubit rotations by diabatically shuttling the spin between the two quantum wells [Figure d-f]. We will present and discuss the measurements in the context of its potential for quantum simulation and computation.

[1] H. Tidjani, et al., Physical Review Applied 20.5 (2023).

[2] A. Ivlev*, H. Tidjani*, et al., Applied Physics Letters 125.2 (2024)

[3] H. Tidjani*, D. Denora*, et al., in preparation

Session: Poster 2.38


a
V_S (mV)
−4
10
U_{14} (mV)
ε_{14} (mV)
ε_{14}
(1,1)
(0,2)
d
V_S (mV)
0.1
2.4
ε_{down}
b
ε_{14}
(0,2)
(1,1)
MW
Q4u
τ
t
e
Qd
Qu
t_{down}
ε_{down}
time
c
B_x = 30mT
T_2^* = 2.31μS
$P_\uparrow$
τ (μs)
f
$P_\uparrow$
0.04
0.50
ε_{down} (mV)
t_{down} (ns)

Enhancement of electron spin resonance Rabi Frequency via Spin-Orbit Near Anticrossing in n-Type Silicon-MOS Quantum Dot

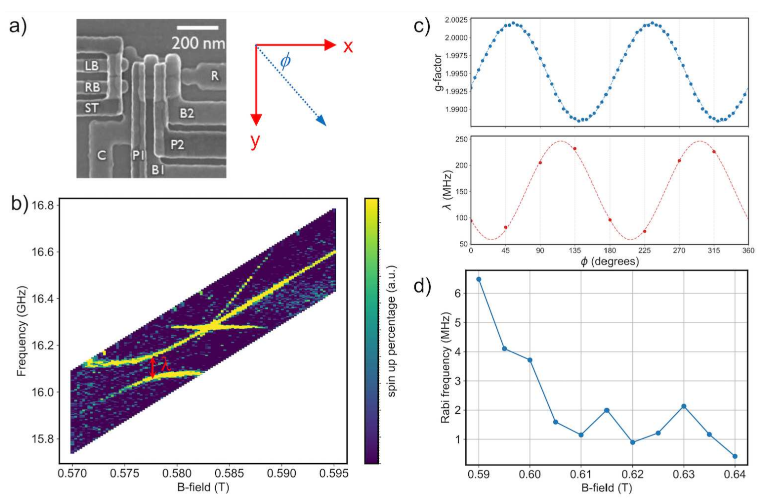
Xunyao Luo, Xander Peetroons, Tsung-Yeh Yang, Normann Mertig, Sofie Beyne, Yosuke Shimura, Julien Jussot, Clement Godfrin, Bart Raes, Roy Li, Roger Loo, Sylvain Baudot, Stefan Kubicek, Shuchi Kaushik, Danny Wan, Kristiaan De Greve, Noriyuki Lee, Itaru Yanagi, Toshiyuki Mine, Satoshi Muraoka, Shinichi Saito, Digh Hisamoto, Ryuta Tsuchiya, Hiroyuki Mizuno, Charles G. Smith and Andrew Ramsay

We report ESR experiments on a single electron spin qubit in natural silicon quantum dot fabricated on a silicon on insulator wafer by IMEC, as shown in figure a). An RF-SET is used for real time single shot charge detection. Qubit initialization and readout are implemented via Elzerman style energy selective spin to charge conversion, and coherent control is achieved by electron spin resonance pulses applied through a nearby superconducting antenna.

Using ESR spectroscopy, we observe an anti-crossing of the spin-up ground and a spin-down excited state, which could be the valley or an orbital. The coupling strength of the anti-crossing is measured to be around 100MHz. The anti-crossing occurs at B = 0.577 T, indicating that the energy difference of the ground and the first excited states is around 130μeV, see fig. b). The g-factor has a small anisotropy with in-plane B-field, fig. c). The spin-orbit coupling is highly anisotropic with in-plane magnetic field, and is misaligned with respect to the g-factor, see fig c). As the B-field approaches the anti-crossing, the Rabi frequency increases rather than decreases, see fig. d), suggesting the antenna also drives an electric-dipole transition between the ground and excited electronic states. Simultaneously, the relaxation time (T1) decreases sharply around the anti-crossing. Finally, we study the effect of the gate-voltages on the anti-crossing and qubit performance.

Acknowledgement: This work was supported by JST Moonshot R&D Grant Number JPMJMS2065.

Session: Poster 2.39



Tuning Valley Splitting in a 5% Ge Quantum Well

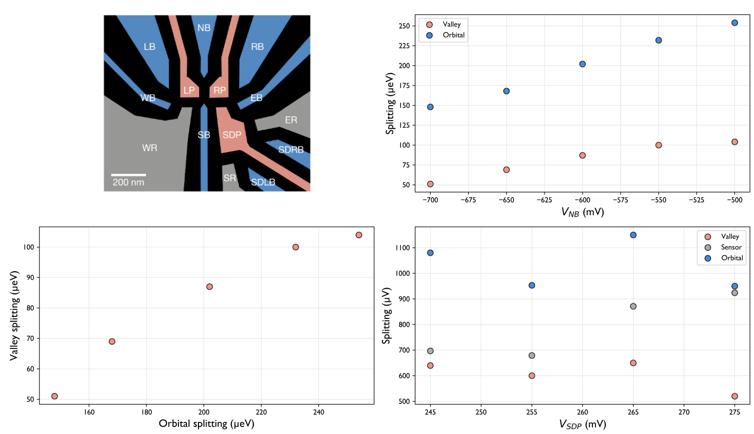
Alysa M. Rogers, Sanghyeok Park, Jared Benson, C. E. Sturner, Davide Degli Esposti, L.E.A. Stehouwer, Maia Rigot, Larysa Tryputen, Emma C. Brann, Owen M. Eskandari, Mark Friesen, Giordano Scappucci and Mark Eriksson

As the number of qubits on a chip increases, the number of qubits with valley splitting too small for high fidelity qubit operation increases. There recently have been several proposals suggesting ways to increase the valley splitting in Si/SiGe heterostructures [1]. Here, we study a Si quantum well with 5% Ge doping. We use pulsed-gate spectroscopy and Coulomb diamond transport measurements to measure the valley splitting as we change barrier gate voltages to move the dot position and change its size. The orbital and valley splittings are both found to be small here, as expected for larger-size dots; however, the splittings are also found to be gate-tunable. We find that decreasing the size of the quantum dot, as measured by the orbital splitting, increases the valley splitting. We also report transport measurements in the quantum Hall regime. We analyze the data following the method in Stehouwer et al. [2], and show that increasing magnetic confinement also increases valley splitting. In the quantum dot device we use in this work, the sensor quantum dot is very close to the qubit quantum dot, and we use the sensor quantum dot as a reservoir. Pulsed-gate spectroscopy is thus sensitive to states in both the qubit quantum dot and the sensor quantum dot, and we show how to differentiate these sets of states using pulsed-gate spectroscopy acquired while varying the voltage of the plunger gate on the sensor quantum dot.

[1] Paquelet Wuetz, B., Losert, M.P., Koelling, S. et al. Atomic fluctuations lifting the energy degeneracy in Si/SiGe quantum dots. Nat Commun 13, 7730 (2022).

[2] Stehouwer, L.E.A., Losert, M.P., Rigot, M. et al. Engineering Ge profiles in Si/SiGe heterostructures for increased valley splitting. https://arxiv.org/abs/2505.22295

Session: Poster 2.40



Modeling Ge hole spin with finite barriers

Jiawei Wang, Xuedong Hu and Herbert F. Fotso

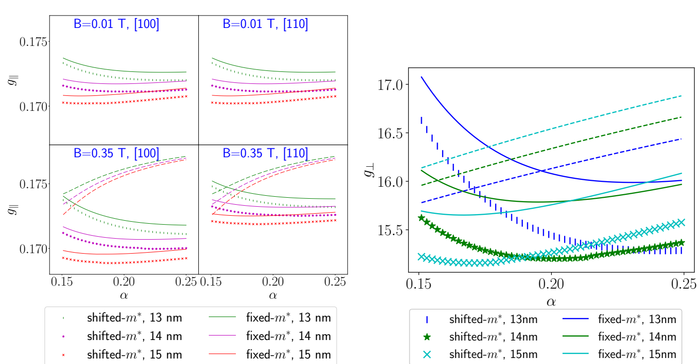
Quantum dot based on the Ge/GeSi heterostructure is a good candidate for hole spin qubit. The strong spin-orbit coupling for holes originates mainly from the mixing of bands at finite momentum even close to the Γ point and is sensitive the momentum change. Fast electrical control of hole spin is thus intrinsically possible, while an accurate study of sensitivity to system setup is required. On the other hand, the valence-band offset of the Ge/GeSi heterostructure does not prevent a non-negligible tunneling of hole to the barrier. This makes it necessary to explore the significance of barrier engineering.

In this talk, we are going to present our theoretical study of single-hole spectra in a planar quantum dot based on a Ge/GeSi heterostructure. Calculations are performed using the LCAO technique with single-band QD orbitals. Our focus is on the anisotropic g-factor of the heavy-hole qubit states. We study the variation of the anisotropic g-factor with changing silicon concentration in the barrier material at different thicknesses of Ge layer, as well as different dot sizes and magnetic field directions. While the large difference between in-plane and out-of-plane g-factor is known, anisotropy can also be seen when changing the magnetic field direction in the x-y plane. A comparison with the hard-wall prediction (dashed lines) shows that both models may predict coinciding g-factor for a particular silicon concentration. However, they produce very different functional dependence on silicon concentration in general.

We acknowledge financial support by NSF, US AFOSR, and UB CAS.

Hole spin splitting in a Ge quantum dot with finite barriers, Jiawei Wang, Xuedong Hu, Herbert F Fotso, 2503.11106 (2025)

Session: Poster 2.41



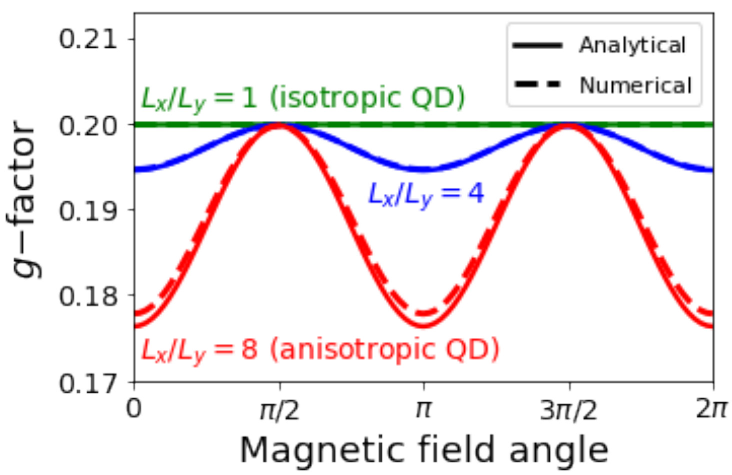
Effects of the spin-orbit coupling and confinement geometry on germanium hole spin qubits

Omadillo Abdurazakov, Ralph Colmenar, Arthur Lin, Charles Tahan and Yun-Pil Shim

Hole spin qubits are among the most promising platforms for scalable quantum computing in semiconductor systems, offering ultrafast and fully electrical gate operations enabled by strong spin-orbit coupling. Recent progress in quantum confinement and strain engineering of germanium heterostructures has accelerated the development of high-performance hole spin qubit devices. However, the complex valence band structure that underlies the spin-orbit interaction in these systems presents significant theoretical challenges. Most theoretical studies of germanium holes rely on numerical solutions of the Luttinger-Kohn Hamiltonian. While this approach yields highly accurate results, it often lacks the intuitive, analytical insight necessary to guide the design and optimization of qubit devices. In this work, we develop an analytical model that captures key physical properties of germanium hole systems, particularly those arising from the interplay between spin-orbit coupling and quantum dot confinement geometry. We consider a hole spin qubit confined in an anisotropic harmonic potential subjected to in-plane electric and magnetic fields. By incorporating an effective Rashba spin-orbit interaction—originating from broken structural inversion symmetry at the quantum well interface—we derive an effective Hamiltonian for the qubit subspace. This leads to compact analytical expressions for important qubit parameters, such as the effective g-factor and Rabi frequency. Our results provide clear explanations for the observed dependence of the effective g-factor on the direction of the applied magnetic field and the symmetry of the quantum dot potential, as seen in both experiments and numerical simulations. This analytical framework offers a more intuitive understanding of the underlying physics and serves as a practical tool to optimize qubit performance through control of gate-induced confinement and magnetic field orientation.

work in progress

Session: Poster 2.42



Excited States, Exciting Physics: SiMOS spin Qubits

Bart Raes, Thomas Van Caekenberghe, Clement Godfrin, Arne Loenders, Imri Fattal, Gulzat Jaliel, Vukan Levajac, Sofie Beyne, Stefan Kubiceck, Sugandha Sharma, Sylvain Baudot, Yannick Hermans, Yosuke Shimura, Roger Loo, Massimo Mongillo, Danny Wan and Kristaan de Greve

Low-lying excited valley or orbital states pose a significant challenge to the operation and scalability of electron spin qubits. They can limit high-temperature performance, spin initialization and manipulation, Pauli spin blockade readout, and coherent spin shuttling.

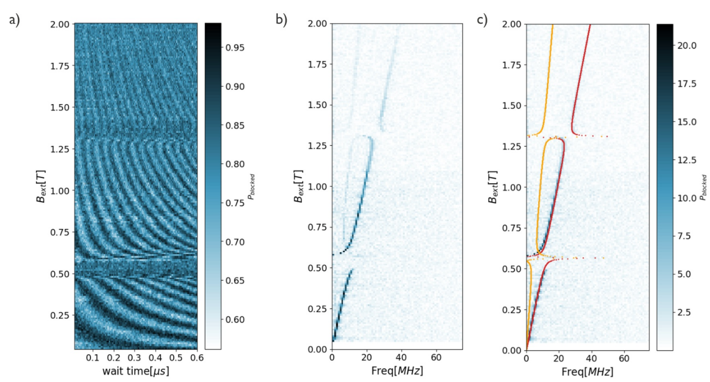
In gate-defined quantum dots (QDs) formed in Si/SiGe heterostructures, the energy splitting between low-lying valley states varies widely- from as little as 6 μeV to over 200 μeV , strongly influenced by interface quality and QW width. In SiMOS, higher valley excited state energies are generally expected due to the larger conduction band offset. Experiments show that the tunable out-of-plane electric fields in MOS structures allow for a wide range of observed valley splittings, ranging from 50 to over 500 μeV.

In this work, we study excited valley or orbital states in SiMOS overlapping-gate spin qubits fabricated using EUV on Imec's 300 mm pilot line. By monitoring both the singlet-triplet (ST0) oscillations and the ESR spectrum versus the applied magnetic field, excited states manifest as distinct anti-crossings (Figure 1). By modelling the magnetic-field-dependent frequency ST0 oscillation frequencies - or alternatively the ESR spectrum-, with a double quantum dot (DQD) Hamiltonian including excited states, we extract both the energy and coupling strength of the excited levels. We present data obtained on several SiMOS DQD devices operated in the 4-electron isolation regime for various pitches and oxide thicknesses.

Figure 1(a) ST0 oscillations versus applied magnetic field. (b) FFT spectrum of data in panel a (c) fit of the FFT spectrum show in panel b using a double quantum dot (DQD) Hamiltonian including excited states.

work in progress

Session: Poster 2.43



Harnessing Large Spin-Orbit Interactions for Next-Gen Hole Spin Qubits.

Stefano Bosco

Hole nanostructures are leading candidates for large-scale quantum computers due to their pronounced spin-orbit interactions (SOIs) and remarkable tunability. In this poster, I will discuss various strategies for harnessing this tunability to enhance the performance of current hole spin qubits, with a focus on both silicon and germanium qubits. The influence of SOIs extends to two-qubit gates, where exchange anisotropies, induced by these interactions, offer avenues for accelerating the execution of two and three-qubit gates without compromising fidelity. This implies that by leveraging the unique properties of SOIs, novel methods can be devised to expedite gate operations, and encode more reliably quantum information, thus paving the way towards large-scale spin based quantum information processing.

Session: Poster 2.44

Exploring the influence of atomistic alloy disorder on exchange coupling between electron spins in Si/SiGe

Mitchell Ian Brickson, Steve Young and N Tobias Jacobson

Ample experimental and theoretical evidence suggests that intrinsic alloy disorder plays an important role in the valley physics of electron spin qubits in silicon [1-4]. Since qubit properties such as exchange coupling are sensitive to the valley degree of freedom, the random valley splitting and valley phase in quantum dots may pose a challenge for consistent fabrication and control of these qubits. We present a computational exploration of the effects of alloy disorder on the exchange interaction for electrons in Si/SiGe double quantum dots. Our methods combine envelope function techniques with localized potentials to describe the effects of specific realizations of alloy disorder on the valley physics of Si electrons, and we use configuration interaction methods to describe the two-electron physics. This allows us to calculate the differences in valley physics between neighboring dots and the resulting voltage dependence of exchange coupling. We also assess the sensitivity of exchange with respect to gate voltages to predict dephasing rates due to charge noise. We compute the voltage dependence of exchange for different Ge concentration profiles and compare its statistical variation. We hope that this work will contribute to the understanding of what material parameters make for consistent yield in Si qubits to minimize the complications of valley physics. SAND No.: SAND2025-09588A

[1] Paquelet Wuetz, et al. Nat. Comm. 13:7730 (2022)
[2] McJunkin, et al Nat. Comm. 13:7777 (2022)
[3] Losert, et al. PRB 108, 125405 (2023)
[4] Peña, et al. npj QI 10, 33 (2024)

work in progress

Session: Poster 2.45

From Mobility to Fidelity: Demonstrating High-Quality Hole Spin Qubits in a Natural Silicon Foundry Platform

Isaac Vorreiter, Jonathan Wendoloski, Scott D. Liles, Jonathan Y. Huang, Joe Hillier, Roy Li, Stefan Kubicek, Clement Godfrin, Danny Wan, Bart Raes, William Gilbert, Chih-Hwan Henry Yang, Wee Han Lim, Md. M Rahman, Kok Wai Chan, Steve Yianni, Andrew Dzurak, Kristiaan De Greve and Alex Hamilton

Hole spins in silicon quantum dots are a promising platform for scalable spin qubits. The strong spin-orbit coupling enables rapid gate operations, tunability of spin properties, and access to sweet spots in the decoherence landscape. However, hole spin qubits in silicon MOS have historically lagged behind the electron counterparts, in part due to increased susceptibility to disorder and more complex spin physics. A key question is whether industrial-grade silicon MOS devices can achieve the quality required to support high-fidelity hole spin qubits.

In this work, we present two complementary approaches that demonstrate high quality p-type quantum devices fabricated on a foundry-compatible silicon platform. First, we assess and compare interface qualities of n-type and p-type devices using mobility measurements in Hall bar structures. We find a peak electron mobility of nearly 40,000 cm^2/Vs, and a record hole mobility of 2,000 cm^2/Vs, the highest reported for a p-type silicon MOSFET. We show the difference in electron and hole mobility is due to non-parabolic band bending, confirming identical oxide qualities for electron and hole quantum devices. Secondly, we benchmark the performance of hole spin qubits in quantum dot devices manufactured on foundry compatible processes. We achieve single-qubit fidelities up to 99.8% and demonstrate a two-qubit gate quality factor of 240, indicating a physical fidelity limit near 99.7%. These results highlight the maturity of silicon hole spin platforms and their potential for integration into future quantum CMOS technologies.

Session: Poster 2.46

Feedback and Pulse Engineering with Hole Spin Qubits

Daniel J. Halverson, Jonathan Huang, Isaac Vorreiter, Joseph Hillier, Scott D. Liles, Alexander Hamilton, Royu Li, Bart Raes, Stefan Kubicek, Danny Wan, Nard Dumoulin Stuyck, William Gilbert, Chih-Hwan Henry Yang, Clement Godfrin, Andrew Dzurak, Kristiaan De Greve, Sofie Beyne, Julien Jussot and Sugandha Sharma

Silicon hole-spins offer a promising platform for quantum computing as they can be driven at high speeds with only electric fields. While the strong spin-orbit interaction enables fast single-qubit control, it also increases susceptibility to charge noise compared to electron qubits in the same environment. This noise causes shifts in both the qubit's Larmor and Rabi frequencies, characterised by noise on different components of the hole g-tensor. Optimisation of hole spin qubits so far has primarily focused on operating in electromagnetic field sweet-spots, which have been shown to improve dephasing times. However, engineering techniques such as real-time feedback and pulse shaping have the potential to improve robustness to charge noise and improve single qubit gate fidelity.

In this work we implement dynamic feedback and pulse shape engineering to enhance the fidelity of single qubit gates for hole spin qubits in MOS silicon. We measure the noise spectra for both the Larmor and Rabi frequencies over long time-scales to predict shifts in these parameters between single-qubit operations. We then implement feedback on the driving frequency and amplitude to correct for larger shifts in the Larmor and Rabi frequencies. This is combined with shaped pulses to make operations more robust to noise at time scales which cannot be addressed by feedback. Lastly, we employ randomised benchamrking to assess how these techniques improve the fidelity of single qubit operations.

work in progress

Session: Poster 2.47

Statistical characterization of valley coupling in Si/SiGe quantum dots via g-factor measurements near a valley vortex

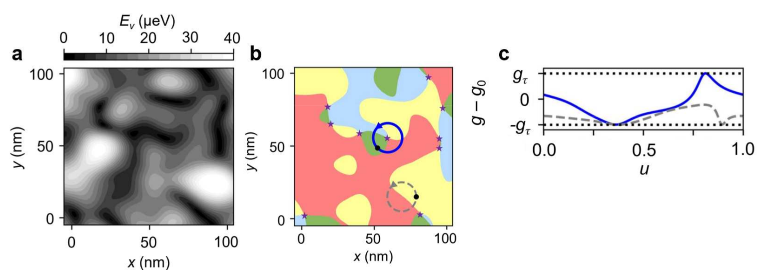
Benjamin Woods, Merritt P. Losert, Nasir R. Elston, Mark A. Eriksson, Susan N. Coppersmith, Robert Joynt and Mark Friesen

The presence of low-energy valley excitations in Si/SiGe heterostructures often causes spin qubits to fail. It is therefore important to develop robust protocols for characterizing the valley coupling. Here, we show that realistically sized samplings of valley energy distributions tend to dramatically overestimate the average valley coupling. But we find that knowledge of the valley phase, in addition to the valley splitting, can significantly improve our estimates. Motivated by this understanding, we propose a novel method to probe the valley phase landscape across the quantum well using simple g-factor measurements. An important calibration step in this procedure is to measure the g-factor in a loop enclosing a valley vortex, as shown in panels b and c of the Figure, where the valley phase winds by $\pm 2\pi$ around a zero of the valley splitting. This proposal establishes an important new tool for probing spin qubits, and it can be implemented in current experiments.

Figure Caption: a) Valley splitting Ev landscape for a given alloy disorder realization for a Si/SiGe dot of radius ℓ = 14.2 nm with zero deterministic valley coupling, $\Delta_0 = 0$, and alloy-disorder valley coupling Δ_δ that follows a complex normal distribution with standard deviation σ_Δ = 20 µeV. b) Colors correspond to the 4 quadrants of the complex valley coupling Δ plane, where Δ is related to the valley splitting by Ev = 2|Δ|. Valley vortices, where Ev = 0, are marked by purple stars. c) g-factor fluctuations along the two paths in (b). The g-factor difference along the solid blue path reaches its maximum and minimum because the path encloses a single valley vortex.

arXiv:2507.05160 (2025) https://arxiv.org/abs/2507.05160

Session: Poster 2.48



From RF Response to SOC Parameters: Simulating Magnetospectroscopy of Double Quantum Dots

Angus A. Russell, Lorenzo Peri, Chris J. B. Ford and M. Fernando Gonzalez-Zalba

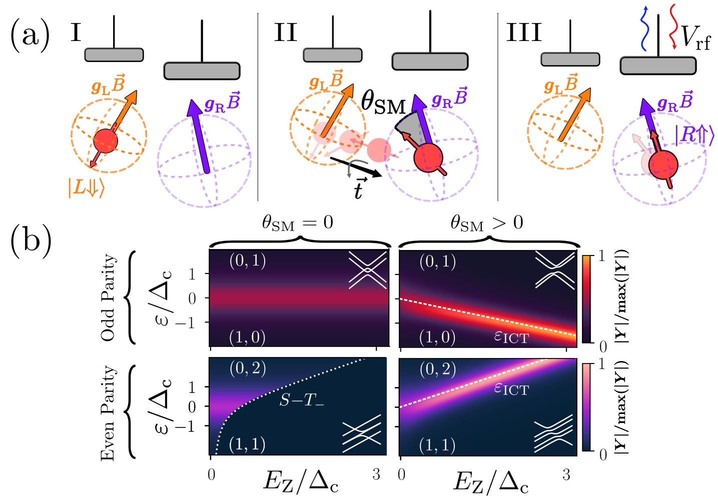
Spin-orbit coupling (SOC) in semiconductor spin qubits presents both opportunities and challenges for scalable quantum computing. While SOC enables all-electrical qubit control and addressability, it can also degrade qubit performance, particularly by reducing readout fidelities through the lifting of Pauli spin blockade. Accurate characterization of SOC effects is therefore essential for optimizing qubit operation.

Magnetospectroscopy—dispersively measuring interdot charge transitions while varying an external magnetic field—provides a powerful technique for probing SOC in quantum dot systems. However, the complex interplay between spin and charge degrees of freedom, combined with the strong anisotropy of SOC, can make these measurements challenging to interpret, particularly when the SOC is significant.

We present comprehensive magnetospectroscopy simulations for both odd and even parity double quantum dot transitions in the presence of strong SOC (right column in sub-figure (b)). By reformulating the problem in a physically intuitive internal basis where spins align with their local quantization axes, we establish a direct connection between measurable signal features and fundamental SOC parameters, principally the spin misalignment angle θSM (schematic illustration shown in subfigure (a)). We illustrate how the full width at half maximum of the dispersive signal quantitatively reveals the spin-flip probability when tunneling at a sufficiently high field, and how the position of the peak with respect to zero detuning provides information about the g-tensors.

Our simulations span from the ideal adiabatic regime to experimentally realistic scenarios with competing energy scales, i.e. the relationships of resonant frequency, decoherence rate, and temperature relative to the different anti-crossings and Zeeman energies. This comprehensive approach yields a taxonomy of magnetospectroscopy signatures that enables precise SOC characterization from experimental data. This work extends the modelling capabilities beyond the current limits, providing practical guidance for interpreting real experimental measurements where multiple competing effects can change the signatures compared to the ideal case.

Session: Poster 2.49



Reduction of hole state g-factor anisotropy using parabolic Ge/SiGe quantum wells

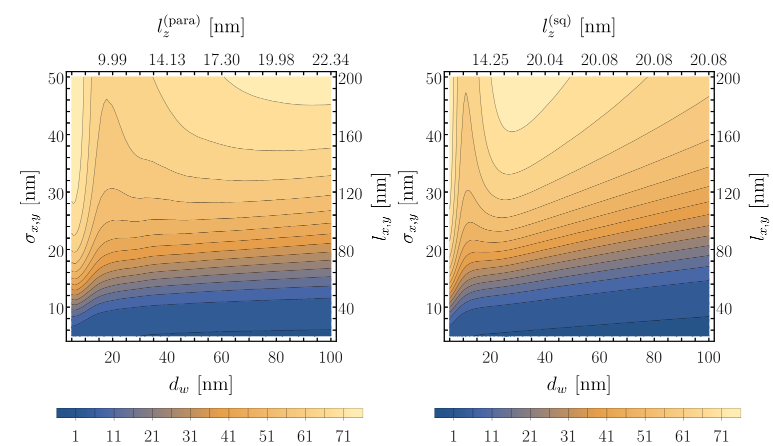
Arthur Lin, Ralph L. Colmenar, Yun-Pil Shim, Garnett W. Bryant and Charles G. Tahan

Hole spins in Ge quantum dots have emerged as a promising platform for semiconductor spin qubits. Among many positive attributes is a strong spin-orbit coupling allowing for an all-electrical spin control. However, in highly anisotropic systems such as Ge/SiGe quantum wells, the spin-orbit interaction also increases the sensitivity of the g-factor to charge noise and inhomogeneous strain, which degrades qubit control and coherence. Understanding the underlying contributions to hole-spin g-factors and reducing the anisotropy is crucial in engineering better qubits.

In this work, we consider the feasibility of using parabolic quantum wells as a practical method of achieving thicker wells and a more isotropic confinement. In addition to the growth challenges of ticker square wells due to accumulative strain, our model shows a limitation imposed by the bias voltage of the control gates. Both issues are absent in parabolic quantum wells, leading them to be an ideal candidate for studying more symmetrical hole-spin qubits.

Using a finite well Luttinger-Kohn and atomistic tight-binding models, we calculate the g-factor of parabolic and square wells of various widths. Both models show a reduction of g-factor anisotropy for the square and parabolic wells as the well width is increased. However, as per out prediction, the electrical bias limits the scaling of square wells at larger well widths. Additionally, we discovered a drop in the out-of-plane g-factor at smaller well widths, which we attribute to an increase in HH-LH mixing (per the Luttinger-Kohn model) or a decrease in the effective Peierels contribution to the g-factor (per the tight-binding model). This highlights the sensitivity of hole state g-factors to heterostructure variations and noise at smaller well widths, further motivating the use of larger well widths for more uniform qubits.

Session: Poster 2.50



Enhancing Valley Splitting in Si Quantum Dots Using Deposited Stressors for Shear Strain in Wiggle Well Heterostructures

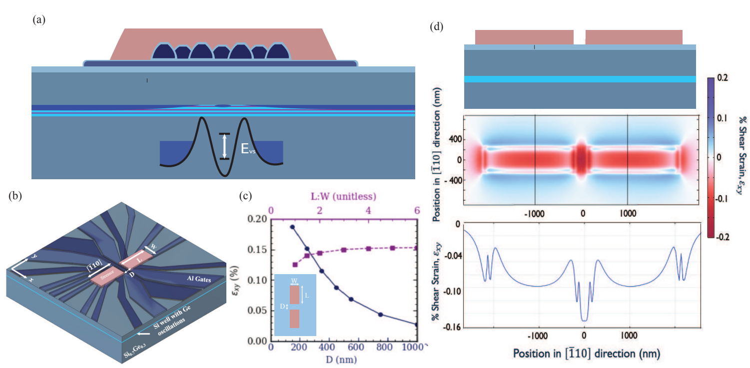
Emily S. Joseph, Tali Oh, Donald E. Savage, Donald S. Stone, DeAnna Campbell, Benjamin Woods, Mark Friesen and Mark Eriksson

Achieving consistently high valley splitting is essential for scaling silicon quantum dot arrays, where low valley splitting can lead to leakage and control errors. In this work, we present strain simulations of silicon/silicon-germanium heterostructures designed to enhance valley coupling through engineered stress. We show that stressed thin films deposited above the gate stack—when properly shaped and positioned—can generate over 0.15% shear strain in silicon quantum wells located 40 nm below the surface (fig a-b). This magnitude of shear strain, when applied to a silicon well with an oscillating Ge concentration, is predicted to deterministically enhance the valley splitting energy to beyond 200 μeV [1]. The strain response is highly sensitive to the placement of stressors relative to the [110] crystallographic axis and quantum dot locations (fig d). To guide optimal device design, we simulate a range of stressor geometries, beginning with a single stressor of length L and width W, and extending to paired stressors separated by distance D (fig c). We then incorporate aluminum gate structures that cross over or under the stressors, capturing more realistic device architectures. Finally, we evaluate how variations in L, W, D, stressor thickness t, and distance from the quantum well impact the shear strain delivered to the quantum well.

"Coupling conduction-band valleys in SiGe heterostructures via shear strain and Ge concentration oscillations." Benjamin D. Woods, et al., npj Quantum Inf 10, 54 (2024).

work in progress

Session: Poster 2.51



Effective 2D Envelope Function Theory for Silicon Quantum Dots

Christian Walter Binder, Andrew J. Fisher and Guido Burkard

We present a new method that rigorously reduces the full 3D Hamiltonian of silicon quantum dots—incorporating both charge and valley physics—into an effective 2D envelope function theory. This is achieved by integrating out the strongly confined vertical direction using a Born-Oppenheimer-inspired approach. The resulting dimensional reduction leads to a major speed-up in simulations: single-electron quantities such as tunnel couplings and shuttling trajectories can be computed significantly faster, while two-electron observables, such as exchange couplings (J), become accessible within minutes even in realistic device geometries.

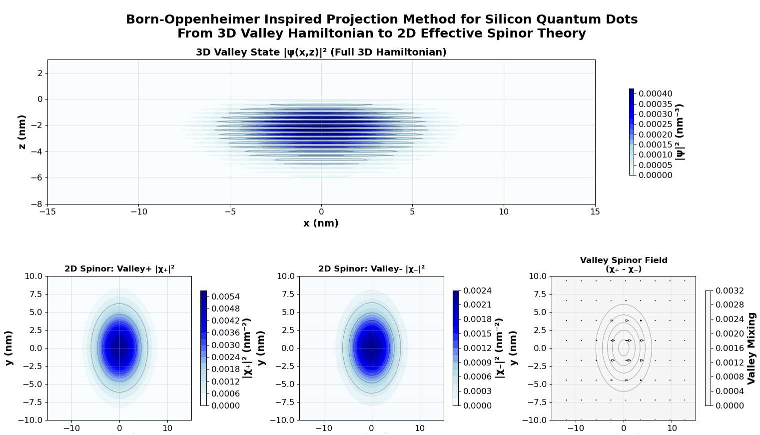
Importantly, both J and tunnel couplings can be accurately calculated in the presence of interface roughness, which is systematically handled by our projection scheme. We benchmark our approach against full 3D simulations and demonstrate excellent agreement. Crucially, all calculations are performed using experimentally relevant parameters and realistic device potentials, obtained by solving the Laplace equation for electrostatic gate configurations—ensuring close alignment with fabricated devices.

Our framework also enables efficient generation of valley landscapes in both Si/SiO_2 and Si/SiGe platforms, capturing the effects of vertical confinement modulation and disorder. Furthermore, we heuristically extend the theory to include spin physics via a position-dependent g-tensor, enabling simulations in the full orbital-spin-valley Hilbert space. This extension supports modeling of spin readout and two-qubit gate operations in the presence of valley effects.

Beyond its computational advantages, the formalism provides conceptual clarity and didactic value, enabling a rigorous treatment of valley effects in both SiGe and MOS quantum dot systems. This work significantly advances the simulation toolkit available for silicon qubit design, paving the way for faster, more accurate modeling in the development of scalable quantum technologies.

https://arxiv.org/pdf/2508.00139

Session: Poster 2.52

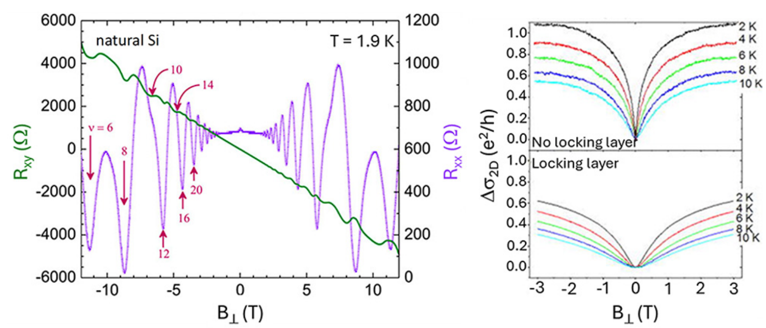


Measurements to predict qubit performance

Curt A. Richter, Joshua Pomeroy and Michael Stewart

Measurements with relatively fast turnaround times are sought that can determine the end performance of quantum devices and circuits. Such measurements could be used to assess new materials and will speed the optimization of fabrication processes for quantum devices. Unfortunately, this long-desired target has not been fully achieved. Ideally, quantum operations could be performed on quantum circuits and their performance determined and correlated to starting materials and processing details. However, such measurements are expensive in both time and money. To be impactful, new characterization approaches must be faster and cheaper than the full quantum manipulation of devices at dilution refrigerator temperatures. Charge noise is considered by many to be the best assessment parameter short of the full quantum gold standard. Additional metrology is needed to provide information regarding the fundamental mechanisms that are causing less than optimal performance. By varying parameters such as temperature and magnetic field, charge transport measurements can characterize the fundamental properties of quantum materials and devices. Furthermore, scattering mechanisms that are likely to cause dephasing and charge noise can be determined. By harnessing quantum effects such as weak-localization and Shubnikov – de Haas oscillations, we have determined the effect of different fabrication approaches on Si-based devices. For example, we have quantitatively characterized the spread of P-dopants in devices formed by using hydrogen-based scanning probe lithography, and we contrasted the properties of devices fabricated from isotopically purified Si with those fabricated on natural Si substrates. We are developing test structures, measurement methods, and analyses to extract parameters that can be directly correlated with key quantum metrics such as decoherence times in Si quantum information devices to enable rapid, systematic feedback loops that link material growth and fabrication processes with qubit performance.

Session: Poster 2.53



A spin qubit pair in germanium with matching g-tensors and long coherence time

Federico Poggiali, Asser Elsayed, Cornelius Carlsson, Davide Degli Esposti, Dario Denora, Marion Bassi, Lucas E. A. Stehouwer, Menno Veldhorst and Giordano Scappucci

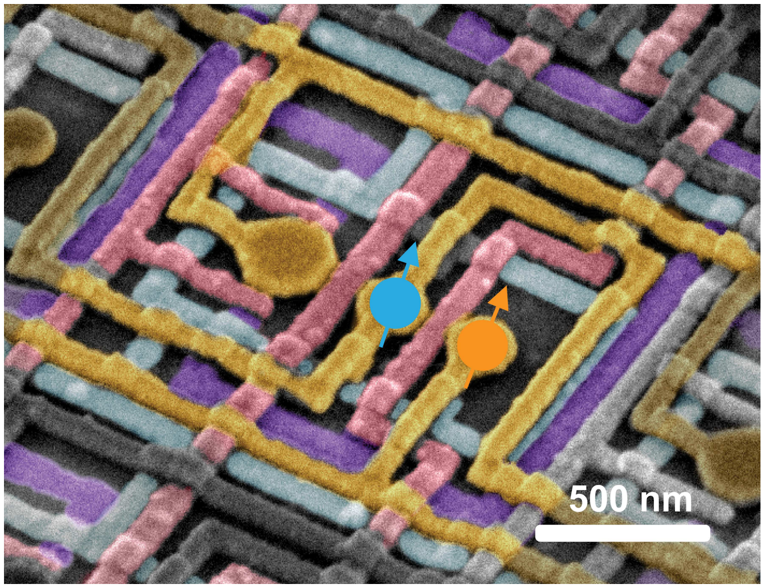
Operating at sweet spots enhances multiple aspects of hole spin qubit performance, including coherence times and gate fidelities [1–3]. However, the parameter ranges that define such operating conditions may be narrow, limiting their practical applicability and making it challenging to achieve mutual sweet spots for more than a single qubit.

In strained Ge quantum wells, the strong anisotropy of the g-tensor is a further complication, as local strain and charge disorder introduce additional variability among qubits on the same device. To address these challenges, our group has developed Ge/SiGe quantum wells [4] grown directly on germanium substrates, with recent studies demonstrating improvements in quantum dot uniformity with the associated material stack [5].

Building on this, we have explored this new material with our QARPET architecture [6], which is specifically designed for large-scale characterization of quantum dot qubits and features a cross-bar array of repeating unit cells. Within this architecture, we observed two qubits (distanced 200 nm) with closely matched g-tensors, providing avenues for mutual sweetspot operation.

[1] Hendrickx et al., Nat. Mater. (2024).
[2] Piot et al., Nat. Nanotechnol. 17, 1072–1077 (2022).
[3] Bassi et al., arXiv:2412.13069 (2024).
[4] Stehouwer et al., Appl. Phys. Lett. 123, 092101 (2023).
[5] Stehouwer et al., Nat. Mater. 24, 845–853 (2025).
[6] Tosato et al., QARPET: A Crossbar Chip for Benchmarking Semiconductor Spin Qubits, arXiv:2504.05460 (2025).

Session: Poster 2.54


500 nm

Nuclear spin-free 70Ge/28Si70Ge heterostructures

Patrick Daoust, Nicolas Rotaru, Alexis Dubé-Valade, Sebastian Koelling, Éloïse Rahier, Patrick Del Vecchio, Debojyoti Biswas, Marcus Edwards, Mukhlasur Tanvir, Ebrahim Sajadi, Joseph Salfi and Oussama Moutanabbir

Spin qubits based on germanium (Ge) heterostructures are frontline candidates for quantum processors with long coherence times. This is in part due to the advantages of hole spins in Ge, such as their large spin-orbit interaction and reduced hyperfine coupling with nuclear spins. As hole qubits in planar Ge heterostructures are very sensitive to the nuclear spin environment, fabricating and characterizing structures devoid of such nuclear spins has become a recent objective of the quantum semiconductor research community. Following our recent demonstration of highly crystalline, defect-free, nuclear-spin-depleted ^{70}Ge quantum-well (QW) heterostructures grown in a reduced-pressure CVD, we herein demonstrate the successful homoepitaxy of nuclear-spin free $^{70}Ge^{28}Si_{0.17}\,^{70}Ge_{0.83}$ QWs on commercial substrates. We present structural, crystalline and transport properties of the obtained heterostructures.

Session: Poster 2.55

Suppressing Si Valley Excitation and Valley-Induced Spin Dephasing for Long-Distance Shuttling

Yasuo Oda, Merritt Losert and Jason P. Kestner

We present a scalable protocol for suppressing errors during electron spin shuttling in silicon quantum dots. The approach maps the valley Hamiltonian to a Landau-Zener problem to model the nonadiabatic dynamics in regions of small valley splitting. An optimization refines the shuttling velocity profile over a single small segment of the shuttling path. The protocol reliably returns the valley state to the ground state at the end of the shuttle, ensuring the spin and valley degrees of freedom are unentangled, after which a single virtual z-rotation on the spin compensates its evolution during the shuttle. The time cost and complexity of the error suppression is minimal and independent of the distance over which the spin is shuttled, and the maximum velocities imposed by valley physics are found to be orders of magnitude larger than shuttling speeds achieved experimentally so far. This protocol offers a chip-scale solution for high-fidelity quantum transport in silicon spin-based quantum computing devices.

https://arxiv.org/abs/2411.11695

Session: Poster 2.56

Towards excited state control and readout of quantum dot spin qubits via THz radiation

Haiqi Zhou, Seong W. Oh, Jicheng Jin, Shize Che, Bo Zhen and Anthony Sigilito

Scalable control and readout remain major challenges for semiconductor spin qubits. Conventional readout and control schemes require dense wiring and local gate control, which limits extensibility to large arrays. Inspired by techniques from AMO systems, we explore the use of THz radiation to access excited orbital states in gate-defined semiconductor quantum dots, as a potential path towards scalable, non-local spin qubit control and readout. In this experiment, we integrate a continuous-wave THz laser with a 6-dot Si/SiGe quantum device in a dilution refrigerator equipped with optical viewports, allowing direct THz radiation illumination of the quantum dot region. Under THz illumination near 120 GHz, we observe an additional current peak extending into the Coulomb blockage region, consistent with photon-assisted tunneling via an excited orbital state. Device characterization shows an orbital excitation energy of approximately 0.5 meV, matching the THz photon energy. These results demonstrate THz-driven coupling to orbital states in gate-defined quantum dots. Future work will focus on probing spin selectivity, investigating g-factor modulation, and applying this scheme to multi-dot systems. Our approach offers a promising step toward scalable spin qubit architectures enabled by long-range optical access.

Session: Poster 2.57

Digital-Controlled Conveyor-Belt Spin Shuttling for Scalable Silicon quantum computer

Ryo Nagai, Takashi Takemoto, Yusuke Wachi and Hiroyuki Mizuno

We propose a digital-controlled conveyor-belt scheme for shuttling single-electron spins in silicon. The basic structure of our proposal is illustrated in the left figure. The point is that only a few DC generators are placed at room temperature. The waveform applied to the gate electrodes are generated by the few DC levels and it is deformed to near-sinusoidal form by switch matrix and RC filters in a cryogenic. The schematic figure of generating the waveform is shown in the right figure.

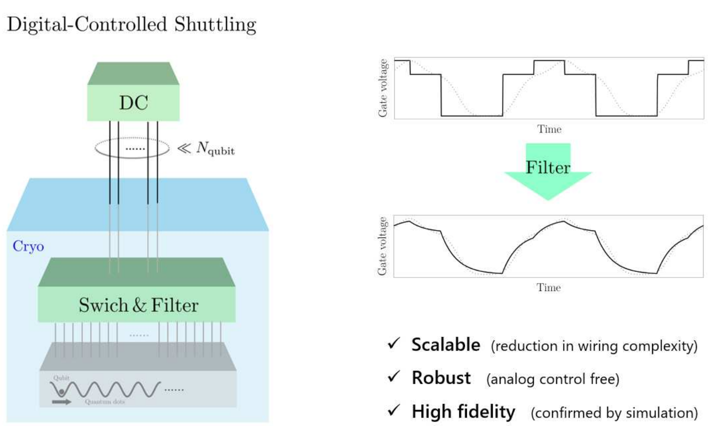
This architecture has three key advantages: (i) Scalability: wiring from room temperature is few and independent from the number of qubits. (ii) Robustness: locating the waveform generator beside the quantum dots suppresses distortions from cables and connectors. The effects of the variation of the time constant of RC filters are mild. (iii) High fidelity: electrostatic and circuit simulations, including valley-state dynamics, show that 20-40 nm gates driven by 10-300 mV amplitudes at ≤100 MHz achieve shuttling fidelities above 99.9%, comparable to the conventional analogue sinusoidal control.

We also estimate the total cryogenic power dissipation and confirmed that the heat dissipation stays below a few milliwatts, well within dilution-refrigerator limits. The proposed method therefore provides a practical path to large-scale, fault-tolerant silicon quantum processors.

This presentation is based on arXiv:2502.20955. This work is supported by JST Moonshot R&D Grant No. JPMJMS2065.

arXiv:2502.20955

Session: ICOSS



Reduction of the impact of the local valley splitting on the coherence of conveyor-belt spin shuttling in 28Si/SiGe

Mats Volmer, Tom Struck, Davide Degli Esposti, Giordano Scappucci, Łukasz Cywiński, Hendrik Bluhm and Lars Reiner Schreiber

Long-range, high-fidelity spin transport remains a key bottleneck for scalable silicon qubit processors [1-3]. Here we demonstrate valley-adaptive conveyor-mode shuttling of a single electron in a purified $^{28}Si/Si_{0.7}Ge_{0.3}$ quantum-well device. By rastering a 40 × 400 nm² area, we map the valley-splitting landscape with nanometer precision [4,5], finding a disorder-limited distribution from 0 to 200 μeV and an autocorrelation length of ≈17 nm, consistent with the dot size. A mere 18 nm lateral path adjustment can bypass low-splitting sites, enabling coherent back-and-forth shuttling over >100 μm; for a 10 μm round-trip at 20 MHz we record an infidelity of 6 %. Operating below 20 mT suppresses relaxation hotspots and doubles the dephasing time, confirming recent theoretical predictions [6].

We employ sinusoidal four-phase gate pulses to create a travelling potential wave; single-shot Pauli-spin-blockade readout monitors the singlet probability after each shuttle, yielding real-time valley gaps and coherence decay. Seven parallel traces, each spanning 400 points over 392 nm, provide 2800 valley data points whose histogram follows a Rice distribution, emphasizing random-alloy disorder. Gaussian fits show no spatial correlation beyond 30 nm, guiding future mapping of micron-scale channels. Furthermore, we combine the valley map with a g-factor map to deduce further information.

These results validate adaptive route-planning [7] as a practical strategy for integrating micron-scale spin-shuttle interconnects into CMOS-compatible qubit layouts and provide benchmark data for material engineering, velocity optimisation and low-field operation.

[1] R. Xue ea., Nat. Commun. 15, 2296 (2024).
[2] T. Struck ea., Nat. Commun. 15, 1325 (2024).
[3] M. de Smet ea., Nat. Nanotechnol. https://doi.org/10.1038/s41565-025-01920-5 (2025).
[4] M. Volmer ea. npj Quantum Inf. 10, 61 (2024).
[5] M. Volmer ea. In preparation (2025).
[6] V. Langrock ea., PRX Quantum 4, 020305 (2023).
[7] M. Losert ea., PRX Quantum 5, 040322 (2024).

Session: ICOSS

Spin Qubit Leapfrogging: Shuttling electrons on top of another

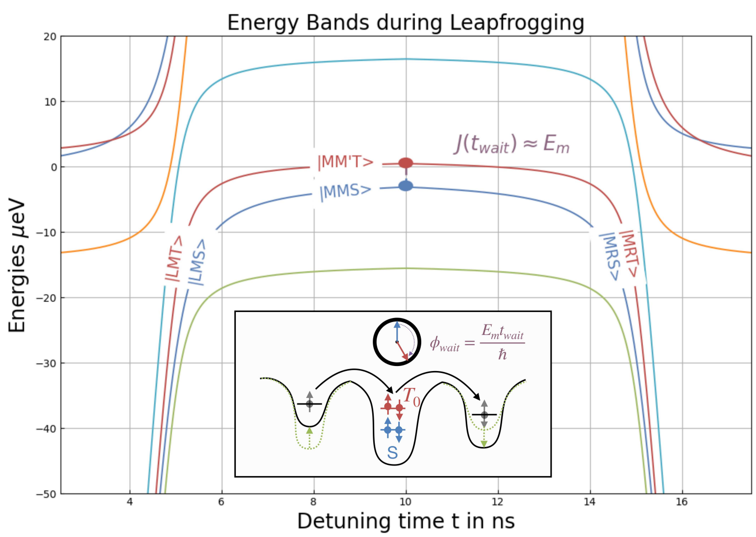
Nicklas Alexander Meineke and Guido Burkard

In recent years spin shuttling has distinguished itself as a promising candidate for achieving high fidelity medium range interactions between spin qubits and presents a powerful tool for enabling scalable semiconductor spin quantum computing architectures in the future. A dominant source of errors encountered during spin shuttling in silicon is the spontaneous of the electron transition into the excited valley state, which leads to unaccounted for dephasing and irregular behaviour during gate application.

Modelling the process of a shuttled spin qubit encountering an occupied stationary quantum dot, we investigate the dynamics of the adiabatic (1,1)-(0,2) charge transition in a silicon double quantum dot with non-vanishing inter-valley coupling. This enables us to describe the process of the mobile electron leapfrogging over the stationary one i.e. transitioning from a (1,1,0)- to a (0,1,1)-charge state, occupying a (0,2,0)-state in between. The figure displays this process graphically and also shows the energybands of the instantaneous eigenstates during the protocol. Here one sees that in the (0,2,0)-configuration the triplets will occupy a valley excited state to circumvent Pauli spin blockade leading to a singlet-triplet splitting approximately equal to the valley splitting in the stationary dot.

Consequently this protocol will implement an entangling gate, which can be tuned by waiting in this configuration. For the protocol to be noise-resilient and controllable the middle dot needs to operate at very low valley splitting. As a result this opens up the possibility to isolate and make practical use out of low-valley-splitting hotspots on a wafer, which would otherwise act as sources of error.

Session: ICOSS



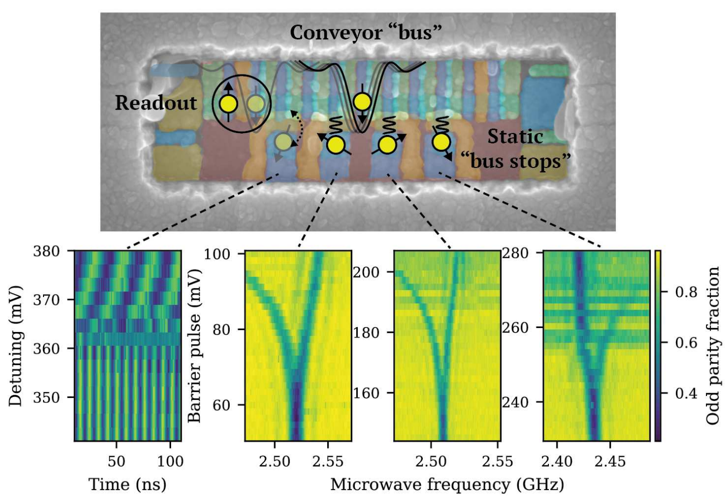
Don't miss the bus: operating a sparse silicon quantum processor

Brennan Undseth, Nicola Meggiato, Larysa Tryputen, Davide Degli Esposti, Giordano Scappucci and Lieven M. K. Vandersypen

Advances in spin shuttling have established it as a high-fidelity method of coherently transferring spin information at the micron scale, and both bucket-brigade and conveyor-mode spin shuttling have been used as a means of device exploration and characterization. Furthermore, shuttling permits the dynamic reconfiguration of qubit connectivity that is crucial in many large-scale quantum computing architectures. Here, we commission a bilinear array of quantum dots in a 28Si/SiGe heterostructure with two distinct rows of gates: one clavier-style row serving as a conveyor "bus", and one sparse row of "bus stop" quantum dots into which single spins may be parked. The concept of operation is illustrated on top of the device SEM. Using a single readout zone at one end of the conveyor, we explore the conveyor operation and the interdot charge transitions between the conveyor and the bus stops via Ramsey experiments as exemplified in the bottom-left panel. We then use these transitions to virtualize control of the double-dot potentials in a modular fashion. After loading a spin into a bus stop from the conveyor, we can initialize another spin into the conveyor and tune two-qubit logic between the conveyor spin and the bus stop spins. The bottom-middle and right panels illustrate exchange control for three of the bus stops using electric-dipole spin resonance. The conveyor then serves as a proper bus with which to connect beyond-nearest-neighbor spins and acts as a natural ancilla for (up to) four-way quantum non-demolition (QND) parity readout. The experimental techniques developed here showcase the utility of shuttling for tuning sparse arrays far from local charge sensing and spin readout. The universal qubit control, connectivity, and weight-four parity measurements enabled in this architecture provide the necessary ingredients to explore sophisticated protocols such as the [[4,2,2]] error-detecting code.

work in progress

Session: ICOSS



Static and Dynamic Simulations of Shuttling for FDX-22 and SiGe quantum devices

Andrii Sokolov, Conor Power, Xutong Wu, Agostino Aprá, Claude Rohrbacher, Mathieu Moras, Panagiotis Giounanlis, Sergey Amitonov, Nodar Samkharadze and Elena Blokhina

As quantum computing architectures advance toward scalability, the ability to coherently shuttle quantum states across large arrays of quantum dots becomes essential [1,2]. In particular, spin-based silicon quantum processors require reliable and low-decoherence electron transport methods to enable long-range interactions and flexible qubit connectivity. This work presents a comprehensive, physics-informed algorithm for optimising bias waveforms used in conveyor-mode electron shuttling in linear quantum dot arrays. The algorithm integrates self-consistent Poisson–Schrödinger solvers to maintain a constant ground state energy during transport, thereby preserving coherence and minimising motional excitation. A key innovation is the generation of time-dependent voltage sequences that yield near-constant shuttling velocity, informed by the spatial evolution of quantum states and gate lever-arm parameters.

The method also includes a robust DC bias optimisation scheme to prevent excessive heating and ensure the formation of large, movable quantum dots without decoherence-inducing potential barriers using the QTCAD framework [3]. The approach is validated across multiple device platforms, including FD-SOI, SiMOS and SiGe, revealing how gate geometry, material interfaces, and layout constraints impact transport stability. In FD-SOI systems, the presence of interface-induced potential barriers introduces scattering effects that degrade performance. In contrast, SiMOS and the 6-dot SiGe devices with finely tuned gate geometries exhibit smoother quantum dot motion and more uniform energy landscapes. The study highlights practical limitations of conveyor-mode transport in current technologies and offers concrete guidelines for future device engineering to support scalable, high-fidelity quantum shuttling operations.

In addition, our approach includes investigating valley splitting on shuttling using the QTCAD Atom package.

In this work, we also discuss the 3D Split-operator method [4] to verify the obtained results and to estimate the limiting shuttling speed for the given device geometry.

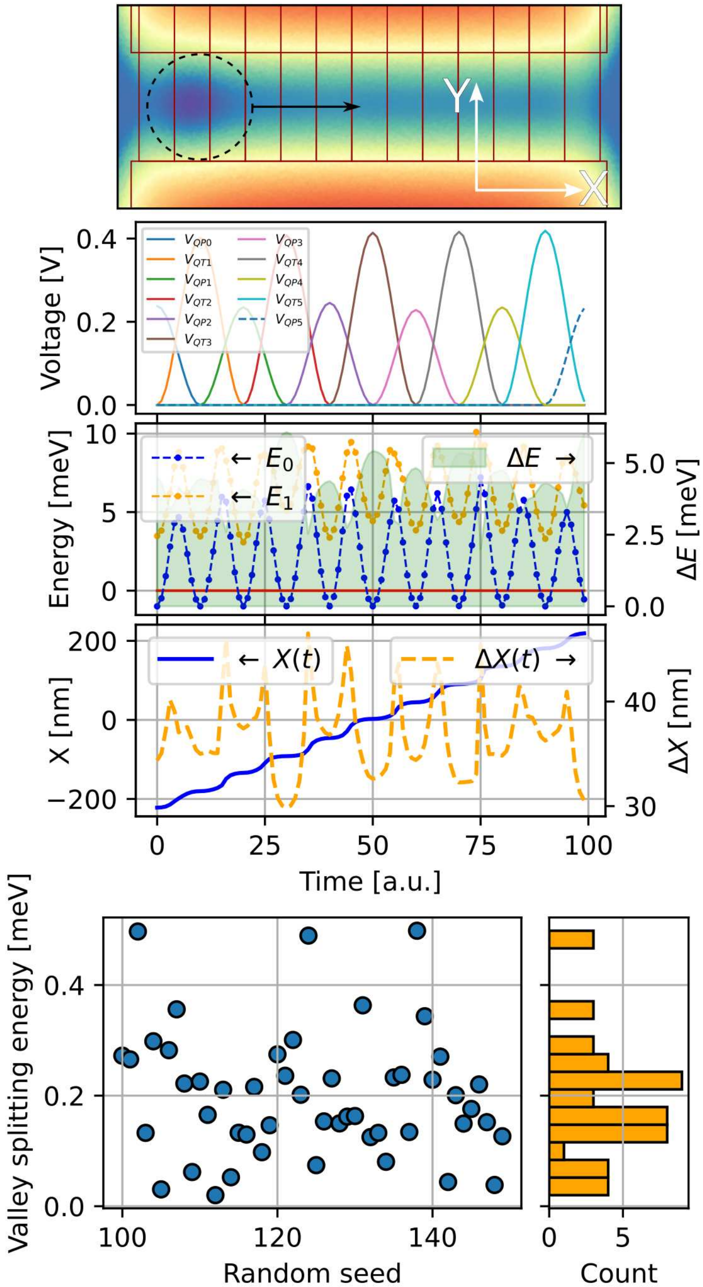
[1] DOI: 10.1038/s41467-024-49182-4

[2] arXiv: 2406.07267v1

[3] DOI: 10.1063/5.0097202

[4] DOI: 10.1007/978-3-030-50433-5$_5$0

Session: ICOSS


Y
X
Voltage [V]
V_{QP0}
V_{QT1}
V_{QP1}
V_{QT2}
V_{QP2}
V_{QT3}
V_{QP3}
V_{QT4}
V_{QP4}
V_{QT5}
V_{QP5}
Energy [meV]
← E_0
← E_1
ΔE →
ΔE [meV]
X [nm]
← $X(t)$
$\Delta X(t)$ →
ΔX [nm]
Time [a.u.]
Valley splitting energy [meV]
Random seed
Count

Spin-orbit-enabled universal two-qubit gate set on moving spins

David Fernández-Fernández, Yuta Matsumoto, Lieven Vandersypen, Gloria Platero and Stefano Bosco

Shuttling spin qubits in systems with large spin-orbit interaction (SOI) can cause decoherence and errors during motion. However, in this work, we demonstrate that SOI can be harnessed to implement a universal set of high-fidelity two-qubit (2Q) gates. We consider two spin qubits defined in a semiconductor double quantum dot that are smoothly, electrically moved toward each other. By controlling the shuttling speed and waiting times, and leveraging strong intrinsic or extrinsic SOI, we show that a universal set of high-fidelity 2Q gates can be realized. Crucially, performing 2Q operations during qubit transport enables direct and flexible distributed entanglement generation between distant sites, alleviating the need for complex static coupling schemes and lengthy gate sequences. Our findings establish a practical route toward direct, universal 2Q gate implementation via spin shuttling, significantly reducing control overhead in scalable quantum computing architectures.

work in progress

Session: ICOSS

Quantum operations of moving spin qubits

Maximilian Rimbach-Russ

The scalability and power of quantum computing architectures depend critically on the availability and quality of their operations. Mobile qubits are particularly attractive as they enable dynamic and reconfigurable qubit architectures. Such flexibility also relieves architectural constraints, as recently demonstrated in atomic systems based on trapped ions and neutral atoms manipulated with optical tweezers. In solid-state platforms, highly coherent shuttling of electron spins was recently reported [1]. Unwanted transitions into non-computational states such as low-lying orbital or valley states, however, can degrade the fidelity.

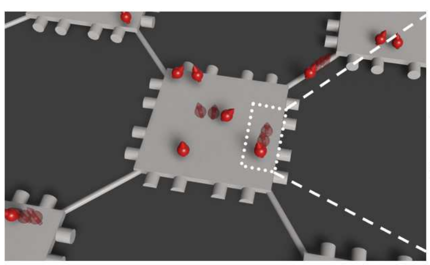
The availability of performing high-fidelity quantum operations "on the fly" during the movement instead of stopping reduces waiting times and further increases the potential for scalability. In solid-state platforms, highly coherent diabatic single-qubit operations [2] and two-qubit operations between mobile qubits were recently reported [3]. However, diabatic operations of spin qubits are even stronger limited by unwanted transitions into non-computational states such as low-lying orbital or valley states.

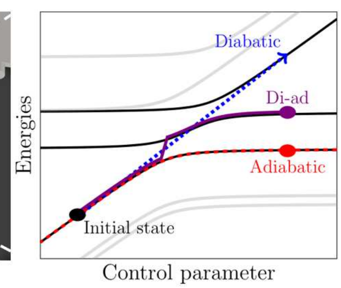
In this talk, I will introduce a new versatile framework for efficient pulse shaping for high-fidelity state transfer in the adiabatic and diabatic limit. The framework allows for high-fidelity state adiabatic transfer in the presence of small anti-crossings [4,5]. Furthermore, we extend the method by interpolating smoothly between adiabatic and diabatic dynamics to minimize unwanted excitations while maximizing desired transitions. We apply the new method to optimize the fidelity of hopping spins in the presence of small tunnel couplings and diabatic single-qubit operations while shuttling.

[1] De Smet, et al. Nat. Nanotechnol. 20, 7, 866.
[2] Wang et al. 385, 6707, 447.
[3] Matsumoto et al. " arXiv:2503.15434.
[4] Meinersen et al. arXiv:2409.03084.
[5] Meinersen et al. arXiv:2504.08031.

arXiv:2409.03084, arXiv:2504.08031, and work in progress.

Session: ICOSS





Non-adiabaticity of electron pick-up process by surface acoustic wave for qubit transport

Zongye Wang and Xuedong Hu

Surface acoustic waves have been suggested as a carrier to enable remote transport of a single or multiple electrons from one quantum dot to another while maintaining quantum information encoded in the electron's spin or orbital degrees of freedom. It is widely believed that the process where SAW picks up the electron from a fixed quantum dot is adiabatic, with the electron wavefunction following the instantaneous ground state centered at the collective potential minimum. In this work we explore the adiabaticity of this electron transfer from a static to a moving (or vice versa) dot as we vary system parameters such as relative dot sizes, bias potential, and speed of the moving dot. In particular, we showed that with parameters commonly seen in experiments, the electron pick-up process by SAW is non-adiabatic. The electron dynamics can be described by a highly excited "classical" wave packet. The high degree of excitation could negatively affect the electron spin decoherence, causing loss of quantum information encoded in the spin.

work in progress

Session: ICOSS

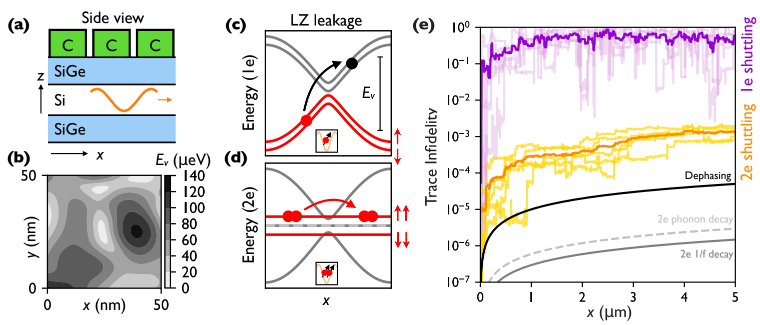
Spin shuttling with very low valley splittings in Si/SiGe heterostructures

Merritt Losert, Susan Coppersmith and Mark Friesen

Conveyor mode shuttling is a key technology enabling qubit transfer across a heterostructure (a). For electron spins in Si/SiGe heterostructures, variable valley splittings are a key challenge for high-fidelity shuttling (b). Without fine-tuning the shuttling path, Landau-Zener-like excitations lead to leakage outside the qubit subspace (c). Here, we propose an alternate qubit encoding, based on two-electron valley singlet states, that is immune to Landau-Zener leakage (d). Specifically, we encode our qubit in the polarized spin triplet, valley singlet states. In contrast with single-electron spins, in this encoding the shuttling fidelity improves as the valley splitting decreases and as the shuttling speed increases. The dominant leakage mechanism for this qubit encoding is the second-order spin-orbit coupling between the qubit subspace and the remaining low-energy states, coupled through virtual excitation of excited orbital states. We demonstrate that high-fidelity spin shuttling is achievable in the small valley splitting limit, without fine-tuning the shuttling path (e).

work in progress

Session: ICOSS



Multiscale simulations of atomistic-disorder-induced valley-leakage error during electron shuttling

Raphael J. Prentki, Pericles Philippopoulos, Mohammad Reza Mostaan and Felix Beaudoin

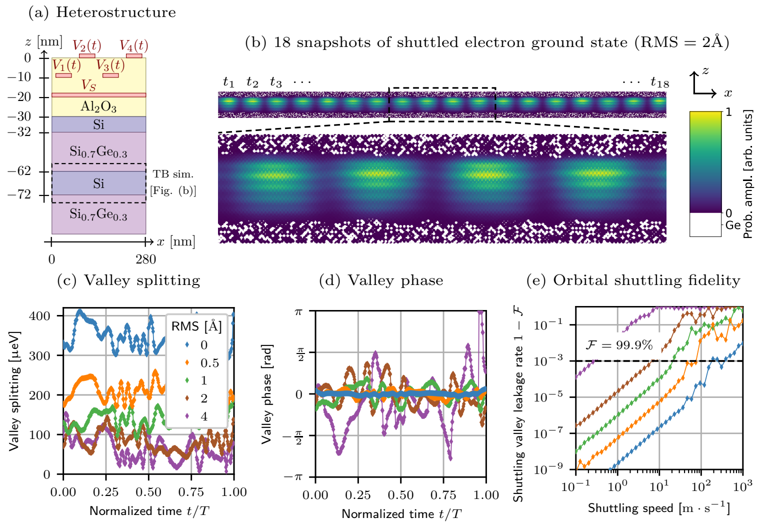
Electron conveyor-belt shuttling between qubit registers is emerging as a key enabler of scalable silicon spin-qubit quantum computing. As an electron is shuttled over microns or more, it samples angstrom-scale disorder (e.g. random alloying and interface roughness), causing its confinement potential to fluctuate. In turn, the valley splitting and valley phase fluctuate, driving leakage into valley-excited states and capping high-fidelity shuttling speed. Reliable predictions of shuttling fidelities thus require multiscale simulations that link atomistic and mesoscopic physics.

Here, we develop a multiscale simulation workflow based on the QTCAD® package to quantitatively analyze this problem. As a vehicle to this study, we consider the quantum bus (QuBus) architecture; the clavier gate voltages Vi(t) are sinusoidal with period T [Fig. (a)]. First, we obtain the time-dependent confinement potential via finite-element solutions of the Poisson equation. Second, we construct conveyor-belt atomic structures with random alloy disorder and Si/SiGe interface roughness; we relax them within the Keating model to capture strain. Third, we run position-tracked atomistic tight-binding (TB) calculations [Fig. (b)] to extract the electron's time-dependent valley splitting [Fig. (c)] and valley phase [Fig. (d)]. Finally, these time traces parametrize a time-dependent Schrödinger equation in the valley subspace, wherein the time derivative of the valley phase drives leakage into the valley-excited state, which we solve to obtain the orbital shuttling fidelity [Fig. (e)].

Applying this method, we examine Si/SiGe interfaces with roughness root-mean-square (RMS) values between 0 and 4 Å. We find that the device with pristine interfaces (RMS = 0 Å) achieves orbital fidelities above 99.9% for shuttling speeds below 100 m/s, whereas even modest roughness exponentially degrades fidelity. Our results thus highlight the critical impact of interface roughness on valley phase stability and electron shuttling fidelity.

Work in progress

Session: ICOSS


(a) Heterostructure
(b) 18 snapshots of shuttled electron ground state (RMS = 2Å)
(c) Valley splitting
(d) Valley phase
(e) Orbital shuttling fidelity
Al2O3
Si
Si0.7Ge0.3
TB sim. [Fig. (b)]
Prob. ampl. [arb. units]
Valley splitting [µeV]
Normalized time t/T
RMS [Å]
Valley phase [rad]
Shuttling valley leakage rate 1 − F
F = 99.9%
Shuttling speed [m · s−1]

Impact of Device Imperfections on Charge Transport and Valley Excitations During Electron Shuttling in Si/SiO$_2$

Christian Walter Binder, Jack James Turner, Guido Burkard and Andrew Fisher

There have been extensive theoretical studies and high-fidelity experimental demonstrations of shuttling in Si/SiGe, but considerably less work has been done on this topic in Si/SiO. To address this, we build on previous 2D simulation work by performing full 3D modelling of conveyor-mode charge shuttling in realistic Si/SiO2 devices with charged defects, gate imperfections, and roughness at the oxide interface. Using solutions to the Poisson and time-dependent Schrödinger equations for different shuttling speeds and gate voltages, we find that positive defects directly in the shuttling path capture passing electrons when using lower clavier gate voltages of 250mV. Increasing the conveyor confinement with gate voltages of 500mV ensures the passing electrons escape the trap, but they emerge in an orbitally excited state potentially opening spin-flip pathways via spin-orbit coupling and phonon relaxation. On the other hand, single negative defects don't disrupt transport by knocking electrons into adjacent minima, but do induce orbital excitation for lower clavier gate voltages of 250mV. These excitations are suppressed by increasing the confinement, and so are not expected to present an obstacle to charge shuttling. Our simulations also show charge shuttling remains robust against 30% variations in clavier gate footprint and interface roughness as high as rms=0.9nm. However, when we use these modelling tools to compute the valley splitting and phase for different interfaces, we find that even modest roughness creates adversarial valley landscapes with low splitting and rapidly changing phase. We observe that the electron is highly susceptible to valley excitations when shuttling across these interfaces for even slow shuttling speeds, which may lead to spin-dephasing and leakage out of the computational subspace. This highlights the importance of mitigation strategies currently being explored in the Si/SiGe literature to Si/SiO2 devices, for example using variable shuttling speeds and paths or compensating for channel-specific dephasing with Z-rotations.

work in progress

Session: ICOSS