Poster Abstracts

In alphabetical order (last name)

Hybrid circuit QED with double quantum dots

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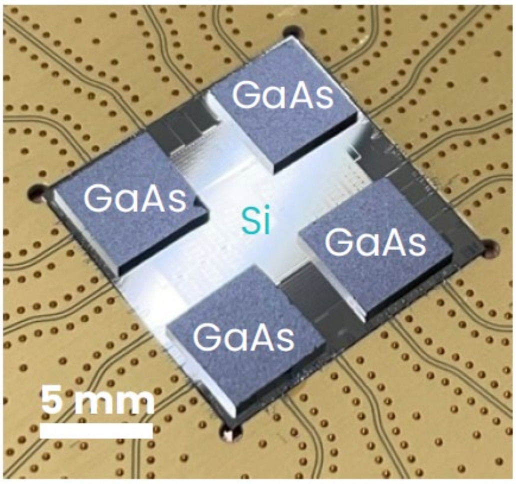
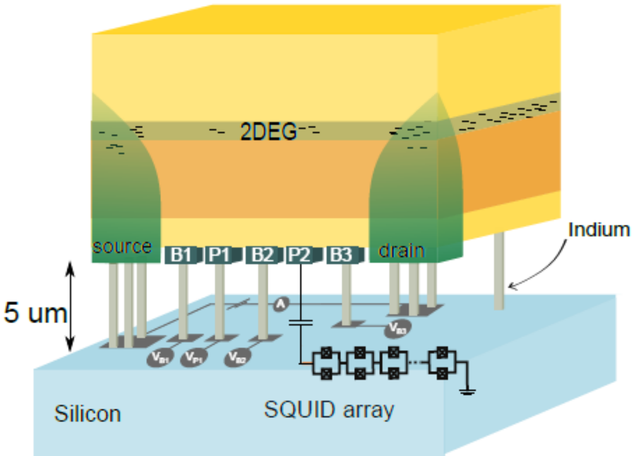
First steps towards the 3D integration of superconducting devices with semiconducting quantum dots have been taken. For this purpose, a process for realizing a metallic stack allowing galvanic contact between two chips via indium bump bonds has been established. The benefits of this technology include separate fabrication optimization, versatility on the semiconducting side, modular approach and scalability. Making using circuit QED techniques, we present an implementation for Transmon-assisted double quantum dot charge sensing. Using this technique, remote and scalable probing of DQDs would be possible.





Chip Packaging For Advanced Quantum Experiments

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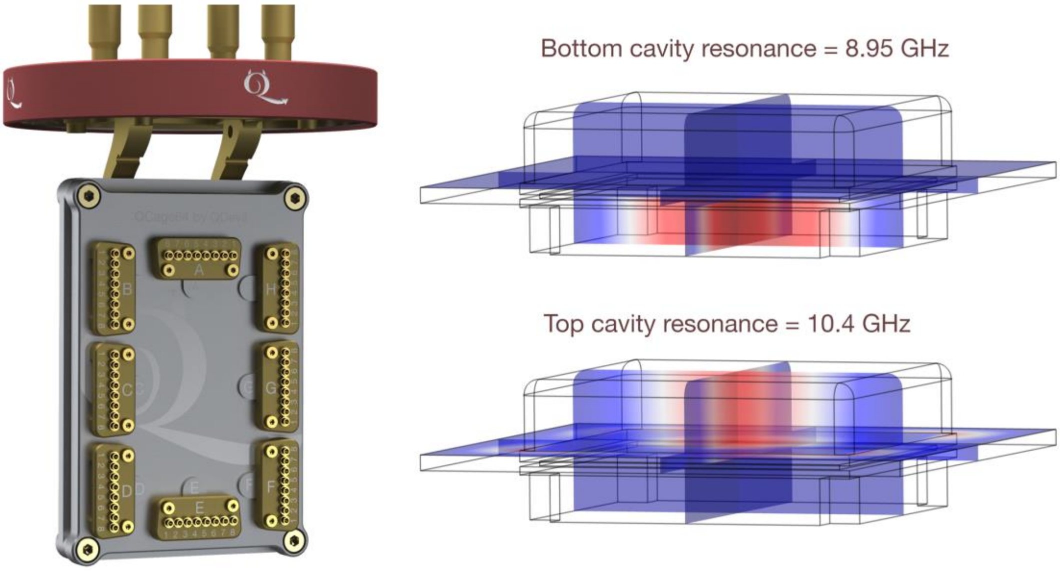
Highly advanced quantum nanodevices are nowadays being developed to explore the frontiers of condensed matter physics. Furthermore, the advent of the Noisy Intermediate-Scale Quantum (NISQ) hardware era is bolstering the demonstration of surface codes algorithms as well as quantum simulators [1,2]. The complexity of such state-of-the-art experiments requires interfacing quantum chips with the external world in a fully controllable environment. Avoiding impedance mismatching, electrical and magnetic noise as well as achieving complete thermalisation of the quantum chip are key ingredients for successful experiments. Concurrently, given the space constraints in dilution refrigerators, achieving high density I/O wirings while maintaining large bandwidth will be essential for the development of future NISQ as well as fault tolerant quantum computing processors.

QCage [3] is the latest addition to the Quantum Machines product family. This multi-qubit chip packaging solution has shown reflection levels below 30 dB in the 4 – 8 GHz frequency bandwidth while being characterized at 40 mK [4,5]. By knowing the transfer function, we simulated qubit gate fidelities with four orders of magnitude improvement compared to a non-optimized chip packaging solution (i.e., reflection values in the order of 15 dB) [5]. Furthermore, we developed a fully EMC tight assembly composed of layers of mu-metal and bulk aluminium. This additional shielding helps improve the magnetic and electrical insulation (particularly against high frequency radiation) while still offering ideal thermalisation of the quantum chip with a minimal time delay during the cooldown procedure.



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Induced p-wave pairing in the Al-InAs heterostructure

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We present a theoretical study of a 2D superconductor-semiconductor heterostructure consisting of Al and InAs layers subjected to a homogeneous magnetic field. Our model takes into account several factors, including the spin-orbit coupling in the InAs layer, superconductivity in the Al layer, hopping between layers, potential disorder, and both Zeeman and orbital contributions from the magnetic field. Using this model, we demonstrate the presence of induced p-wave pairing in InAs and calculate the total density of states of the heterostructure. Furthermore, we study the response of the superfluid density of the system.

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EDSR-mediated Silicon spin qubit control and spin-magnon coupling

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One of the challenges of building large scale spin-qubit based quantum processors is the coherent coupling between distant spins. In this poster, we will first present a method of controlling an electron spin qubit in a Silicon quantum dot using electric dipole spin resonance (EDSR) [1]. This is done by creating a magnetic field gradient in the plane of the spin using micromagnets. These gradients induce a spin-orbit coupling, thus allowing fully electrical spin manipulations [2].

A second step, we are currently developing, consists in exploiting the dynamics magnetization of such magnets to drive a spin qubit. The objective is to use the ferromagnetic resonance (FMR) of the magnets to mediate between the microwave field and the spin qubit. For this purpose, we will first characterize the FMR of similar micromagnets as the aforementioned experiment using a 2D microwave cavity and adapt the geometry to reach the best coupling.

Finally, if dipolar coupling is large enough we intend to explore if the spin-magnon strong coupling is reachable [3]. This, however, is dependent on having a low damping ferromagnet, with small, nm-scale dimensions capable of strongly concentrating the microwave field in a small volume and having long-lived magnons (decay rate of ~1 MHz). This a route to be explored, with materials such as $Fe_{75}Co_{25}$ [4] or vanadium alloyed iron [5].

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Crossed Andreev Coupling in Parallel InAs Nanowires

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Parallel InAs nanowires connected by an epitaxially grown superconductor (SC) shell recently became available to create hybrid nanostructures[1]. The defect-free SC-semiconductor interface and the vicinity of two quasi-one-dimensional channels can enhance the crossed Andreev reflection (CAR) between quantum dots (QD) formed in the separate wires. These properties allow high-efficient Cooper pair splitting (CPS)[2], can lead to the strong hybridization of the QDs resulting in an Andreev molecule[3], or create a SC island-semiconductor hybrid QD[4], which are milestones toward more exotic states, like Majorana or parafermions[5]. We demonstrate the experimental realization of CPS, Andreev molecule, and SC island-QD hybrid in different parallel nanowire-based nanocircuits (see Fig. 1). The CAR-mediated interaction between parallel QDs is characterized, while the electron transport in the CPS and Andreev limit is analyzed theoretically and matched to the measurements.

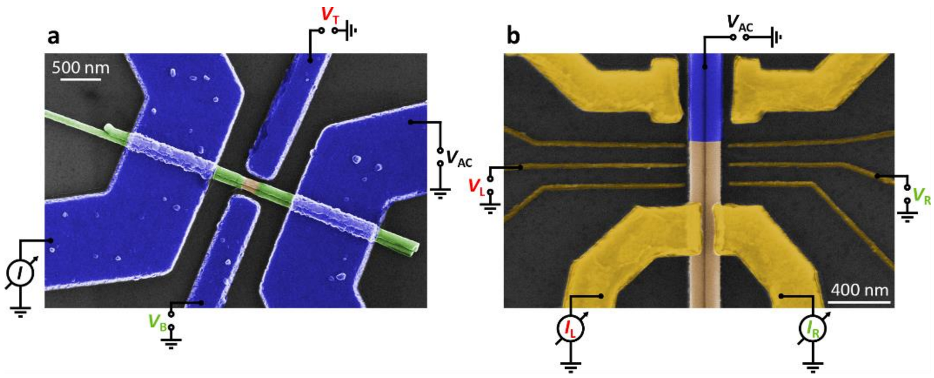

Fig. 1. Scanning electron micrographs of the devices in which **a** an Andreev molecule, **b** CPS were captured with strong capacitive (C) and superconducting coupling.

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Majorana-like Coulomb spectroscopy in the absence of zero bias peaks

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The search for Majorana zero modes in hybrid semiconductor-superconductor devices has been a topic of great interest in the field of topological quantum computing [1, 2, 3, 4]. Despite multiple claims of Majorana detection through tunneling or Coulomb blockade spectroscopy, these findings remain disputed. Our study [5] presents an experimental protocol that enables both types of measurement on a single hybrid island by adjusting its charging energy through tunable junctions to the normal leads. By checking the consistency between Coulomb blockade spectroscopy and zero-bias peaks in non-blockaded transport, this approach reduces ambiguities in Majorana detections. Specifically, we observed even-odd modulated, single-electron Coulomb blockade peaks in InAs/Al hybrid nanowires, without accompanying low-bias peaks in tunneling spectroscopy, which we theoretically interpreted as low-energy, longitudinally confined island states rather than overlapping Majorana modes. Our study emphasizes the importance of combined measurements on the same device for the reliable identification of topological Majorana zero modes.

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Hole spin qubits in Si and Ge quantum dots

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Hole nanostructures are frontrunner candidates to scale up quantum computers because of their large spin-orbit interactions (SOIs). Although these interactions directly couple the qubit to charge noise, hole spin qubits in Si FinFETs can be operated at sweet spots where this noise is completely removed [1].

We show theoretically that at these sweet spots the noise caused by hyperfine interactions, another critical source of noise in spin qubits, is suppressed, resulting in highly coherent qubits even in natural Si and Ge. The presence of these sweet spots could cut major manufacturing costs [2].

Also, the SOI can be engineered by the design of the dot [3-7]. For example, in planar Ge heterostructures, the SOI is cubic in momentum, resulting in relatively slow qubits. An anisotropic potential overcomes this limitation, enabling large linear SOI, and speeding up gates by two orders of magnitude [3].

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Fermionic-Bosonic Qubit

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We propose a novel superconducting circuit aiming at more robust quantum states, and featuring two distinct quantum degrees of freedom. It consists in the parallel combination of a large inductance, a capacitor and a quasi-ballistic single-channel weak link. The large inductance results in large fluctuations of the phase across the weak link. The weak link implements a Josephson coupling that depends on an internal fermionic degree of freedom associated with the Andreev level. The electromagnetic modes of the circuit depend on the fermionic occupation, leading to a "fermionic-bosonic" qubit.

We present preliminary calculations of the wave functions, the relaxation and dephasing rates due to noise in the external flux and weak link channel reflectivity. We find that in addition to having little dispersion and disjoint supports, the small energy difference between the states leads to a reduced effect of ohmic bathes on the relaxation indicating very promising coherent properties.

Germanium quantum wells for spin qubit applications

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In recent years, there has been an exponential rise in the interest with quantum computing. One among the numerous qubit realization schemes is the spin degree of freedom of electrons or holes in semiconductor quantum dots (QDs). [1], [2]

Hole spin qubits are created by electrostatically gating a 2DHG to define QDs with discrete energy levels, and the spin states are Zeeman-split by a magnetic field.

Germanium is the mainstream semiconductor with the highest p-type mobility: this is leading to a renewed interest in Ge as a material for applications beyond the dominance of silicon. Ge quantum wells (QWs), are attracting interest due to possible applications which benefit not only from the properties of the 2-dimensional hole gas (2DHG) formed in the Ge QWs, but from the compatibility of SiGe with Si-based growth and fabrication.

Moreover, holes in Germanium are particularly well-suited for qubit realization due to the strong spin-orbit coupling (SOC). The SOC enables spin-flip transitions to be induced by applying an oscillating lateral electric field, eliminating the need for a localized time-varying magnetic field. Additionally, since the most common isotopes of Si and Ge have spin-0, electron or hole spin dephasing is significantly reduced compared to III-V based systems, making Ge a promising candidate for quantum computing applications.

A Ge QW has been grown by a plasma-activated variant of chemical vapor deposition, LEPECVD (low-energy plasma-enhanced CVD) on a $Si_{0.3}Ge_{0.7}$ layer on virtual substrate with a linearly graded concentration profile from pure Si to $Si_{0.3}Ge_{0.7}$ as a buffer layer.

Electrical characterization measurements has been performed at low temperature (1.6-10 K) on Hall bar devices, both gated and ungated, in order to understand the effect of the Al_2O_3 oxide deposition and of the metallic gate on the carrier mobility as a function of sheet density, reaching a value higher than 100000 cm^2/Vs. An analysis of scattering mechanisms has been performed, and the percolation density, one of the most relevant figures of merit for qubit stability, has been measured with a value of around 10^{11} cm^{-2}. Shubnikov–de Haas (SdH) oscillations and quantum Hall effect were observed.

Finally, the Landau level lifetime, which corresponds to the quantum scattering lifetime, was extracted from SdH oscillations. This proved to be relatively high as compared to the momentum lifetime coming from mobility, which may help to explain the excellent results obtained by collaborating research groups which fabricated qubits on this material. [3]

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Characterizing superconductivity in full-shell Al/InAs nanowires

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In the past decade, hybrid superconductor-semiconductor nanostructures have attracted great attention as a promising platform for the search of topological superconductivity [1, 2] and for the development of hybrid superconducting qubits [3]. Recent progress in this field has been enabled by the development of growth methods that warrant a clean interface between superconductor and semiconductor, such as the epitaxial growth of superconductors onto InAs and InSb nanowires [4-6]. Among these cleaner crystals, hybrid InAs-Al wires have been developed first and have been, by far, explored the most. Despite the significant role that the superconducting shell plays in the above experiments, there are few works that fully characterize it [7]. In this work, we perform a detailed characterization of the superconductivity of the Al shell in full-shell Al/InAs nanowires. To this end, we employ DC transport to probe the resistance of the superconducting shell in different conditions of magnetic field and temperature, also in the Little-Parks regime, as well as in the presence of microwaves. Our results show a complex behavior which points towards the formation of normal regions in the superconducting shell for increasing temperature or perpendicular magnetic fields.

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Signatures of interacting Andreev bound states in hybrid three-terminal Josephson junctions

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Hybrid Josephson junctions with three or more superconducting terminals coupled to a semiconducting region are expected to exhibit a rich variety of phenomena [1-7]. Andreev bound states arising in such multiterminal devices have been predicted to form unconventional energy band structures, which can be engineered by controlling superconducting phase differences between the individual junctions.

Here we report on tunneling spectroscopy measurements in three-terminal Josephson junctions realized in a gate-tunable InAs/Al heterostructure [8]. The three terminals are connected to form two loops where phase differences are controlled independently. Signatures of hybridization between Andreev bound states are observed in the form of avoided crossings in the spectrum. Measurements are well explained by a numerical model of interacting Andreev bound states. Our results provide a demonstration of hybridizing bound states and novel band structure. Future extensions of the device geometry could focus on addressing spin-resolved energy levels, paving the way for Andreev spin qubits [9,10].

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Half-integer Shapiro steps in highly transmissive InSb nanoflag Josephson junctions

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We study a hybrid semi-super Josephson junction out of a InSb nanoflag with Nb contacts [1].

The high transparency of the superconductor-semiconductor interfaces enables ballistic transport by parallel short and long conduction channels.

Under microwave irradiation, half-integer Shapiro steps appear, as reported for other types of hybrid junctions [2, 3]; yet, our steps are remarkably robust to temperature and rf power, thus suggesting a non-equilibrium origin. The observed phenomenology is only partially captured by the adiabatic approximation in terms of a non-equilibrium current-phase relation.

On the one hand, we expect further theoretical developments to address such strong second harmonic supercurrents in ballistic, highly transparent hybrid junctions; on the other hand, future experiments could employ InSb nanoflag Josephson junctions for coherent manipulation of Andreev states.

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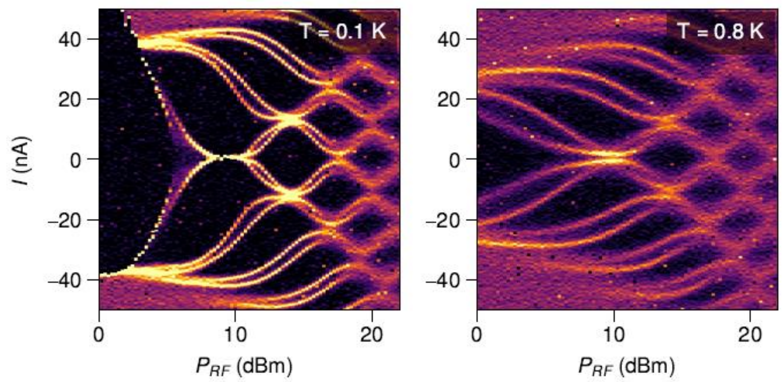

Variability in Si/SiO_2 and Si/SiGe Spin Qubits due to Interfacial Disorder

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Silicon is a particularly attractive material to host semiconductor spin qubits for quantum computation [1] because the fabrication processes are well established and the main isotope ^{28}Si is free of nuclear spins which may interact with the carrier spin via hyperfine interaction. In a spin qubit, the spin carrier is spatially confined in a semiconducting material that forms a quantum dot. The confining interfaces to adjacent regions play a crucial role in this context because they furthermore induce couplings to the carrier's valley and spin degree of freedom which are exploited to coherently drive spin transitions. In the most successful types of Si spin qubits, the spatial confinement is realized by interfaces to SiO_2 [2] or SiGe [3]. However, these interfaces are intrinsically disordered on an atomic scale, yielding detrimental variabilities of essential parameters such as the energy level splittings at the valence or conduction band edges of the semiconductor. Ultimately, this results in quantum decoherence since even basic operations like spin rotations cannot be carried out precisely. Distinct correction of the parameters of each device could quickly become a bottleneck, especially for applications like quantum computation, in which thousands of spins need to be controlled individually. While experimental evidence for significant variability in present Si spin qubits has been reported [4], a systematic theoretical investigation of this variability has not been conducted so far. However, a better theoretical understanding could provide valuable insights to improve the reproducibility of Si-based quantum devices.

In this work, we study the valley and spin splitting of conduction band electrons confined in explicit atomistic models of Si/SiO_2 and Si/SiGe nanostructures. Valley splitting results from interference effects between the Si *z* valley states at the interface, and spin splitting arises due to a relativistic interaction of the particle's spin with its motion along the inhomogeneous potential at the interface. Our realistic model structures [5] consist of a Si slab (2-7 nm thick) confined by amorphous SiO_2 or SiGe in the (100) direction. The splittings are obtained from density-functional theory (DFT) and tight-binding calculations. We explicitly compare qualitatively similar amorphous interfaces and show that the resulting valley and spin splittings inherently vary within one order of magnitude, emphasizing the relevance of interfacial disorder for quantum devices.

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Manhattan-style SIS tunnel junction fabrication for superconducting qubit

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Reliable and reproducible fabrication of Josephson tunnel junction is a crucial engineering task for producing superconducting circuits for quantum and other integrated circuit application. Here we report our recent efforts on fabricating Al-AlOx-Al tunnel junction using bridge-free manhattan technique and their application towards developing superconducting qubits. The manhattan fabrication technique has shown to produce lower scatter in wafer scale junction resistance variation compared to Dolan-Niemer shadow-angle evaporation technique [1]. Our technique includes cross-type junction electrode fabrication along with bandage step for preparing low resistance contact with the base metallization layer [2] inducing minimum damage to the subtrate wafer surface relevant for producing high coherence quantum circuits. We have achieved junction yield better than 90% in multiple fabrication iterations and room temperature resistance variation better than 15% in die scale fabrication and average T1 time ranging from 35-40 microsecond. We have also measured the aging of the junction through repeated room temperature resistance probing and measuring qubit transition frequency fluctuation over period of couple of months while qubit chip resting in atmospheric environment.

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Two-qubit logic between distant spin qubits in silicon

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Coupling spin qubits to microwave photons provides an elegant approach for mediating long-range spin-spin interactions. The circuit quantum electrodynamics (QED) framework enables two-qubit gates which can be used for on-chip quantum links. In previous work, resonant spin-spin-resonator coupling in a silicon quantum device was demonstrated [1]. Most two-qubit gate schemes require a spin-spin coupling in the dispersive regime that is larger than the spin dephasing rates, as was recently observed in spectroscopic measurements [2]. In this work, we probe such a dispersive spin-spin interaction in the time-domain and demonstrate a two-qubit gate between spin qubits in silicon separated by 250 µm.
We form a double quantum dot (DQD) in a ^{28}Si/SiGe heterostructure at each end of a 250 µm long high-impedance superconducting resonator [3]. We trap a single spin in each DQD, and we enable tunable spin-charge hybridization with micromagnets. Due to mitigation of microwave losses [4], we can tune the spin-charge hybridization to reach the strong-coupling regime with spin-photon couplings up to around $g_s/2\pi$ = 40 MHz. The readout is implemented by direct dispersive spin sensing using the same resonator, with the signal-to-noise ratio largely improved by a Josephson traveling-wave parametric amplifier [5].
We first show universal single-qubit control over two flopping-mode qubits [6] and characterize their coherence times. Next, we bring the two spins into resonance with each other, but detuned from the resonator photons, and observe exchange (iSWAP) oscillations between the two remote spins up to 17 MHz. This frequency is consistent with the spectroscopic measurements [2]. Furthermore, we demonstrate that the coupling strength (2J) as well as the coherence times of the qubits can be tuned by two knobs: the inter-dot tunnel coupling and the spin-cavity detuning. In future work we intend to implement single-shot readout and improve the spin lifetimes while dispersively coupled to the resonator. These results pave the way for scalable networks of spin qubits on a chip.

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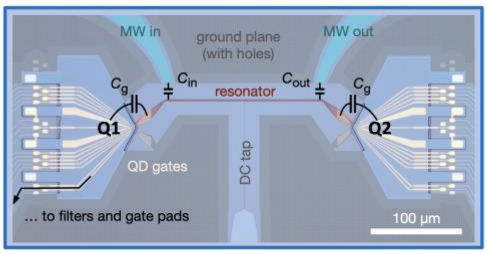

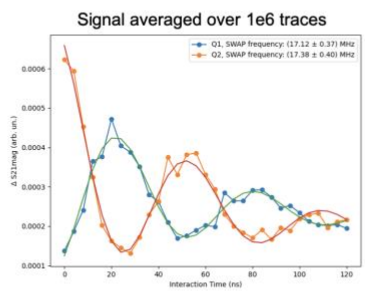

Design for an optomechanical microwave-to-optical transducer using bulk acoustic wave resonators

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A low-noise, efficient, bi-directional microwave-to-optical transducer could connect superconducting circuits in distant dilution refrigerators, offering a promising route towards powerful, large-scale quantum computers and networks. We present our advances in developing a device in which a Bulk Acoustic Wave (BAW) resonator mediates interactions between the microwave field of a transmon qubit and a telecom-frequency mode of a Fabry-Perot cavity [1,2].

In the development of such a transducer, several main challenges have to be overcome. First, the qubit, its readout resonator and the BAW resonator must fit within a ~1cm optical cavity, while maintaining the possibility to align the cavity and its inputs. Second, the detrimental effects of laser light on superconducting qubits must be well understood and mitigated. Third, to show low-noise transduction, we need sufficiently high generation rates of single transduced optical photons to perform a Hanbury-Brown-Twiss experiment in reasonable time. This poster will address how we tackle these challenges.

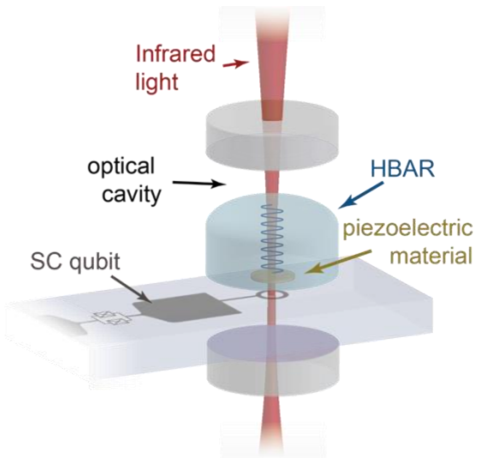

Figure 1. Schematic of a device transducing microwave signals from a superconducting (SC) qubit, via a high-overtone bulk acoustic wave resonator (HBAR) to optical photons.

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Electrically controlled spin mechanical coupling in a carbon nanotube resonator

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Coupling of a quantum system like a single spin to a mechanical resonator has many interesting applications in classical and quantum information processing, as well as sensing, long-distance spin-spin coupling, and investigating motion at the quantum limit. We report on the first realization of spin mechanical coupling on a fully suspended carbon nanotube resonator. Strong spin-orbit interaction allows both the coherent manipulation of a single electron spin and mediates the coupling between the spin and the nanotube motion. We observe both resonant and off-resonant coupling, as a shift and broadening of the electron dipole spin-resonance (EDSR)-frequency, respectively. We develop a complete theoretical model that matches the experimental data and provides a detailed understanding of the complex mechanisms at play. Our results demonstrate the potential of hybrid semiconductor circuits for applications requiring both mechanical and electric degrees of freedom on chip.

Microwave-induced conductance replicas in hybrid Josephson junctions without Floquet-Andreev states

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Light-matter interaction enables engineering of non-equilibrium quantum systems. In condensed matter, spatially and temporally cyclic Hamiltonians are expected to generate energy-periodic Floquet state, with properties inaccessible at thermal equilibrium [1-5]. A recent work explored the tunnelling conductance of a planar Josephson junction under microwave irradiation, and interpreted replicas of conductance features as evidence of steady Floquet-Andreev states [6]. Here we realise a similar device in a hybrid superconducting-semiconducting heterostructure [7], which utilises a tunnelling probe with gate-tunable transparency to simultaneously observe Andreev states and supercurrent. We show that, in our devices, spectral replicas in sub-gap conductance emerging under microwave irradiation are caused by photon assisted tunnelling [8-10] of electrons into Andreev states. The current-phase relation under microwave irradiation is also explained by the interaction of Andreev states with microwave photons, without the need to invoke Floquet states. For engineering and control of non-equilibrium quantum states of matter, it is of paramount importance to recognise the intricacies of mesoscopic systems. This study harnesses gate-tunable devices to build an understanding of light-matter coupling in hybrid nanostructures.

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Flip-chip-based microwave spectroscopy of Andreev bound states in a planar Josephson junction

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We demonstrate a flip-chip-based approach to microwave measurements of Andreev bound states in a gate-tunable planar Josephson junction using inductively-coupled superconducting low-loss resonators. By means of electrostatic gating, we present control of both the density and transmission of Andreev bound states. Phase biasing of the device shifted the resonator frequency, consistent with the modulation of supercurrent in the junction. Two-tone spectroscopy measurements revealed an isolated Andreev bound state consistent with an average induced superconducting gap of 184 μeV and a gate-tunable transmission approaching 0.98. Our results represent the feasibility of using the flip-chip technique to address and study Andreev bound states in planar Josephson junctions, and they give a promising path towards microwave applications with superconductor-semiconductor two-dimensional materials [1].

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cQED with grAl and hole spins in planar Ge

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Hole spins enable fast and all-electric control [1], due to strong intrinsic spin-orbit interaction (SOI). Since the SOI also couples spins to the electric field of a photon in a microwave resonator, strong hole-spin-photon coupling is expected. Recent experiment with holes in silicon indeed confirms this prediction [2], with the coupling largely exceeding the best figures reported with electrons [3, 4].

Here we report on hole double quantum dots (DQD) hosted in Ge/SiGe heterostructure coupled to a granular aluminum (grAl) resonator. grAl offers high kinetic inductance, magnetic field resilience and compatibility with multilayer lift-off based fabrication [5]. Assessing these properties, we demonstrate a resonator with a characteristic impedance of Z_0 ~ 13 kΩ (due to the large kinetic inductance of L_{kin} ~ 2 nH/sq) resilient to out of plane magnetic fields exceeding B_{perp} ~ 280 mT with $\kappa/2\pi < 5$ MHz, well suited for spin-photon coupling experiments. We will also present our recent results of integrating these resonators with germanium DQDs in a cQED architecture, which aims for long-range coupling of hole spin qubits.

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Coulomb drag in a 2x4 Ge quantum dot ladder device

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In the quest for a large scale quantum computer, near term applications of imperfect devices are a key ingredient to further push innovation [1]. A desirable feature of these systems is the capability to simulate small yet complex quantum systems. While digital quantum simulators are growing in size, the gate fidelities are not yet high enough to perform meaningful quantum simulations. On the other hand, analog quantum simulators might be able to operate with much larger error rates while still providing interesting insights into complicated many-body quantum systems beyond the capabilities of classical computers [2]. Among the available platforms, semiconductor quantum dots excel for their tunability, thermal energies smaller than other relevant energies in the system and the naturally-occurring long-range Coulomb interaction [3]. Combined with the possibility of global transport measurements, local spin and charge detection they are a unique platform for the exploration of exotic phases of matter and have already shown impressive results featuring Nagaoka ferromagnetism[4], collective Coulomb blockade [5] and topological many-body states[6]. Here we present the control of a 2x4 Ge quantum dot ladder device and explore the effect of Coulomb drag. We tune the device in the single charge regime with two separate channels: a drive and a drag channel. By monitoring the charge state of the array we are able to observe excitonic Coulomb drag upon varying the energy detuning of the drag channel while purposefully transferring a charge in the drive channel. Our work establishes quantum dot arrays as excellent prototypes for the exploration of exotic phases of matter governed by the Coulomb interaction.

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Modelling superconductor-semiconductor hybrid devices in Germanium

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Quantum experiments based on holes confined in Germanium heterostructures have rapidly developed in the last years due to a range of formidable properties. In two-dimensional hole gases, the small in-plane effective mass relaxes fabrication restraints, the strong spin-orbit coupling allows to electrically manipulate the hole-spins, while highly transparent interfaces to a range of superconductors make superconductor-semiconductor -hybrid devices viable[1]. Here, we develop theoretical models to exploit these properties for high-fidelity spin operations and long-range coupling via a superconductor.

While the spin-orbit coupling enables electric manipulation of the hole-spins, it also makes them susceptible to charge noise. Here, we study decoherence free sweet spots in the electric field dependence of the hole g-factor in harmonic quantum dots.

In a hybrid device with a superconductor coupled to two spatially separated quantum dots, Cooper-pairs can be split via crossed Andreev reflections. This allows for long-range spin-coupling[2] or the implement a of the parity qubit[3]. We study how this setup is modified in a hole system, where spin-orbit is present, and the superconductor-semiconductor interface needs better understanding.

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Spins in Cryogenic Crystals

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Hybrid quantum systems, which leverage spin ensembles and superconducting resonators have been a fruitful platform for studying different sciences ranging from quantum physics[1] and information[2], spin-spin systems[3], to quantum sensing[4]. Here, we demonstrate a novel platform which couples superconducting resonators to cryogenic crystals (solid hydrogen, Ne, Ar,…) doped with alkali atoms (Rb, Na, Cs,...). Alkali atoms have hyperfine transitions conveniently in the GHz regime, while the noble gas crystals offer a soft, inert matrix which effectively preserves the atomic properties[5,6,7]. We have achieved strong coupling between the doped atoms and the resonator cavity, as well as report on various parameters such as ensemble line-widths, T1 times, etc…

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Protocol to measure the non-Abelian Berry phase by pumping a spin qubit through a quantum-dot loop

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A quantum system constrained to a degenerate energy eigenspace can undergo a nontrival time evolution upon adiabatic driving, described by a non-Abelian Berry phase [1]. This type of dynamics may provide logical gates in quantum computing that are robust against timing errors [2]. A strong candidate to realize such holonomic quantum gates is an electron or hole spin qubit trapped in a spin-orbit-coupled semiconductor, whose twofold Kramers degeneracy is protected by time-reversal symmetry [3-4]. Here, we propose and quantitatively analyze a protocol to measure the non-Abelian Berry phase by pumping a spin qubit through a loop of quantum dots. A modified version of the protocol allows to characterize to local internal Zeeman field directions in the dots of the loop. The elements of the protocols have all been demonstrated in spin qubit experiments.

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20/03/2023

Coherent coupling of two distant Andreev level qubits

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Andreev qubits are an emerging platform for quantum computation. These qubits utilize the discrete superconducting quasiparticle levels (Andreev levels) that appear in weak links between superconductors. The Andreev qubits combine the scalability of the superconducting circuits and a compact footprint. Until now, the experiments on Andreev qubits [1] and Andreev spin qubits [2] have focused on the manipulation and readout of single qubits. However, realizing universal quantum computation based on Andreev qubits requires connectivity between pairs of Andreev qubits that enables implementation of two-qubit gates.

Here, we experimentally study Andreev qubits in InAs nanowires with epitaxial Al. We demonstrate for the first time a non-local interaction over millimeter distance of two Andreev pair qubits, mediated by a novel microwave cavity architecture. This architecture is based on a molecular state resonator, that minimizes microwave leakage from the antisymmetric coupling mode to the readout circuit, but allows fast readout via the symmetric mode. We have observed parity switching in both qubits and, more importantly, Andreev state entanglement in the even parity case, paving the way for distant two-qubit gates based on Andreev qubits. We additionally demonstrate that the symmetry of the coupling mode is reflected in the symmetry of the entangled two-qubit state.

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Phase-Tunable Cooper pair splitter

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We study Cooper-pair splitting (CPS) in a three-terminal device implemented in an InSbAs two-dimensional electron gas. The device consists of two quantum dots coupled via a Josephson junction (JJ). The dots act as charge and energy filters and allow us to select between two non-local processes: CPS or elastic co-tunnelling (ECT). The junction is embedded in a superconducting loop, thus allowing us to control the phase difference across the JJ with an applied flux. Tuning the device in the CPS-only allowed regime, we demonstrate that the non-local current depends periodically on the flux through the loop. The periodicity is consistent with the flux-dependent modulation of the Andreev bound state (ABS) energy, extracted from tunnelling spectroscopy measurements. This work demonstrates that the CPS amplitude is directly linked to virtual processes mediated by ABSs. Moreover, such a device could be used a flux-controlled source of entangled electrons.

Spin Qubits Variability: Origin, Quantification and Implications

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Semiconductor spin qubits may show significant device-to-device variability in the presence of spin-orbit coupling mechanisms. Interface roughness, charge traps, layout or process inhomogeneities indeed shape the real space wave functions, hence the spin properties. It is, therefore, important to understand how reproducible the qubits can be in order to assess strategies to cope with variability, and to set constraints on the quality of materials and fabrication.

We have quantified the induced variability for electrons and holes in Si MOS devices, and for holes in Ge/SiGe devices. We explore its impact on single-qubit properties (Larmor and Rabi frequencies), and on the two-qubit properties (tunnel coupling). We show that, in Si MOS devices, the defective nature of SiO_2 and the proximity of the charge defects to the quantum dots may yield to very heterogeneous qubit arrays. For hole qubits in Germanium, the epitaxial interfaces ensure a low level of electrical disorder in the qubits vicinities, and we consistently recover much more homogeneous quantum dots. Nonetheless, the small in-plane *g* factors and the particular mechanisms driving the spin rotations [3] still leave a non-negligible variability on the spin properties of the Ge qubits.

We finally discuss the implications of variability on the performance of an eventual mid- or large-scale quantum processor, where constraints on the number of DC and AC lines may jeopardize its operation. We show that a large Larmor frequency variability may compromise the addressability of some qubits, and a variability on the Rabi frequencies decreases the number of operations one can realize with the processor before encountering an error. Overall, a large scattering of the qubit properties complicates the scalability of spin qubits and the implementation of shared-control gate architectures.

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Superconductivity from a melted insulator

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Chains of Josephson junctions are model quantum many-body systems which can be driven through a superconductor-insulator transition. In previous experiments, nominally insulating Josephson chains have displayed superconducting behaviour. This superconductivity, though not understood, is essential for technologies such as quantum-limited amplifiers and inductively shunted qubits.

We resolve the nature of superconductivity in Josephson chains by extensively comparing transport and circuit quantum electrodynamics measurements. Analysing observed scaling behaviour in transport with constraints from microwave measurements, we find that apparent superconductivity is in fact the high-temperature fate of a melted insulator.

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Manipulation of a carbon nanotube qubit in a circuit QED architecture

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We investigate a carbon nanotube double quantum dot (DQD) with ferromagnetic contacts in a microwave cavity. Such a scheme has been shown to yield a large spin-photon coupling thanks to hybridization of spin and orbital degrees of freedom. We identify isolated internal transitions of the DQD which exhibit expected features such as power broadening and the AC-Stark shift. In the time domain, we perform Rabi oscillations by adressing the DQD transition through the cavity at 280 mK and at zero external magnetic field. These results are promising for the use of spin-photon interfaces in carbon based qubits.

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Coherent spin-photon control and multi-photon processes-like features in Si double quantum dot.

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Spins in semiconductor quantum dots constitute a promising platform for scalable quantum information processing [1]. Coupling them strongly to the photonic modes of superconducting microwave resonators would enable fast non-demolition readout and long-range, on-chip connectivity, well beyond nearest-neighbor quantum interactions [2]. Previous work in our team demonstrated spin-photon coupling rate as high as 330 MHz largely exceeding the decoherence rate of the spin, opening a path towards hybrid spin circuit quantum electrodynamics [3]. Here we present first results on coherent control of the spin state paired with dispersive readout through a resonator. In addition, multi-photon processes are spectroscopically investigated. [4]

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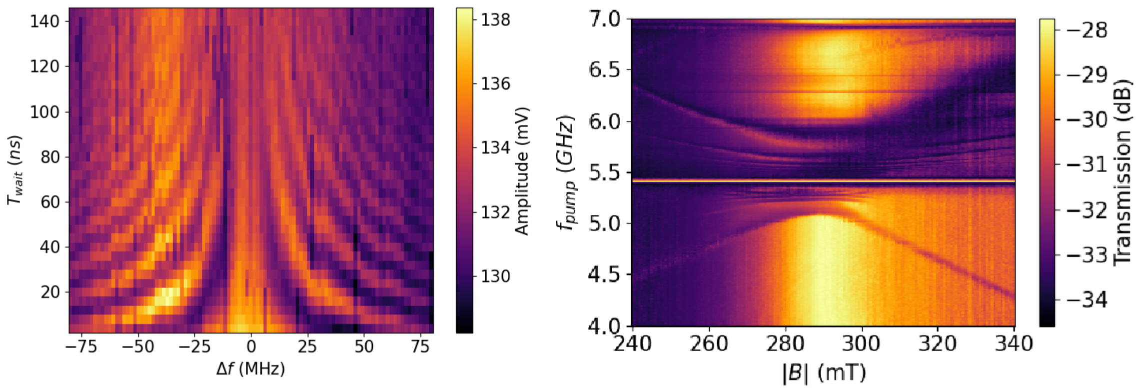

High-impedance technology for hybrid semiconductor-superconductor platforms

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Typically, spin-spin interaction is short-range, which limits the scaling capabilities of gate-defined quantum dots (QDs)-based architectures. Combining semiconductor QDs with superconducting resonators in a circuit QED framework can be a promising strategy to overcome this issue [1]. In fact, in circuit QED experiments, a qubit is coupled to microwave photons stored in a superconducting resonator. Nevertheless, this coupling is usually low due to the small dipole moment of electrons (or holes) confined in QDs. One way to improve the coupling strength is to increase the impedance of the resonator. High-impedance resonators can be realized by using arrays of Josephson Junctions [2] or, alternatively, leveraging of the high kinetic inductance of disordered superconductors, like NbN, NbTiN or granular Al [3]. The latter provide a promising alternative, as they are usually much more resilient to magnetic fields.
In this work, we first characterize high-impedance resonators on a Ge/SiGe heterostructure, showing that Q_is of ~ 1000 – 5000 are achievable. Then, we demonstrate charge-photon coupling between a hole charge qubit defined in a double QD (DQD) and a SQUID array resonator. The coupling manifests in a shift of the cavity frequency due to the dispersive interaction with the qubit far detuned from the resonator. Moreover, charge stability diagrams of the DQD can be completely mapped probing the change in transmission through the resonator in correspondence of a hole tunneling event.

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Single microwave photon detector : A previous design and its improvement

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Single microwave photon detection can be achieved by using a transmon qubit : Reading the qubit in its excited state means that a photon has been detected, whereas reading the qubit in its ground state means that no photon has been detected. The detection process, say the excitation of the qubit by the impinging microwave photon, is based on a four-wave-mixing process. The design itself is based on dissipation engineering, coupling other resonators and a pump line with the transmon qubit. The second generation of Single Microwave Photon Detector (SMPD) has been already used for single spin detection (with success) and axion detection (as a proof of principle). The performances of the SMPD are evaluated with two figures of merit : its dark count rate or rate of false positive measurements, which shall be as low as possible, and its efficiency or percentage of measurements where the impinging photon has not been missed, which shall be as high as possible. Making those two figures of merit better is the key to obtain a more sensitive detector. It has been noticed that the main contribution to the dark count rate on the second generation of SMPD was the thermal population of the input line. Therefore, a third generation of SMPD with a tunable bandwidth ability has been designed and is currently being tested.

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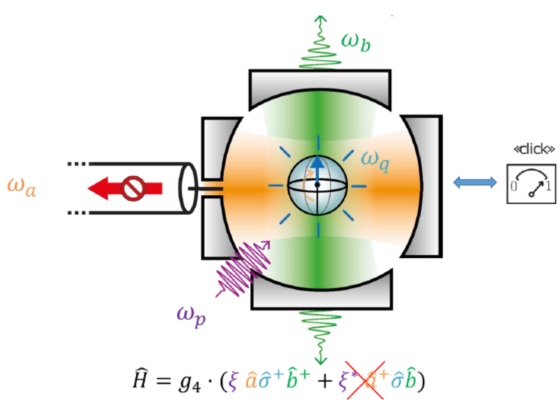

Strong coupling between a microwave photon and a singlet-triplet qubit

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Spin qubits offer a promising approach towards scalable quantum computing due to their long coherence time, small size, and fast gate operation times [1]. The combination with circuit quantum-electrodynamics could enable interconnectivity between distant qubits by using superconducting resonators as quantum buses, as is standard for superconducting qubits [2]. A promising way to couple the spin degree of a qubit to microwave photons of a superconducting resonator is by exploiting electron-dipole spin resonance which relies on spin-orbit interaction. This simplifies the devices architecture, since it does not require micromagnets [3-5].

In contrast to previous work, we are making use of the *intrinsic* spin-orbit interaction of zincblende InAs nanowires (NW) [6]. We use NWs that contain a built-in crystal-phase defined double quantum dot (DQD), where the tunnel barriers are grown in wurtzite crystal structure [7]. The DQD is coupled to a high quality, magnetic field resilient resonator [8]. To maximize the photon-qubit interaction [9] we use a high-impedance resonator with an impedance of ~2 kΩ. We investigate the hybrid DQD-resonator system and observe the formation of a singlet-triplet qubit. We reach the strong coupling limit between the singlet-triplet qubit and a single photon stored in the resonator.

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Compiling the surface code to a crossbar spin qubit architecture

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Spin qubits in quantum dots provide a promising platform for realizing large-scale quantum processors since they have a small characteristic size (10-100 nm) [1] compared to superconducting qubits (100 microns) [2]. They also have long coherence times, high-fidelity universal quantum control and the capability of high-temperature operation. One difficulty of having e.g. a few thousand qubits on a single chip is a large number of control lines: this number scales linearly with the qubit count. A crossbar control architecture was proposed to overcome this issue, where the number of control lines scales as the square root of the qubit count [3, 4]. In this poster, we present the compilation of the surface code error detection cycle to the crossbar architecture. We decompose the quantum circuit of the Z and X stabilizer measurements in terms of the native gates of the spin qubit architecture. We also construct a gate voltage pulse sequence protocol for the error detection cycles. During this protocol, coherent phase errors can occur on idle qubits, due to the built-in constraints of the crossbar architecture. For some of these errors, we devise mitigation strategies based on the dynamical fine-tuning of the on-site energies. Our results can be used in the design of near-term qubit experiments using the crossbar architecture.

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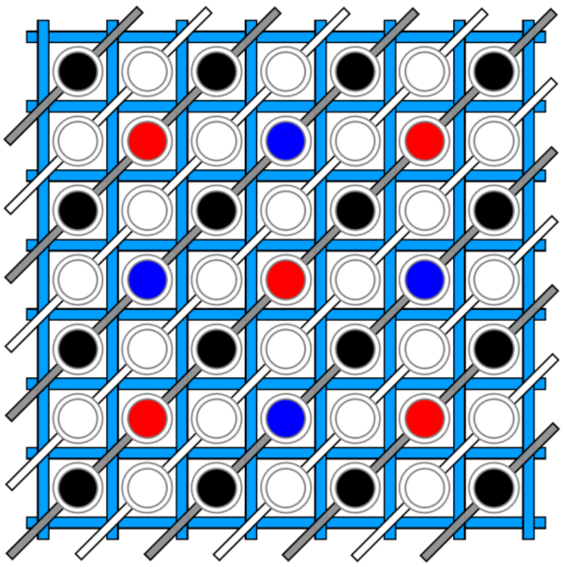

Operational Sweet Spot of Hole Spin Qubit

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We demonstrate an operational sweet spot for a Ge/Si core/shell nanowire hole spin qubit, for which both Rabi frequency and spin echo coherence times show a maximum. This sweet spot is related to the optimal operation point theoretically predicted for hole spins in the group IV crystals [1]. To find this sweet spot we studied the dependence of the g-factor, its first derivative with respect to the gate voltage, Rabi frequency, and coherence time as a function of the barrier gate voltages of the double quantum dot. We show that the EDSR drive is a dominant spin rotation mechanism, while rotations induced by the g-tensor modulation show qualitatively different voltage dependences. Fitting measured data to a simple model [2] we were able to extract the intrinsic g-factor and estimate the spin-orbit length of the nanowire.

We also found a charge configuration of the double dot for which both spins can be individually addressed by two different microwave frequencies. Tuning the interdot tunnel barrier allowed us to operate the device in a regime with the exchange coupling changing from 50 MHz to 200 MHz for different double dot detunings paving the way to perform the exchange-based two-qubit operations.

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A Microscopic Model of a Quantum Dot Embedded in a Transmon

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Transmons can be made controllable by embedding a quantum dot within the Josephson junction. This exploits the full microscopic degrees of freedom by coupling the excitations of the QD level to the transport of Cooper pairs across the junction.

Modelling both the quantum dot and Josephson physics coherently is not possible with standard methods. The main problem is the charging energy in the superconductors.

We present a flat-band, charge conserving model that accounts for the quantum dot physics, superconducting charging energy and phase dynamics in the Josephson junction. It can be diagonalised exactly, allowing for time evolution and non-equilibrium calculations.

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Gate-tunable, superconductor-semiconductor parametric amplifier

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We have built a parametric amplifier with a Josephson field effect transistor (JoFET) as the active element embedded within a half-wave coplanar transmission line resonator. The JoFET has been fabricated from an aluminum-indium arsenide superconductor-semiconductor heterostructure with a controlling top gate. The device's resonant frequency is field-effect tunable over a range of 2 GHz. The JoFET amplifier has 20 dB of gain, 4 MHz of instantaneous bandwidth, and a 1 dB compression point of -125.5 dBm when operated at a fixed resonance frequency.

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Direct manipulation of a superconducting spin qubit strongly coupled to a transmon qubit

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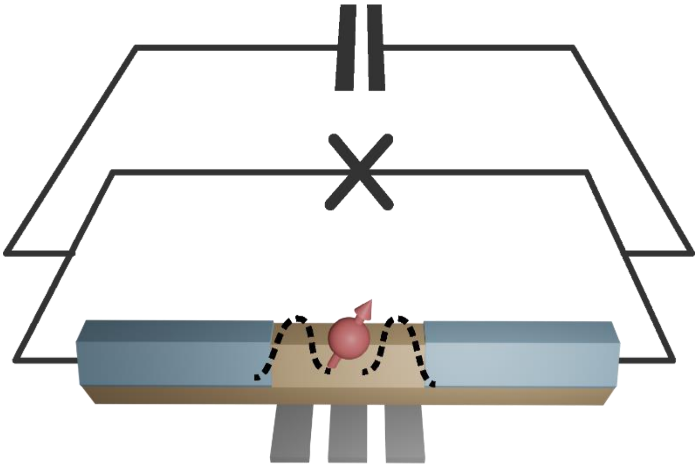
Spin qubits in semiconductors are currently one of the most promising architectures for quantum computing. However, they face challenges in realizing multi-qubit interactions over extended distances. Superconducting spin qubits (or Andreev spin qubits) provide a promising alternative by encoding a qubit in the spin degree of freedom of an Andreev level. This poster presents our recent results[1,2,3] on the implementation of an InAs/Al nanowire-based Andreev spin qubit. We encode the qubit in the spin-split doublet ground state of an electrostatically-defined quantum dot Josephson junction with large charging energy. Additionally, we use a magnetic field to enable direct spin manipulation over a frequency range of 10 GHz. Using an all-electric microwave drive we achieve Rabi frequencies exceeding 200 MHz. We furthermore embed the Andreev spin qubit in a superconducting transmon qubit, demonstrating strong coherent qubit-qubit coupling. These results are a crucial step towards a hybrid architecture that combines the beneficial aspects of both superconducting and semiconductor qubits.



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Longitudinal coupling between electrically driven spin-qubits and a resonator

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At the core of the semiconducting spin qubits success is the ability to manipulate them electrically, enabled by the spin-orbit interactions. However, most implementations require external magnetic fields to define the spin qubit, which in turn activate various charge noise mechanisms. Here we study spin qubits confined in quantum dots at zero magnetic fields, that are driven periodically by electrical fields and are coupled to a microwave resonator. Using Floquet theory, we identify a well-defined Floquet spin-qubit originating from the lowest degenerate spin states in the absence of driving. We find both transverse and longitudinal couplings between the Floquet spin qubit and the resonator, which can be selectively activated by modifying the driving frequency. We show how these couplings can facilitate fast qubit readout and the implementation of a two-qubit CPHASE gate. Finally, we use adiabatic perturbation theory to demonstrate that the spin-photon couplings originate from the non-Abelian geometry of states endowed by the spin-orbit interactions, rendering these findings general and applicable to a wide range of solid-state spin qubits.

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Flux-Tunable Hybridization in a Double Quantum Dot Interferometer

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Tuning the hybridization between fermionic modes with magnetic flux to distinguish parity states is crucial for topological quantum computation [1,2]. We demonstrate tuning of the tunnel coupling between two such modes with flux, implemented in a phase-coherent loop comprising two quantum dots in an InSbAs two-dimensional electron gas. Using reflectometry at radio frequencies on the dots' plunger gate electrodes, we extract the inter-dot tunnel coupling as a function of flux through the loop, observing oscillations of the coupling with a periodicity of a flux quantum across numerous inter-dot charge transitions. This is found to be consistent with reflectometry measurements of the Aharonov-Bohm effect in the open loop measured with the tunnel barriers lowered. Next, in different tunnel coupling regimes we benchmark the contrast of these hybridization oscillations, observing that they vary depending on the modes involved, but are generally not suppressed at their minima. These results establish the feasibility and contrast limitations of conducting parity readout of hybrid qubits with tunnel couplings tuned by flux.

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Hole spin manipulation in inhomogenous and non-separable fields

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The usual models for electrical spin manipulation in semiconductor quantum dots assume that the confinement potential is separable in the three spatial dimensions and that the AC drive field is homogeneous. However, the electric field induced by the gates in quantum dot devices is not fully separable and displays significant inhomogeneities. Here, we address the electrical manipulation of hole spins in semiconductor heterostructures subject to inhomogeneous vertical electric fields and/or in-plane AC electric fields.

We consider Ge quantum dots electrically confined in a Ge/GeSi quantum well as an illustration. We show that the lack of separability between the vertical and in-plane motions of the hole gives rise to an additional spin-orbit coupling mechanism (beyond the usual linear and cubic in momentum Rashba terms) that modulates the principal axes of the hole gyromagnetic g-matrix. This non-separability mechanism can be of the same order of magnitude as Rashba-type interactions and enables spin manipulation when the magnetic field is applied in the plane of the heterostructure even when the dot is symmetric (disk-shaped) [1]. More generally, we show that Rabi oscillations in strongly patterned electric fields harness a variety of g-factor modulations mediated by the deformations of the dot during its motion in a process known as g-tensor modulation resonance (g-TMR) [4].

This collection of g-TMR-like mechanisms shall play a role in forefront experiments in germanium [2, 3]. Their fingerprints could actually be revealed in a complete experimental map of the Rabi frequencies as a function of the orientation of the magnetic field [4]. We discuss the implications for designing and modeling such devices and the underlying physical mechanisms at play.

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Hybrid circuit QED with graphene quantum dots

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Graphene is an increasingly promising host material for spins because its naturally low nuclear spin density and its weak spin-orbit coupling promise long coherence times. A tunable bandgap in bilayer graphene allows to electrostatically define quantum dots (QD) with well controlled ambipolar operation in the single hole or electron regime. Even though the technology is still new, notable advances towards spin qubits in graphene have been made, including the better understanding of individual quantum states [1,2] as well as the demonstration of important primitives such as Pauli spin and valley blockade [3]. Long spin (valley) relaxation times of up to 50 ms (500 ms) have been measured recently with Elzerman readout using a nearby quantum dot as a charge detector [4,5]. It is expected that faster charge sensing with higher fidelity can be achieved by dispersively coupling charge carriers in a double QD to microwave photons in a superconducting resonator [6,7].

Here we report on progress towards integrating graphene QD devices with on-chip superconducting microwave resonators in a hybrid circuit QED architecture. We outline our main advances in design and fabrication of graphene-based hybrid devices and show first proof-of-principle measurements of dispersive charge sensing with microwave resonators.

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Towards a depletion mode single-hole spin qubit in Ge

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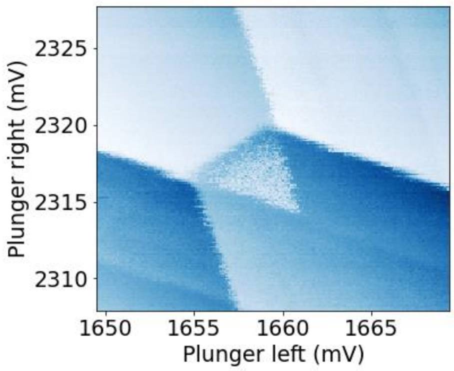
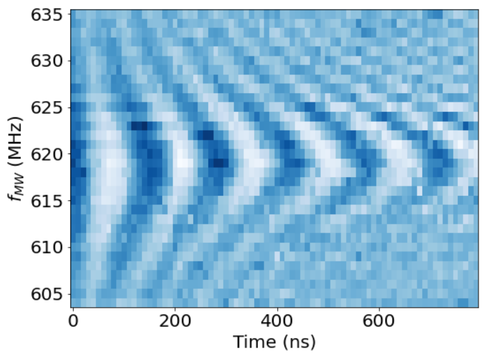
Group IV spin qubits are promising candidates for the realization of quantum processors due to their scalability, CMOS compatibility and long coherence times. In particular, Ge has become a very attractive platform because of the low effective mass and strong spin orbit interaction, which allows electrically driven spin qubits. From 2018 and within just three years a Loss-DiVincenzo (LD) [1], a singlet-triplet hole spin qubit [2], two-qubit gate devices [3] and a four-qubit Ge quantum processor [4] have been realized demonstrating the potential of Ge for quantum information [5]. Here we show our progress towards a depletion mode single-hole spin qubit in a Ge/SiGe heterostructure platform.





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Strong nonlocal tuning of the current-phase relation of an Andreev molecule

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Recent advances in hybrid superconducting – semiconducting structures allows for well-controlled fabrication of complex nanodevices. Placing two Josephson junctions next to each other, closer than the superconducting coherence length, the Andreev bound states hybridize into an Andreev molecular state. Here we investigate the scenario where the Josephson junctions are formed of a quantum dot. Similar molecular states were theoretically investigated in ballistic channels, in the absence of electron-electron interactions, where the non-local tunability of the supercurrent was argued [1-2]. In quantum dots, the presence of the Coulomb interaction and the possibility of electrostatic gating allows for a more versatile tunability. First of all, doublet ground states are only possible with finite Coulomb interactions.

In this contribution we discuss how the molecular state is formed and how the supercurrent of a given junction is affected by the control parameters of the other junction, namely the level position and the superconducting phase difference. Besides the usual parity driven 0-π transition we identified 0 and π regions within the same ground state. We demonstrate a large, strongly tunable φ0 phase in the absence of spin-orbit interaction. Furthermore exotic current phase relations and superconducting diode effect are discussed. The non-local tunability of these effects are the smoking gun features of the Andreev molecular state. This work opens the way of a better understading of complex hybrid devices.

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Identifying Pauli spin blockade using deep learning

Jonas Schuff[1], Dominic T. Lennon[1], Simon Geyer[2], David L. Craig[1], Federico Fedele[1], Florian Vigneau[1], Leon C. Camenzind[2], Andreas V. Kuhlmann[2], G. Andrew D. Briggs[1], Dominik M. Zumbühl[2], Dino Sejdinovic[3], and Natalia Ares[4]

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Pauli spin blockade (PSB) can be employed as a great resource for spin qubit initialisation and readout even at elevated temperatures but it can be difficult to identify. We present a machine learning algorithm capable of automatically identifying PSB using charge transport measurements. The scarcity of PSB data is circumvented by training the algorithm with simulated data and by using cross-device validation. We demonstrate our approach on a silicon field-effect transistor device and report an accuracy of 96% on different test devices, giving evidence that the approach is robust to device variability. Our algorithm, an essential step for realising fully automatic qubit tuning, is expected to be employable across all types of quantum dot devices.

Magic magnetic-field directions of spin-orbit coupled double quantum dot

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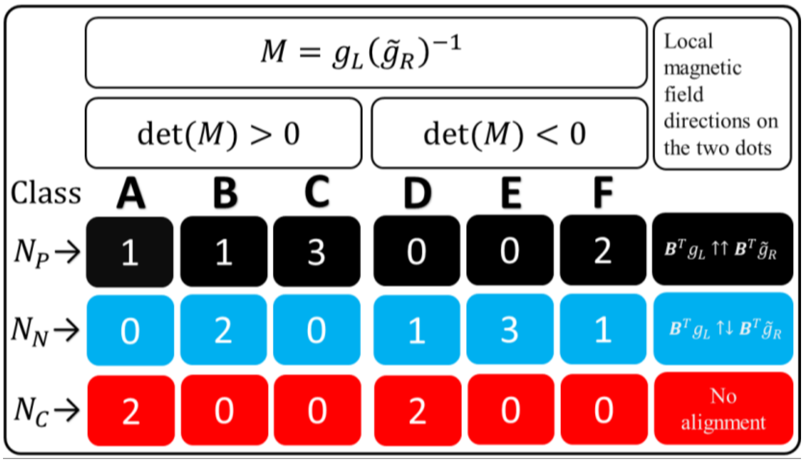

Fundamental building blocks of spin-based quantum computing have been demonstrated in double quantum dots (DQDs) with spin-orbit coupling. Here, we show that spin-orbit coupled DQDs can in general be categorized in six classes according to partitioning of the space of their g-tensors. We predict that spin physics is particularly simple if the external field is pointing to $n \in \{0,1,2,3\}$ special directions ('magic directions'), where the number n is determined by the class. Orienting the magnetic field to one of the magic directions prompts spectral degeneracies which is beneficial as relaxation sweet spot, for high-fidelity shuttling, suppressed Pauli blockade leakage current and suppressed quantum capacitance.

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Tuneable impedance environment for quantum phase slip experiments

Jorden Senior[1], Heorhii Bohuslavskyi[1], Janne Lehtinen[2], Joel Hätinen[1], Alberto Ronzani[1], Pranauv Selvasundaram[2], Emma Mykkänen[1], Robab Najafi Jabdaraghi[2], Sara Pourjamal[1], Mika Prunnila[1], and Antti Kemppinen[1]
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Tunneling of magnetic vortices through a thin superconducting nanowire, i.e. quantum phase slips (QPS), can cause an insulating transition instead of the typical zero resistance state. This phenomenon is dual to Cooper pair tunneling in a Josephson junction with quantum conjugate variables phase and charge exchanged. Thus, in analogy with the Josephson voltage standard yielding an ultra-precise frequency-to-voltage conversion [1], the QPS nanowire may allow a very precise quantum current standard. However, even though the experimental realization of coherent QPS was reported [2], and weak reverse Shapiro effect-like features in superconducting nanowires observed in [3,4], more observations have been elusive, and only recently started to materialize [5,6].

We have developed an mK-temperature-operational silicon MOSFET platform [7] to be used as an integrated tunable impedance environment for ultra-thin TiN and NbN superconducting nanowires. Our goal is to provide experimental data and theoretical models for the fundamental understanding of the QPS effect and to study the impact of geometric and material inhomogeneity, charge disorder and noise [8].

Recently, we have begun validation of the platform by embedding a Josephson junction in the tunable environment, observing the evolution of the Coulumb blockade across the junction by gate-tuning the environment across the resistance quantum threshold.

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Acknowledgements:

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Majorana-Magnon Interactions in Topological Shiba Chains

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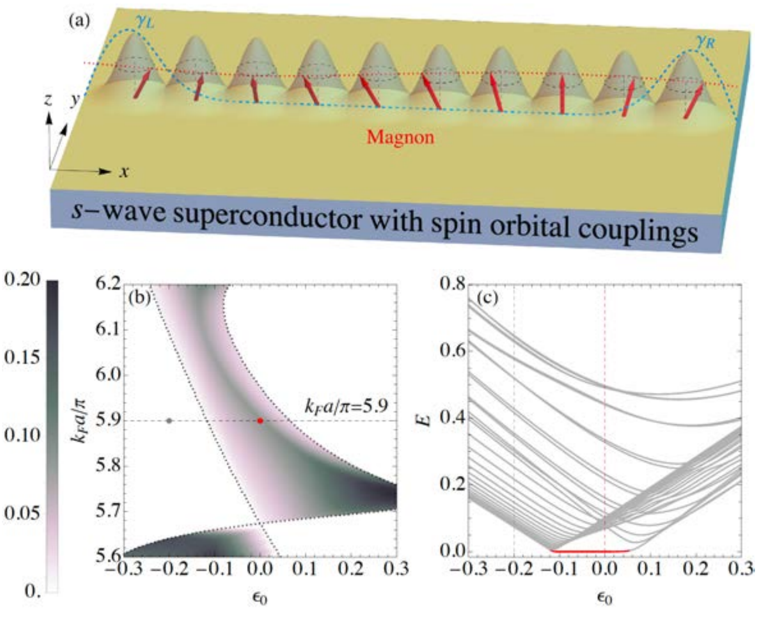
A chain of magnetic impurities deposited on the surface of a superconductor can form a topological Shiba band that supports Majorana zero modes and hold a promise for topological quantum computing. Yet, most experiments scrutinizing these zero modes rely conductance measurements, which only capture local properties. Here we propose to leverage the intrinsic dynamics of the magnetic impurities to access their non-local character (see the figure below). Specifically, we calculated the spin susceptibility and showed that the uniform magnonic mode, which spreads over the entire chain, becomes imprinted with the parity of the ground state. We found that the visibility of the spin susceptibility associated with the two parities oscillates between -1 and 1 in the topological regime as a function of the magnon frequency, while it is arbitrary in the trivial regime. These two distinct patterns originate from interference effects and are robust against moderate disorder. Our approach offers non-invasive alternative to the scanning tunnelling microscopy techniques used to probe Majorana zero modes. Conversely, one could utilize magnons to facilitate the manipulation of Shiba states.



(a) A Sketch of the topological Shiba chain in the presence of magnons.
(b) The phase diagram. (c) The spectrum and the Majorana zero mode.

Cavity-mediated parametric entanglement of driven electron spin qubits via sidebands

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The generation of extended-range entanglement represents a key outstanding challenge in realizing scalable and modular architectures for quantum information processing with semiconductor spin qubits. Hybrid systems in which spins are coherently coupled to photons in microwave cavities have enabled recent demonstrations of long-distance interactions for spin qubits in silicon [1,2]. While these results provide a path to scalability for spin qubit architectures, scaling challenges remain for applying this approach to more than two qubits due to the need for tuning multiple qubit and cavity frequencies into simultaneous resonance, as well as the fabrication and precise tuning of micromagnets required in silicon for spin-charge coupling and qubit-qubit interaction.

To address these challenges, we consider a pair of qubits based on spins in quantum dots that interact via microwave photons in a superconducting cavity, and that are also parametrically driven by separate external electric fields. For this system, we formulate an approach for sideband-based entanglement between the two qubits. We find that the sidebands generated via the driving fields allow for qubit-qubit entanglement through only ac control and with mutually off-resonant qubit and cavity frequencies. The model we derive can be mapped to multiple types of qubits, including both detuning-driven one-electron spin qubits in double quantum dots [3] and three-electron resonant exchange qubits in triple quantum dots [4]. We identify multiple resonance conditions that enable the implementation of entangling gates via highly tunable cavity-mediated qubit-qubit interactions. This approach provides a promising route toward scalability and modularity in spin-based quantum information processing through drive-enabled spectral flexibility, which can additionally be implemented in micromagnet-free systems for spin-photon coupling.

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High-purity germanium and heavily-doped germanium crystals for spectrometry and plasmonics: first results and challenges

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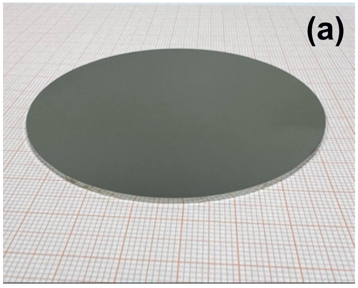
High-purity germanium (HPGe) crystals are used for high energy resolution detectors, photon spectroscopy, in-vivo X-ray spectrometry to analyze both trace (Pb, Hg, As etc.) and major (Sr) elements in the body, collimatorless gamma-ray imaging for medical applications. Although already of good purity, the material needs to be further purified with the zone refining technique. The improvement in purity or reduction in impurity concentration realized is about a factor of 1000 or even more at the completion of this process. We have established an end-to-end HPGe crystalline material development facility and rendering of wafers with our in-house solutions and capability. Large size (> 3 inches dia.) single crystals of Ge are grown in typical growth directions (<100>, <111>) or any specific directions [1] using the Czochralski (Cz) technique and one of the HPGe crystal's polished wafer [2] with net free carrier concentration at least of 10^{11} cm^{-3} and a dislocation density value of mid-10^{3} cm^{-2} is shown in Fig.(a).



Heavily-doped-Ge (HD-Ge) is a novel material for plasmonics, bio-sensors, plasmonstor, and other devices [3]. Achieving higher concentrations (> 10^{19} cm^{-3}) of dopants in Cz Ge growth is very difficult due to segregation coefficients and the solubility limit of the usual n-type and p-type dopants. The growth conditions, co-doping and various doping procedure's influence on the concentration and homogeneity of the grown material is investigated here. One of the Ga-doped ingots is shown in Fig.(b) and the corresponding measured electrically active dopant concentration in the ingot is in the range between 10^{17} – 10^{19} cm^{-3}. Besides describing a broader technical overview, the scientific problems associated with these Ge single crystal growth, namely a type conversion (from p-type to n-type or vice versa, only in the case of HPGe crystals), compensation and the anomaly of segregation behavior of high boron doping from the expected Scheil distribution, higher defect density will also be discussed in detail in this presentation.

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Investigation of SAG PbTe for novel hybrid devices

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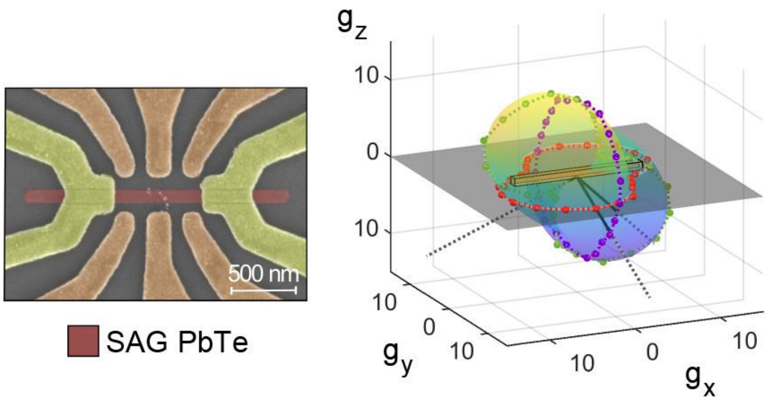
In the search for new, better platforms for studying topological superconductivity, lead telluride (PbTe) nanowires have emerged as possible candidate. This semiconductor has advantageous bulk properties over InAs and InSb: a g-factor of 58[1] and strong spin-orbit interaction[2]. Moreover, bulk PbTe has a dielectric constant of 1350 at low temperature[3], which is expected to influence transport properties significantly. We fabricated and studied devices in selective-area-grown PbTe nanowires[4,5]. Low-temperature measurements of Hall bars, an Aharonov-Bohm loop and quantum dots yielded a mobility of 5600 $cm^2(Vs)^{-1}$, a phase coherence length of $l_\phi > 21$ μm at 12 mK, charging energies below 140 μeV and anisotropic g-factors. The corresponding g-factor tensors had principal g-factors ranging from 0.9 to 22.4 and the dependence of the g-factor anisotropy on the electronic gate configuration implied that Rashba spin-orbit interaction is strong in the PbTe quantum dots. Finally, we report our advances in pairing PbTe devices with different superconductors for realizing hybrid devices.



Scanning electron micrograph of a quantum dot device (left) and g-factor anisotropy (right), where the surface plot and black lines are the g-factor tensor and its principal axes. From Ref. 5.

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Silicon MOSFET gate stack optimization for Fin-FET quantum dots

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A large-scale quantum computer based on the electron/hole spin degree of freedom in Metal Oxide Semiconductor (MOS) silicon quantum dots relies on building reliable and reproducible quantum dot arrays [1,2]. Hence, it is of great importance to fabricate MOS stacks with high quality silicon-oxide interface. Therefore, in this work, we investigate the Si-SiO_2 interface in two-dimensional hole gases in silicon MOSFET Hall bars and capacitor structures. We explore how diffusion barrier reduces oxygen scavenging [3] and characterize the influence of SiO_2 thickness on percolation density n_p, peak mobility μ_{peak} and density of interface traps D_{it}. Furthermore, we show a method to measure impedance in a cryostat at high frequencies circumventing large phase shift of the IV converter using a capacitance-bridge like method.

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Tunable superconductivity in planar Germanium

M. Valentini[1] ,O. Sagi[1], L. Baghumyan[1], K. Aggarwal[2], M. Janik[1], T. De Gijsel[1], J. Jung[3] ,M. Verhijen[3], S. Calcaterra[4], A. Ballabio[4], D. Chrastina[4], E.P.A.M Bakkers[3], G. Isella[4], G. Katsaros[1]

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Replace all of III-V materials, like InAs and InSb, are the leading platforms for the realization of gatemons and for the quest of Majorana zero modes. Here we investigate Ge as an alternative platform [1]. In the past years, dramatic progress has been made in inducing superconductivity in planar germanium either by enhancing the proximity effect using a double layer of superconductors [2] or by creating a low-disorder interface between the germanium hole gas and an annealed germanosilicide superconductor [3]. Here, we show that we can reliably induce superconductivity in a germanium hole gas by evaporating aluminum on top of a thin $Si_{0.3}Ge_{0.7}$ spacer which separates the superconductor from the quantum well. We estimate transparencies close to unity and we reveal a superconducting hard gap which can be tuned by the $Si_{0.3}Ge_{0.7}$ spacer. Finally, we show the exchange of pairs of Cooper pairs between two superconducting leads, highlighting the potential of Germanium quantum well as protected qubit [4].

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Engineering phonon-phonon interactions in multimode circuit quantum acoustodynamics

Uwe von Lüpke[12], Ines C. Rodrigues[12], Yu Yang, Matteo Fadel, Yiwen Chu
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In recent years, remarkable progress has been made towards encoding and processing quantum information in the large Hilbert space of bosonic modes. Mechanical resonators are of great interest for this purpose, since they confine many high quality factor modes into a small volume and can be easily integrated with many different quantum systems. An important yet challenging task is to create direct interactions between different mechanical modes. Here we demonstrate an in-situ tunable beam-splitter-type interaction between several mechanical modes of a high-overtone bulk acoustic wave resonator. The engineered interaction is mediated by a parametrically driven superconducting transmon qubit, and we show that it can be tailored to couple pairs or triplets of phononic modes. Furthermore, we use this interaction to demonstrate the Hong-Ou-Mandel effect between phonons. Our results lay the foundations for using phononic systems as quantum memories and platforms for quantum simulations.

All-optical readout of a superconducting qubit

Georg Arnold*, [1], Thomas Werner*, [1], Rishabh Sahu[1], Liu Qiu[1], Lucky Kapoor[1], Farid Hassani[1], Johannes Fink[1]

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Superconducting circuits are promising candidates for future quantum computing and metrology applications due to their well-controllable parameters and their increasing packing density on micro-chips. Considering the fact that tens of thousands to millions of superconducting circuits will be needed to overcome standards set by high-end classical devices, the control and readout of each individual circuit becomes increasingly important. Current experimental realizations rely on multiple coaxial cables per superconducting circuit. The sheer amount of microwave lines and their respective heat loads will pose a great challenge for the dilution refrigerators they will be operated in. One way to deal with this challenge is to substitute the microwave coaxial lines with thin, high bandwidth, ultra-low heat conductivity optical fibers. Those guide modulated light inside the fridge which gets converted to microwave radiation at the mixing chamber, interacts with superconducting circuits, gets up-converted to optical radiation and is then measured using an optical room temperature setup. The conversion at millikelvin temperatures is done by using an electro-optic converter. In my talk, I will show how we read out a Transmon qubit by using modulated infrared radiation at the fiber input of a dilution fridge, an electro-optic converter at its mixing chamber[1] and an optical heterodyne setup at its output. I will compare our results of three different types of readout for the same qubit, going from all-microwave, to MW-to-optics, to all-optical readout. As outlook, adding optical control to our scheme, will lead to a superconducting qubit which is operated without any coaxial lines connecting it to the outside of the fridge.

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Microwave spectroscopy of Andreev bound states in InSb-Al nanowire Josephson junctions defined using shadow-wall lithography

J.J. Wesdorp[1], P.A. Rot[1], N. van Loo[1], A. Vaartjes[1], M. Pita-Vidal[1], L.J. Splitthoff[1], A. Bargerbos[1], L. Grünhaupt[1], J.C. Wolff[1], G.P. Mazur[1], G. Badawy[3], S. Gazibegovic[3], E.P.A.M. Bakkers[3], L.P. Kouwenhoven[1], G. de Lange[2], C.K. Andersen[1]

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The use of circuit quantum-electrodynamics (cQED) to study semiconductor-superconductor hybrid devices has shown to be a promising technique with high energy- and time-resolution. So far, most studies involving semiconductor-superconductor hybrid nanowires have focused on InAs-Al nanowires with etched junctions due to natural integration of these wires into standard cQED fabrication processes. On the other hand, InSb-Al shadow wall lithography has recently been shown to produce highly transparent and clean Josephson junctions [1]. Here we study Andreev bound states in gate-tunable InSb-Al hybrid Josephson junctions defined using shadow wall lithography on a superconducting NbTiN circuit. We embed the junctions into a radio-frequency SQUID that modulates the inductance of a field-compatible resonator. From gate-dependence of Andreev pair transitions with half flux quantum threading the SQUID loop, we observe highly transparent channels in lowest ABS manifold. Furthermore, by investigating the flux and field dependence up to 200 mT we observe the direct spin-flip transition in the lowest manifold, yielding a hybrid g-factor of 16. Finally, we compare the results an additional Josephson junction measured in DC. The techniques developed in this work could allow for hybrid circuits with alternative material combination or more complex geometries, such as artificial Kitaev chains [2,3].

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Investigation of Electro-nuclear Spin States in LiHoF4 Using Cavity-Magnon-Polariton (CMP) Technique

Yikai Yang[1], P. Babkevich[1], R. Gaal[1], I. Zivkovic[1], and H. M. Ronnow[1]

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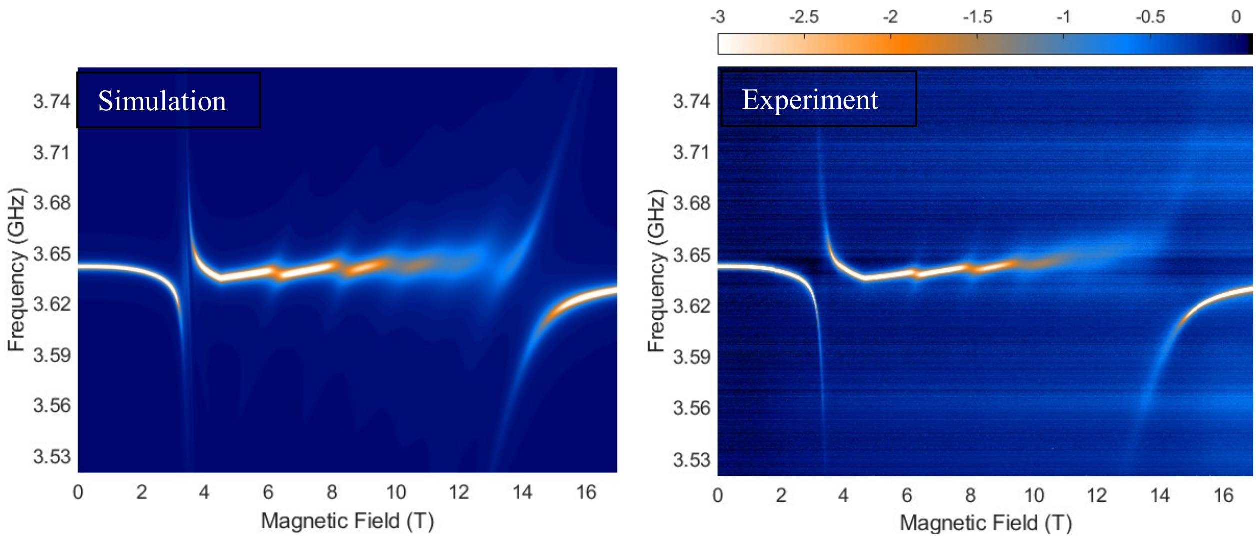
We derive an explicit relation, between the generalized susceptibility from linear response theory[1] and scattering parameters in input-output formalism[2], for multi-mode spin systems without resorting to semi-classical approximations. The method is then applied to a strongly hybridized cavity-magnon-polariton (CMP) system in order to experimentally study the electro-nuclear spin states in an archetypal 3D Ising magnet, $LiHoF_4$. With further help from mean field calculations, we yield quantitative agreement between theoretical and experimental results. By demonstrating the ability of numerically reproducing experimental observations across a wide regime in the parameter space, we show the applicability of the method as a testing ground for theories aimed at characterizing similar complex quantum magnetic systems.



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Towards a 10-qubit quantum processor in planar Germanium

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In recent years, planar germanium qubits emerged as a compelling platform for quantum computation. Their favourable properties enabled to demonstrate four-qubit quantum algorithms [1], in only a few years after their first development. In a first experiment toward scalability, shared-control has been demonstrated to enable the operation of a 16-quantum dot array [2].

Here, we focus on a 10-qubit system, structured in a 3-4-3 array, where we have direct control over the tunnel coupling and the detuning of the individual quantum dots, and can monitor charge transitions using four rf charge sensors. We will show our progress on the system and detail our ambitions to advance the state-of-the-art of semiconductor qubits towards fault-tolerant quantum computing.

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Near quantum-limited amplification up to 1 T using GrAl resonators

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Josephson Junction based amplifiers have become essential components for the readout of microwave quantum circuits. Despite the advances made over the last decade, they still have limited applicability in systems that require high magnetic fields. The use of high kinetic inductance materials like granular Aluminum (grAl), opens the path for low noise amplification in Tesla fields thanks to their in-plane resilience [1] and negligible high order non-linearities [2], which is particularly attractive for the readout of semiconducting spin-qubits [3] and single molecular magnet qubits [4]. Here we present a non-degenerate parametric amplifier made of two coupled grAl resonators forming a Bose-Hubbard dimer [5, 6]. We report near quantum-limited 20 dB amplification, with an instantaneous bandwidth of few MHz and signal-to-pump detuning above 100 MHz, which was stable up to 1 T.

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Enhanced Majorana stability in proximitized quantum dots

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The recent realization of a two-site Kitaev chain, and the formation of "Poor man's Majorana" states within, provide a path forward in the field of topological superconductivity. To use such states as the building blocks for a parity qubit and to create longer Kitaev chains, it is necessary to increase the reproducibility of the two-dot system and to increase the robustness of the Majorana states to external perturbations. Here we use two proximitized quantum dots as the basis for the two-site Kitaev chain. We show that in this manner, we enhance the interaction strength between the two quantum dots and form Poor man's Majorana states which are an order of magnitude more stable to gate fluctuations than what was previously reported. This approach does not depend on fine-tuning energy scales to succeed, making it a cross-platform generic approach to forming a Kitaev chain.

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Coherent coupling of a microwave photon to a hole spin

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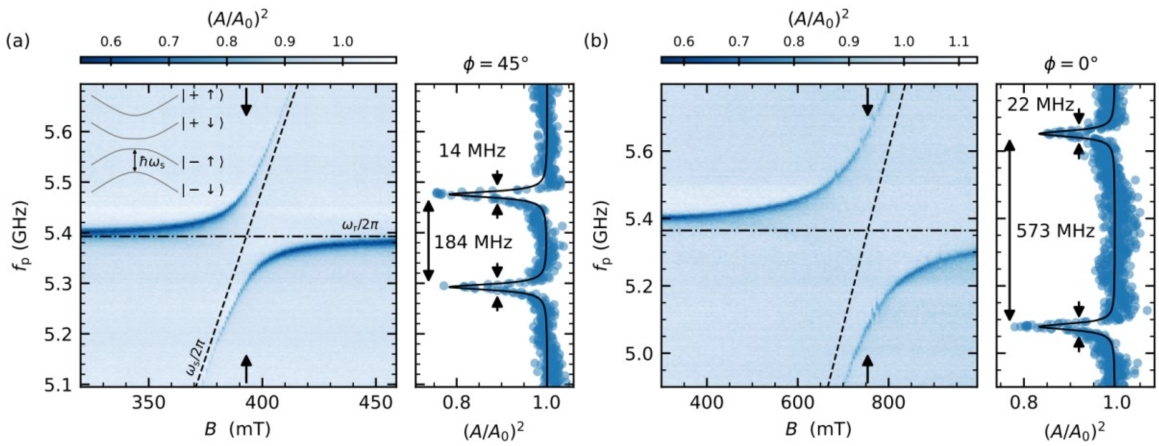
Recently, hole spins in silicon and germanium have shown increasing interest for quantum information processing owing to the advantage of manipulating their state with electric instead of magnetic microwave fields [1, 2]. This is possible due to the strong spin-orbit interaction intrinsically present in the valance band of these materials. Spin-orbit coupling should as well offer the possibility to couple a hole spin to the electric field component of a microwave photon.

Here we show a strong hole spin-photon interaction on a CMOS compatible platform. We find a coupling strength of 300 MHz, exceeding the spin decoherence rate and the photon decay rate by a factor 27 [3]. Our coupling largely exceeds the best figures reported so far in the case of electrons in silicon [4, 5], opening the door to the achievement of high-fidelity two qubits gate with distant spins.



Strong spin-photon coupling: Normalized transmission as a function of probe frequency (f_p) and magnetic field (B) for two different magnetic field orientations. When the spin transition frequency (black dashed line) equals the bare resonator frequency (black dashed-dotted line), an avoided crossing is observed. This is attributed to the strong coupling of a single hole spin to a single microwave photon. Line cuts at the position indicated by the arrows show a vacuum Rabi mode splitting of $2g_s/2\pi$= 184 MHz and 573 MHz, respectively.

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