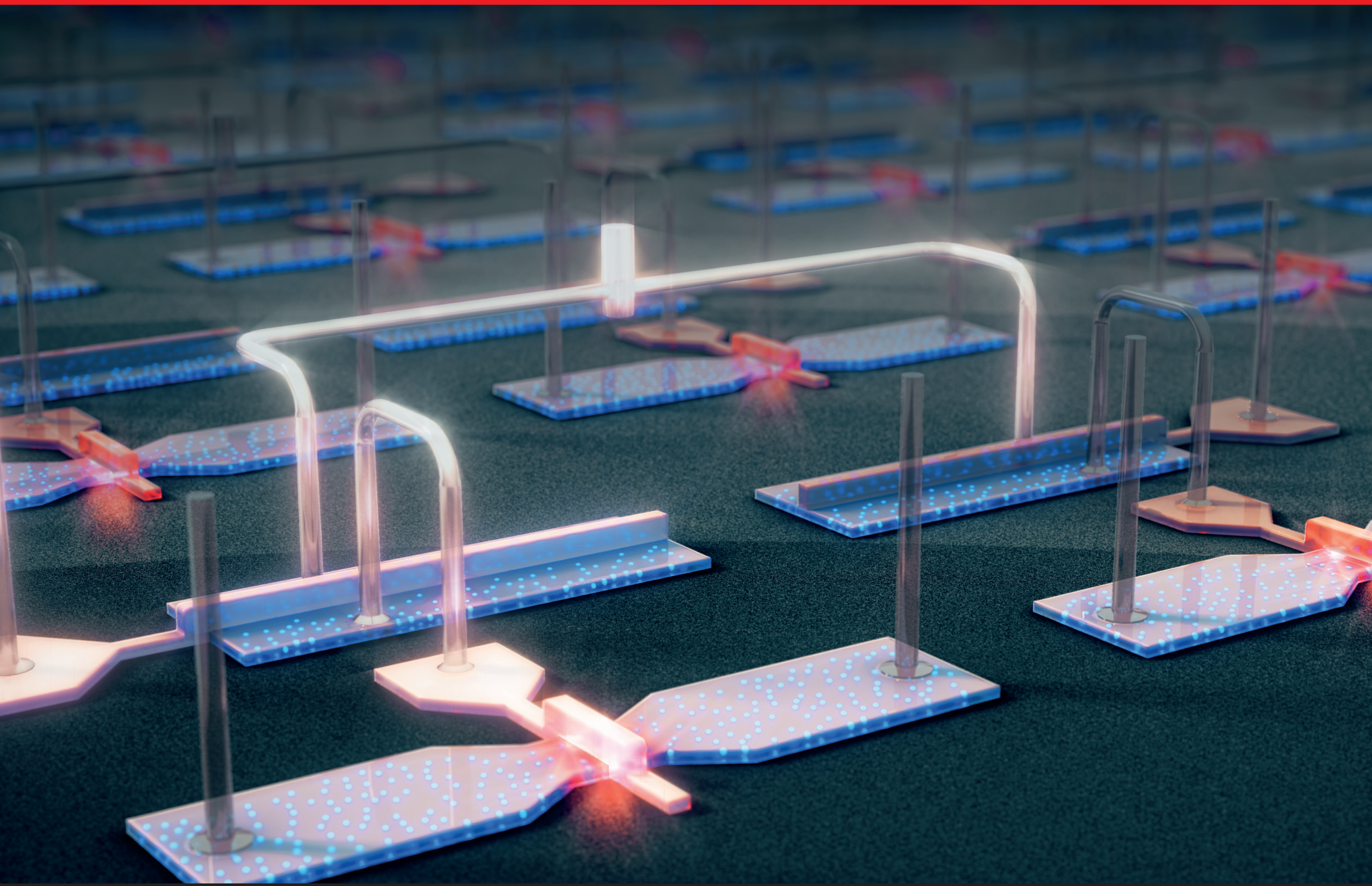
Abstract Booklet



Silicon Quantum Information Processing 2019

11–12 September 2019
Hughes Hall, Cambridge, UK

www.iopconferences.org/iop/1351/home

Organised by the IOP BRSG: Magnetic Resonance Group, Nanoscale Physics and Technology Group, Quantum Electronics and Photonics Group, Quantum Optics, Quantum Information and Quantum Control Group, Semiconductor Physics Group, Superconductivity Group

IOP Institute of Physics

(Invited) Silicon qubits

J Morton

University College London, UK

In this lecture I will present an introduction to the fundamental concepts and recent advances relating to silicon-based quantum processors.

(Invited) Superconducting Qubits

S Filipp

IBM Research, Switzerland

In recent years quantum technologies have rapidly developed towards first realizations of quantum computers that promise to outperform conventional computers in certain types of problems. This includes problems in optimization, machine learning, finite element calculations, but also in the computation of complex molecules. Superconducting qubit architectures are currently one of the most promising candidates to realize such a quantum computer because of their stability, the relatively long coherence times and the scalability. I will give an introduction to superconducting quantum circuits and discuss how to carry out single and two-qubit quantum gates. I will then outline how this platform is used to perform simple algorithms such as the computation of the energy spectrum of small molecules. I will conclude with a discussion on the challenges for further scalability.

(Invited) Introduction to Majorana-based topological qubits

R Aguado

Materials Science Institute Madrid and Quantum Technologies Platform, Spain

After an introduction to Majorana zero modes in topological superconductors and topological qubits based on them, I will present an overview of the state of the art concerning their experimental implementation and detection using hybrid superconductor-semiconductor nanowires.

(Invited) Cryo-CMOS technology for quantum computers

E Charbon

EPFL, Switzerland

With the steady growth in the number of qubits being demonstrated in solid-state technologies, so does the demand for scalable classical control to achieve a fault-tolerant machine. We advocate the use of cryogenically operated complementary metal-oxide semiconductor (Cryo-CMOS) technology to achieve compact, fully scalable systems for the control of large arrays of qubits. In the talk, the challenges of designing and operating complex circuits and systems at 4K and below will be outlined, along with preliminary results achieved in the control and read-out of qubits by ad hoc integrated circuits that were optimized to operate at low power to be compatible with standard dilution fridges. The talk will conclude with a perspective on the field and its trends.

(Invited) Quantum error correction: challenges and opportunities in near-term hardware

D Horsman

Université Grenoble Alpes, France

In this talk I will give a tutorial introduction to practical quantum error correction. I will discuss both the difficulties and the opportunities presented by applying the theoretical results of the last two decades to the quantum technologies now being developed. I will give a user-friendly introduction to the basic machinery of error correction, including stabilizers, error discretisation, and the threshold theorem. As a use-case, I will introduce the basic functioning of the surface code (considered the error correction procedure of choice for large-scale quantum computers). I will then talk about the problems that present themselves in getting quantum devices to the point where active error correction can be implemented. I will finish by discussing recent work on what we can do before then, to use our understanding of QEC to mitigate errors in near-term noisy quantum computers.

(Invited) Looking at the single spin of a quantum dot through a hole

A Crippa

University of Grenoble Alpes, France

Despite spins in semiconductor quantum dots are being considered serious contenders in the global race to quantum information processing, many fundamental scientific questions still stand without a clear answer. For instance, claiming that a single electron spin trapped in a silicon quantum dot “has a weak spin-orbit coupling” or “has a spin g-factor equal to 2” might result too simplistic – a series of recent experiments have exploited sizable intrinsic spin-orbit couplings [1, 2] and tunable Landé g-factors [3] to manipulate and address single electron spins. Moreover, producing quantum dots reliably and repeatedly in view of a possible scale-up requires a precise knowledge of orbital “second-order” corrections to the single spin picture. To quickly present such quantum dot properties, I’ll peek through a hole. I’ll use the positively-charged counterpart of the electron living in the valence band as a key-hole to shed light on few features of certain usage for people on Si electron dots, Ge hole dots and other spin-orbit materials. In particular, I’ll focus on the realistic scenario of low-symmetry quantum dots in p-type silicon etched-nanowire Field Effect Transistors [4] showing how to perform and characterize fast, all-electrical coherent spin manipulation [5] combined with gate-coupled RF reflectometry for qubit readout [6].

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Superconducting Resonators for Frequency-Multiplexed Gate-Based Readout

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Readout of the spin state of an electron, by the spin-to-charge conversion technique [1], requires a method for sensing charge that is faster than the coherence time. Gate-based dispersive readout offers improvements over RF charge sensors by reducing measurement back-action and detector footprint. Gate-based readout is performed by coupling the electric field of a microwave cavity to the electron's charge, via a gate electrode. The spin state of the electron is inferred from spin-dependent capacitance changes which shift the cavity's natural frequency [2].

To minimise measurement integration times, the cavity's internal quality factor and natural frequency of resonance can be increased and its capacitance can be decreased [3,4]. To achieve this, we fabricate superconducting NbN spiral inductors which resonate in the GHz regime. The spirals are fabricated on the same chip as a 50 Ω waveguide, removing the need for a separate coupling capacitor. The mutual inductance between the spiral and the waveguide is sufficient to achieve impedance matching. We measure a frequency shift of 5.3 kHz/aF, a factor 18 larger than when operating at hundreds of MHz and coupling via an off-chip air-gap capacitor [3]. Several spirals, with different inductances, can be placed along a section of waveguide, providing a simplified approach to frequency multiplexing [5].

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Acknowledgements: This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 688539. DJI is supported by the Bristol Quantum Engineering Centre for Doctoral Training, EPSRC grant EP/L015730/1.

Microwave characterisation of confined phosphorous layers in silicon for planar waveguides

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Confined 2D nanostructures made from high density regions of P dopants in silicon are routinely used in the fabrication of atomic-scale prototype devices in silicon. These local regions of delta-doping can be patterned with near atomic scale precision and have been shown to demonstrate ohmic behaviour down to wire widths of 1.5 nm [1]. The patterned structures have been used to fabricate DC electrical componants including source and drain electrodes [2] .We propose the use of these confined Si:P delta-doped monolayers as a potential material for nanoscale planar electronics within a quantum system. This application would enable a simplified fabrication procedure for the qubit and its individual spin control architecture. Here we present the first microwave characterisation of fully-doped Si:P monolayers fabricated through phosphine doping and ion beam implantation. S-parameter measurements were completed at 4.5 K between 4-26 GHz and indicated that Si:P monolayers are viable for electromagnetic transmission. The monolayer transmission line parameters were found with an attenuation constant and a characteristic impedance of 35 dB/mm and 900

Ω respectively at 8 GHz. Research has been focused on graphene due to its attractive electronic properties and nanoscale allotropes. We show that Si:P monolayers have electronic properties similar to graphene, but further benefit from extremely precise, stable and CMOS compatible fabrication techniques.

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Generation and characterisation of high-dimensional discrete cluster states on chip

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The generation of quantum states of light featuring entanglement over many photons and multiple modes allows to access larger Hilbert spaces, thus increasing the resources for applications in, e.g. quantum metrology, communications and computing.

In this context, cluster states [1] are of particular importance as the primary resource for the so-called one-way quantum computation [2]. Among the different approaches for the generation of these complex quantum states, hyperentanglement increases the number of modes combining independent variables, such as polarisation and optical path, or orbital angular momentum. However, such degrees of freedom are either limited in dimensionality (polarisation) or quite difficult to achieve and manipulate.

We proposed an innovative scheme for the generation of hyperentangled states by properly combining the temporal and frequency degrees of freedom readily accessible in an integrated microring resonator. Furthermore, we developed a deterministic phase gate based on a frequency-to-time mapping scheme allowing us to manipulate these variables independently for generating, to the best of our knowledge, the first high-dimensional discrete cluster state on-chip [3]. The characterisation of this multipartite, high-dimensional states is however quite challenging. For this reason, we developed a universal technique to derive experimentally-friendly entanglement witnesses for high-dimensional cluster states [4]. This allowed us to characterise our d-level multipartite cluster state, with fewer measurements compared the full density matrix reconstruction. Finally, we demonstrated proof principle one-way quantum computing operations with our system. Performing temporal or spectral projection measurements, we demonstrated the violation of the Bell inequalities on the remaining maximally entangled states.

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(Invited) Scalable Cryogenic CMOS Electronics for Spin Qubit Control

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Research Center Juelich, Germany

The Central Institute for Electronic Systems at Forschungszentrum Jülich develops, designs and tests scalable solutions for the control and readout of qubits to be used in future quantum computers. The focus lies on highly integrated system-on-chip (SoC) solutions leveraging state-of-the-art commercial semiconductor technologies.

One of the main challenges for integrating a high number of qubits is their connection to the room temperature control electronics and their sensitivity to any kind of noise. Therefore the integration of circuits in close vicinity to the qubit promises significant benefits and will be most likely the only way to reach qubit numbers beyond a thousand. The extremely low temperature poses severe challenges to classical circuit design, amongst others the power budget which is limited by the cooling power of the dilution refrigerator.

The operation of a GaAs qubit requires fast and precise voltage pulses with a dynamic range of approximately 8 mV as well as multiple DC voltages to form potential wells and tune the qubit into operating region. With these requirements a test chip was designed and layouted in a commercial 65nm CMOS process. The chip employs a pulse-digital-to-analog converter, with a sampling rate of 250 MS per second, to generate pulses with ±4 mV amplitude as gate sequences for operating the qubit. For generation of the DC Voltages a low power multi-output channel digital-to-analog converter with an output range of -1 to 0 V is incorporated. The chip can be placed in close proximity to the actual qubit at the milli-kelvin temperature stage.

In this presentation, we will describe the chip architecture in detail, show corresponding simulation results and measured chip performance including first results at cryogenic temperature.

Impact of band-tail tunneling on cryo-CMOS power consumption

A Beckers, F Jazaeri, and C Enz

EPFL, Switzerland

The subthreshold slope of CMOS technology at deep cryogenic temperatures (< 40 K) is worse than predicted by the diffusion model of the drain-source current. This has a direct impact on the required supply voltage to switch the MOSFET between ON and OFF states at deep cryogenic temperatures, and thus on the static and dynamic power consumption in qubit interfaces. Understanding the cause of this degradation is essential to model it correctly in circuit simulators and mitigate its occurence by process optimization. Until now, the responsible physical phenomenon has been sought in degraded electrostatics: i.e., interface traps or band tails. However, this approach has lead to anomalously high interface-trap densities.

We have recently shown that the worse subthreshold slope is a result of quantum transport rather than degraded electrostatics. At deep-cryogenic temperatures, the diffusion current becomes negligible compared to a tunneling current through a band tail. Using the Landauer-Buttiker formalism, we have then proceeded to derive a single expression for the subthreshold swing (SS) due to the band-tail tunneling current. The limit of this expression toward deep-cryogenic temperatures gives the saturation value SS=m(Wt/q)ln10 instead of the diffusion limit SS=m(kBT/q)ln10 (where m is the slope factor including interface traps, Wt the characteristic width of the band tail in the bandgap, q the electron charge, and kB the Boltzmann constant).

At deep-cryogenic temperatures, SS thus becomes independent of temperature and governed by the width of the band tail in the bandgap. Here, we use this limit to investigate the excess power consumption of cryo-CMOS technology due to the band-tail tunneling current. Finally, we present recent progress in the development of a cryo-CMOS compact model including band-tail tunneling.

Practical chip-level platforms for emerging quantum technologies

J Lehtinen, A Ronzani, and M Prunnila

VTT Technical Research Centre of Finland, Finland

Several challenges are inherent both to the development of silicon quantum information processors and quantum electronics in general. Implementing long-lived qubits, quantum-limited amplification, and efficient photonic interfaces in ultra-low temperature environments are among the cornerstones of a silicon-based quantum computing architecture.

In this context, scalability and integration arguments demand heterogeneous on-chip solutions to these problems. Here we present our approaches to developing such transversal platforms, with special focus on a SOI-based quantum nanoelectronic device fabrication protocol.

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(Invited) A silicon quantum-dot-coupled nuclear spin qubit

B Hensen

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Single nuclear spins in the solid state have long been envisaged as a platform for quantum computing1, due to their long coherence times and excellent controllability. Measurements can be performed via localised electrons, for example those in single atom dopants2 or crystal defects3. However, establishing long-range interactions between multiple dopants or defects is challenging. In lithographically-defined quantum dots, on the other hand, tuneable interdot electron tunnelling allows direct coupling of electron spin-based qubits in neighbouring dots4,5. Moreover, compatibility with semiconductor fabrication techniques6 provides a compelling route to scaling to large numbers of qubits. Unfortunately, hyperfine interactions are typically too weak to address single nuclei. I will present recent results7 obtained with electrons in silicon metal–oxide–semiconductor quantum dots, for which the highly confined electron wavefunction results in a sufficiently strong hyperfine interaction to initialise, read-out and control single silicon-29 nuclear spins. We demonstrate high-fidelity projective readout and control of the nuclear spin qubit, as well as entanglement between the nuclear and electron spins. We find that both the nuclear spin and electron spin retain their coherence while moving the electron between quantum dots, highlighting the powerful combination of coherent nuclear spins and long-range electron interactions between quantum dots. I will discuss possible applications and an outlook towards electron mediated long range nuclear entanglement8.

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Single Electron Control in a Two-Dimensional Array in Silicon

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The scalability of quantum information platforms is predicated on the ability to coherently manipulate quantum objects organized in addressable arrays. Recently, linear quantum dot arrays have successfully demonstrated quantum simulation and electron shuttling experiments. However, a significant next step is the coherent operation and readout of these qubits in nearest-neighbor tunnel-coupled two-dimensional arrays. Here, we demonstrate a two-dimensional cell of single-electron quantum dots in silicon with an integrated gate-based RF-reflectometry charge sensor, based on CMOS-foundry-compatible Si MOS nanowire devices fabricated on 300mm wafers. We show the ability to form reconfigurable single, double, and triple quantum dots with tunable tunnel coupling, deterministically control the dot occupation as well as shuttle single electrons in two dimensions and detect their movement using charge sensing. The CMOS-fabricated device has a compact gate design, showing promise for densely-packed silicon arrays for quantum computation and simulation in two dimensions.

A Spin Quintet in a Silicon Double Quantum Dot

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Spins in gate-defined silicon quantum dots are promising candidates for implementing large-scale quantum computing [1-3]. To read the spin state of these qubits, the mechanism that has provided highest fidelity is spin-to-charge conversion via singlet-triplet spin blockade [4], which can be detected in-situ using gate-based dispersive sensing [5]. In systems with a complex energy spectrum, like silicon quantum dots, accurately identifying when singlet-triplet blockade occurs is hence of major importance for scalable qubit readout [6].

In this work, we present a description of spin blockade physics in a tunnel-coupled silicon double quantum dot defined in the corners of a split-gate transistor. Using gate-based magnetospectroscopy, we report successive steps of spin blockade and spin blockade lifting involving spin states with total spin angular momentum up to S = 3. More particularly, we report the formation of a hybridized spin quintet state and show triplet-quintet and quintet-septet spin blockade. This enables studies of the quintet relaxation dynamics from which we find T1 ~ 4 μs. Finally, we develop a quantum capacitance model that can be applied generally to reconstruct the energy spectrum of the double quantum dot including the spin-dependent tunnel coupling and the energy splitting between different spin manifolds. Our results open for the possibility of using Si CMOS quantum dots as a tuneable platform for studying high-spin systems.

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Measuring a quantum dot spin using gate-based reflectometry and spin-dependent tunnelling

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Gate-based reflectometry is an attractive measurement technique for scalable silicon qubit arrays, as it exploits existing gates used to define and manipulate the qubit [1].

Here, we demonstrate gate-based reflectometry readout of a single quantum dot spin in a silicon nanowire using spin-dependent tunnelling [2,3,4]. Our device is based on a silicon etched nanowire field-effect transistor, with a split wraparound top-gate able to electrostatically define and independently control two quantum dots in parallel.

One quantum dot is operated as a charge sensor and attached to an LC resonator for gate-based reflectometry. The charge state of the second dot is detected by the sensor dot via their capacitive coupling, and this can be used for readout the quantum dot spin using spin-dependent tunnelling.

Using this method, we measure the electron spin relaxation time, T1, as a function of the applied magnetic field B, and find T1 approximately follows a B-4 dependence, reaching about 0.2~s at a field of 1~T. By varying the energy at which electrons are loaded into the quantum dot, we confirm the approximate Zeeman splitting of the spin and also directly measure the energy of the first excited state ~ 750 μeV.

Keywords: Nanowire FET, Spin relaxation, Gate-based Reflectometry, Spin-dependent tunnelling.

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Charge noise in a superconducting single-electron transistor coupled to a two dimensional electron gas in silicon

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Charge detection and error counting are a critical part on creating self-calibrating primary electric current sources which employ single-electron pumps. Previously, the low signal-to-noise ratio due to the weak coupling between the detector and an intermediate charge island, in which the single electron pump transfers additional charges, limited the error counting bandwidth.

In this work, we present our experimental results on a superconducting Al–AlxOy–Al single-electron transistor charge detector that is capacitively coupled to a two-dimensional electron gas charge island. We investigate the temperature and the local electrostatic field configuration dependence of the charge noise and measure the capacitive coupling between the detector and the charge island. According to the results, we estimate the characteristics of a charge detection scheme using our circuit, which proposes an increment in the bandwidth for the future error counting experiments.

(Invited) Quantum device measurement and black box tuning using machine learning

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A major obstacle to creating large quantum circuits in semiconducting platforms is device variability. To fully characterize and tune each device is a task that is rapidly becoming intractable for humans without the aid of automation. I will present efficient measurements on a quantum dot performed by a machine learning algorithm. This algorithm employs a probabilistic deep-generative model, capable of generating multiple full-resolution reconstructions from scattered partial measurements. Information theory is then used to select the most informative measurements to perform next. The algorithm outperforms standard grid scan techniques in different measurement configurations, reducing the number of measurements required by up to 4 times.

I will also show the use of Bayesian optimisation for tuning a gate-defined double quantum dot. The algorithm can efficiently navigate the entire gate voltage space, defined as the full voltage range for every gate electrode. We tune the device to the double quantum dot regime with no previous knowledge of the device characteristics in a small fraction of the time that it requires manually.

Gate Fidelity of Bandwidth-limited and Noisy Pulse Sequences for Qubits based on Electrons Confined in Donors and Dots in Silicon

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Various spin qubit architectures have been theoretically investigated and built on the scale of few devices in view of quantum computation applications. In semiconductors three main directions for the creation of spin qubits can be identified: qubits that are based on the spin of electrons in electrostatically defined quantum dots (QDs) [1-3], qubits that use the spin of electrons or nuclei of impurity atoms in the semiconducting host (donors) [4-6] and qubit based on a combination of those two approaches. Here we study three different silicon qubit types, one for each of the three identified directions, namely the qubit based on an electron spin confined in a QD (SS), an electron spin-based donor qubit (D) and singlet-triplet dot-donor qubit (STD). For each type, analytical pulse sequences that generate single qubit rotations along the axis of Bloch sphere are considered [7]. The corresponding qubit dynamics is obtained by employing a master equation approach for the density matrix, where an effective Hamiltonian of each qubit type in the corresponding logical basis is considered. We estimate the effects on the gate fidelity of errors disturbing the control parameters by using a Gaussian noise model and by taking into account the limited bandwidth of the control signals. This study provides a comparison of qubit fidelities highlighting which one is the most robust with respect to the bandwidth limited control signals and to the control noises.

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Entangling gates based on the Rydberg blockade releases constraints on single donor placement in silicon

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Long coherence times, high gate fidelity and scalability are crucial considerations when choosing the optimal quantum computing platform. Electron and nuclear spins of dopants in silicon offer some of the longest coherence times. However, oscillations in the exchange interactions due to the periodicity of the crystal lattice make the fabrication of entangling gate configurations challenging. We study the feasibility of implementing an entangling gate between dopants in silicon based on the Rydberg blockade. We calculate the induced dipole, Van der Waals and exchange interactions between donors in orbital excited states and describe schemes to implement the necessary spin-dependent excitation in both Si:Se+ and Si:P. We find that a blockade gate is indeed possible, and due to spin-valley coupling in Si:Se+, simple to implement. Our study paves the way for near-term large scale quantum computations with donors in silicon by lowering the precision requirements on single donor placement.

A first-principles study of the excited states of deterministically implanted donor arrays in silicon

W Wu and A Fisher

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Deterministically implanted donors in silicon provide a promising route to develop quantum computing [1, 2]. Understanding the excited states of donor clusters in silicon is important for connecting optically the qubits in silicon. Herein we present a systematic theoretical study for the excited states of donor clusters in silicon.

First, we have adopted a spherical band approximation and use hydrogen atoms to represent shallow donors. We have computed the electronic structure and optical properties of a series of donor lines with up to 10 donors [2] by using configuration interaction, time-dependent Hartree Fock (TDHF) and time-dependent density-functional theory. Our calculations show charge-transfer excitations play an important role, dominating the transition for separation ~5nm and dropping down to 10 meV. In addition, we can see the increased exchange interaction upon optical excitation.

Second, we have developed a more realistic theoretical description for the excited states of silicon donors, by taking into account central-cell corrections, anisotropy of the effective-mass equation, and multi-valley effect [4]. We have used TDHF to perform the single-valley and multi-valley calculations for a donor pair, which show distinct features in the excitation spectra arising from multi-valley effect. One interesting consequence is to open up a gap between the ionic state and the 1s→2p intra-atom transition. Single-valley calculations can be useful to understand the excited states of valley-polarized electrons [5]. The excitation energy drops down to ~12 meV.

Our calculations can provide a theoretical foundation for the use of excited states in quantum information processing.

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Optically modulated magnetic resonance of erbium implanted silicon

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Er implanted Si is a candidate for quantum and photonic applications; however, several different Er centres are generated during implantation and annealing. The symmetry, energy level structure, magnetic and optical properties, and mutual interactions of these centres have been poorly understood, which has been a major barrier to the development of quantum and photonic applications. Optically modulated magnetic resonance (OMMR) gives a spectrum of the modulation of an electron paramagnetic resonance (EPR) signal by a tuneable optical field. Our OMMR spectrum of Er implanted Si agrees with three independent measurements, showing that we have made the first measurement of the crystal field splitting of the 4I13/2 manifold of Er implanted Si, and allows us to revise the crystal field splitting of the 4I15/2 manifold. This splitting originates from a photoluminescence (PL) active O coordinated Er centre with orthorhombic C2v symmetry, which neighbours an EPR active O coordinated Er centre with monoclinic C1h symmetry. This pair of centres could form the basis of a controlled NOT (CNOT) gate. The orthorhombic centre is associated with a previously unreported acceptor state lying ~425 cm-1 above the valence band, showing that Er in Si is not a pure donor, as previously thought.

Posters

P1. Engineering the complex space-time L4(C)

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Stochastic fluctuations like the Brownian noise underlying diffusion processes in the silicon nanodevices, thin-film electro-optic coatings and cQED can define the upper boundary of the performances of the quantum information applications, limiting their fidelity, robustness, security and quality levels in the fundamental research as well as in the novel applications in the defence, security and aerospace industries.

Intelligent solutions exist to reduce the effects of the dissipative Wiener processes, correcting errors and protecting against decoherence, like photonic cooling.

Other methods exist to reduce the mechanical damping of the thin film dielectric multilayers, minimising the frequency-dependent noise power spectral density of the photon-atom interactions [1].

The design of alternating metal and dielectric materials is expected to form, maximise virtual photons in the near-field, in the QED semi-classical framework [2], providing imaging benefits [3].

We observe:

- Zero energy-momentum stress tensor photons in the purely-reactive near-field, correspond to negative energy, imaginary wave-vectors;
- QFT allows field excitations corresponding to energy exchanges between space-like separated events, conditioning them to be stochastic;
- SR admits arbitrarily large velocities for moving points carrying no information;
- Novel theorems including space-like solutions (Figure 1) [4];
- New findings proving the cooling of silicon devices by extraction of infra-red virtual photons [5].

We propose a cryogenic design reducing the overall Brownian noise by near-field cooling of the:

- silicon devices, by extraction of thermal virtual photons;
- electro-optic coating, with virtual photons resonators [6].

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P2. Gate-based charge sensing in a foundry-fabricated 2x2 array of quantum dots in silicon

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Massive parallel fabrication of quantum dots in CMOS foundries constitutes a key potential for large, spin-based quantum processors. However, iteration and optimization of different geometries is more difficult compared to individual spin-qubit devices fabricated in academic labs, and high-frequency readout of CMOS devices has so far been based on capacitance sensing.

We report results on implementing charge sensing within a 2x2 array of quantum dots, implemented in fully-depleted silicon-on-silicon devices fabricated at LETI. This is achieved by connecting one plunger gate electrode to a radio-frequency reflectometry circuit and employing one quantum dot (dispersively coupled to that plunger gate) as a charge sensor of the remaining dots in the array. This allows us to verify one-electron occupation of each of the four dots, as well as the systematic tune-up of single, double, and triple quantum dots with any desired few-electron occupation. Application of fast gate-voltage pulses allow us to manipulate the charge states on microsecond timescales with high charge sensitivities, and to extract in time domain characteristic tunneling times between adjacent dots. The combination of high-bandwidth manipulation and charge sensing will be crucial for operating these arrays as multi-qubit quantum circuits.

P3. Rescaling interactions for Quantum Control

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The ability to control a quantum system precisely is indispensable for quantum computing, quantum sensing and all quantum devices. These quantum systems are usually described by an internal or drift Hamiltonian which includes the one- and two-qubit interactions which dictate the time evolution of the quantum system. It is frequently useful to allow the quantum system to evolve under a particular interaction while suppressing the rest, and spin echoes have been used for this purpose for many years. In this work we seek to address a more general problem, by describing a method to not only turn on and off particular interactions but also to rescale their strengths so that we can generate any effective drift Hamiltonian.

P4. Efficient electrical detection of single erbium ions in silicon

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Optically active defects inside the solid state provide a versatile platform for probing various quantum phenomena on an atomic scale with high sensitivity. By creating optical defects inside semiconductors such as silicon or silicon carbide, it is possible to integrate them into electronic devices. The charge carriers inside the semiconductor can be used to electrically induce luminescence or detect absorption at the localized states. The interaction of the defects with charge carriers in the semiconductors, both free and local, creates challenges and opportunities. For example, non-radiative recombination via charge carriers reduces the lifetime of a defect's excited state and its luminescence intensity, but the resulting change in charge makes electrical detection possible.

In this work we present efficient electrical detection of single erbium ions in a silicon transistor. We use a single electron transistor inside a silicon FinFET doped with erbium ions to detect the ionization of a single charge trap following a pulse of light. We show that the ionized charge trap persists in its state long enough for high fidelity charge detection. Furthermore, we find that the charge state can be reset quickly by a pulse of light or gate-controlled tunneling.

With our detection technique we can measure the lifetime of the optically excited state by registering when the trap state is ionized following the optical excitation of the erbium ion. If the lifetime is short due to this non-radiative recombination process, it provides a fast and efficient spin-to-charge conversion for detecting erbium's spin states. From our measurement we find an upper limit of 50 μs, where we are limited by our measurement bandwidth. By combining the here reported excitation and detection mechanism with higher bandwidth measurement techniques, such as cryogenic amplifiers or reflectometry, we should be able to measure shorter non-radiative lifetimes of erbium ions in silicon.

P5. Simultaneous operation of four singlet-triplet qubits in a GaAs multi-dot device

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The development of spin-based quantum processors is currently moving from linear two-qubit devices to larger, two-dimensional qubit circuits, both in silicon and GaAs. The coherent manipulation and readout of small two-dimensional arrays of qubit provides a basic playground for developing techniques that will become essential for larger and larger processors. We demonstrate the simultaneous coherent manipulation and readout of four independent singlet-triplet (ST) qubits located around a central multi-electron dot realized in a GaAs heterostructure. Each qubit is capacitively coupled to a radio-frequency charge-sensing dot with a distinct reflectometry frequency for readout, and two fast gate electrodes for manipulation via nanosecond-scale voltage pulses. We show coherent exchange oscillations within all four qubits, simultaneous T_2^* measurements, as well as the possibility to interlace different types of pulse operations. We also measure gate-voltage cross talk, which is likely to occur in any densely-packed qubit array independent of the material system.

P6. Fully automated 'black-box' tuning of quantum dots: exploring entire high-dimensional parameter spaces

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Semiconductor quantum devices hold great promise for scalable quantum computation, however due to device variability, operational parameters vary from device to device. We propose a statistical tuning algorithm that operates on the entire parameter space and makes few modelling assumptions.

Using this approach we are able to demonstrate tuning on two separate devices and show expected tuning times of under 90 minutes. We also show that the algorithm is approximately 86 times faster than a random search. Additionally, using this approach we are able to give a quantitative measurement of device variability, from one device to another and in a device after a thermal cycle. This is a key demonstration of the use of machine learning techniques to explore and optimise the parameter space of quantum devices and address variability limitations.

P7. Strong coupling between superconducting circuit and ferromagnetic resonance model

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Strong-coupling between microwave photons and ferromagnetic resonance modes (magnons) tends to rely on bulk magnetic crystals, such as millimeter-scale yttrium iron garnet (YIG). We extend these experiments to lower volumes of magnetic material by exploiting low-impedance lumped-element microwave resonators. The low impedance equates to a smaller magnetic mode volume, which allows us to couple more strongly to a smaller number of ferromagnetic spins. Coupling this resonator to thin YIG films, we match the coupling rate of previous experiments, while reducing the number of participating spins by two orders of magnitude [1]. Extending our optimisation of microwave and magnon mode overlap to micro-patterned permalloy, we show the potential for this approach to sensitively investigate magnon and spin-orbit-torque driven dynamics in micromagnets.

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P8. RF sensing of quantum dots fabricated in a 300 mm MOS facility

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Electron spins in metal-oxide-semiconductor (MOS) quantum dots (QD) are promising candidates for scalable qubit architectures due to integrability with mature nano-fabrication methods.

We study MOS few-QD devices, where electrons are trapped electrostatically at the silicon/silicon-oxide interface. The devices are made on 300 mm wafers, using electron beam lithography combined with industrial grade processing methods, with multi-layer titanium nitride gates separated by gate oxide.

We employ radio-frequency (RF) gate reflectometry techniques for charge sensing. In particular, we employ either a fully surface mount component based LC resonator in series with the device [1], or a superconducting spiral inductor resonator in parallel with the device [2].

By mapping out charge diagrams with RF sensing, we characterize up to three-quantum-dot-arrays. In particular, we study the coupling between nearest and next to nearest neighbour quantum dots in the few electron regime. We characterize and thus compare sensitivity and operation in both types of sensor resonators. We also present preliminary results on reproducibility over devices.

Acknowledgements.

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) through the Centre for Doctoral Training in Delivering Quantum Technologies (EP/L015242/1) and QUES2T (EP/N015118/1).

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P9. Fast radio-frequency readout using an ultra-low-noise SQUID amplifier

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Spin qubits based on double quantum dot are promising candidates for quantum computing technologies thanks to their good integration in conventional electronic systems. The complexity arising from the high number of gates leads to long tuning procedures that are limited by the acquisition time of the device transport properties. Moreover, qubit operations require fast readout of their quantum state due to their short lifetime.

Gate reflectometry is a promising approach that combines short acquisition time to low device complexity. Acquisition time and readout fidelity can be largely improved by use of quantum limited cryogenic amplifiers. Here we perform gate reflectometry employing commercially available SQUID amplifier operating in the radiofrequency domain. This device provides about 10 dB additional gain in the amplification chain allowing us to measure a double quantum dot stability diagram in less than 20 ms.

P10. CMOS hole spin qubit readout by gate reflectometry

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The last period has witnessed many breakthroughs in the field of silicon-based spin qubits[1–3]. However, single holes spins in Si remain a barely explored hosting platform if compared to electron spin in quantum dots. Our team has shown that holes in Si transistors can be employed to encode quantum information[4]. Hole spins carry major advantages with respect to their electron counterparts; for instance, we expect long coherence times due to the absence of contact hyperfine interaction; also, strong spin-orbit coupling enables fast coherent spin rotations using a radio-frequency electric field[5]. In favour of a potential scalability of qubit devices, gate radio-frequency reflectometry[6] has been proposed as a competitive technique for spin readout as it involves a minimal hardware overhead at the qubit layer. In this poster, we show the implementation of gate reflectometry on a fully functional spin qubit device[7] consisting of a p-type double-gate transistor made using CMOS industry-standard silicon technology.

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