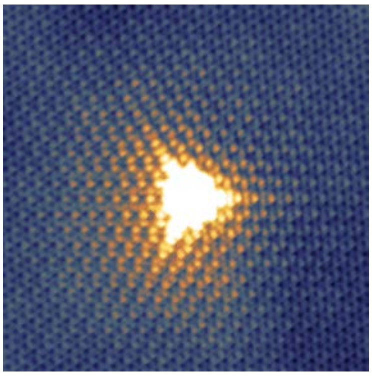
Master thesis Project

Probing the band structure of topological 2D materials with quasiparticle interference.

STM Image of an hydrogen atom grafted at the surface of graphene. This shows typical quasiparticle interferences



Conducting electrons screen defects by forming an oscillation of local density of states around the defect. This phenomenon was uncovered by Jacques Friedel in the 1950's [1]. It is now known as quasiparticle interference since it can be understood as the interference between electronic waves hitting the defect and its reflection. The scanning tunneling microscope (STM) has allowed to visualize these oscillations in the real space and learn a lot about the Fermi surface of materials. Indeed, the quasiparticle interference has a period related to Fermi wavelength and the Fourier transform can allow to reconstruct the Fermi surface. The dispersion of the material can be deduced from a sequence of energy resolved local density of states maps measured by STM. A famous example is the parabolic dispersion of the 2D electron gas at the surface of copper [2] or the linear dispersion in Graphene [3].

We have recently shown that using quasiparticle interference one can also measure graphene's Berry phase [4,5]. This opens new possibilities to use quasiparticle interference to determine the topological properties of materials, which are difficult to measure by other means. The present research project aims at developing the technique and apply it to new graphene based materials like twisted bilayer graphene, superconducting graphene (induced by proximity), Rhombohedral graphene etc. The success will rely on the mastering of creating defects at the surface of graphene either by ion bombardment or hydrogen functionalization.

We are looking for a motivated PhD candidate with a strong background in condensed matter physics interested in low temperature scanning tunneling microscopy. The candidate will be involved in the project from sample preparation to the STM measurements and participate to a long term collaboration with Madrid University (Training in Madrid possible depending on the applicant.). The experimental work will be backed by theoretical input from the University of Bordeaux and Cergy Pontoise.

[1] J. Friedel Nuovo Cimento **7**, 287, (1958)
[2] M. Crommie *et al*. Nature **363**, 524 (1993)
[3] G. Rutter *et al*. Science **317**, 219 (2007)
[4] C. Dutreix *et al*. Nature **574**, 219 (2019)
[5] Y. Guan *et al*. ArXiv:2307.10024 (2023)

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& Clemens.winkelmann@grenoble-inp.fr

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Master thesis Project

Investigation of sub-Kelvin behaviour of advanced SiGe heterojunction bipolar transistors for quantum bits experiments

For decades, 3 technologies of transistors have co-existed. The most ubiquitous device, silicon field-effect transistors (MOSFETs), are by far leading in volume but remain slower and more noisy than competing technologies. At the other extreme, high mobility transistors (HEMTs) can reach very high speeds and ultra-low noise. However, they are based on ‘exotic’ materials such as GaAs or InP, and suffer from much lower production volumes, higher cost and lower yield. Silicon Germanium (SiGe) Heterojunction Bipolar Transistors (HBTs) bridge this gap since they achieve the best performances of Si-based technologies, being fully CMOS compatible, in the so-called Bipolar-CMOS (BiCMOS) technologies. They are now enabling low-noise and high-speed applications, with high-volume production [1].

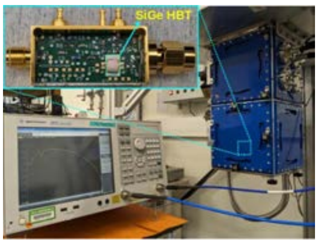
The breakthrough came when a graded content of Ge was introduced in the epitaxial growth of the HBT base. By doing so, a true bandgap engineering is achieved and allows to optimize the transistor characteristics far beyond the limits of pure materials like Si [2].

Our laboratory in PHELIQS at CEA-Grenoble studies spin quantum bits made with Si MOSFETs from CEA-Leti or homemade Ge heterostructures [3,4]. Even though it is not always widely known, all such qubits experiments include a HEMT or a SiGe HBT in the first front-end cryogenic low noise amplifier (LNA) of the readout chain [5]. Recently we have designed and fabricated our own LNAs, using a commercially available BiCMOS technology, which exhibits low performances than more recent technologies.

In this internship we will investigate advanced BiCMOS devices from the B55 technology of STMicroelectronics [6], for applications in quantum bits experiments. We will measure their characteristics down to 3.2K or 0.45K in homemade pulse-tube based cryostats.

This work will be carried in close collaboration with STMicroelectronics which not only provides advanced BiCMOS chips but also shares its deep knowledge of SiGe HBT devices, including previous cryogenic characterizations at high frequency and above 4K.

[1] P. Chevalier and A. Pallotta, IEEE Microwave Magazine, 25, 10, 2024.
[2] Cressler J.D. & Niu G., *Silicon-germanium heterojunction bipolar transistors*, Artech House 2002.
[3] Piot N. *et al.*, Nature Nanotechnology 17, 2022. https://doi.org/10.1038/s41565-022-01196-z
[4] Kiyooka E. *et al.*, in preparation
[5] Bardin J.C., IEEE Solid-State Circuits Magazine, spring 2021. https://doi.org/0.1109/MSSC.2021.3072803
[6] P. Chevalier et al., IEEE IEDM Tech. Digest, 2014 https://doi.org/,doi: 10.1109/IEDM.2014.7046978.



Insert: BiCMOS chip packaged to enable characterization and making a functional amplifier for quantum bits experiments. Measurements with a vector network analyzer will be performed in a cryostat (blue cubes).

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Master /PhD thesis Project

Lossless resilient microwave components based on disordered superconductors

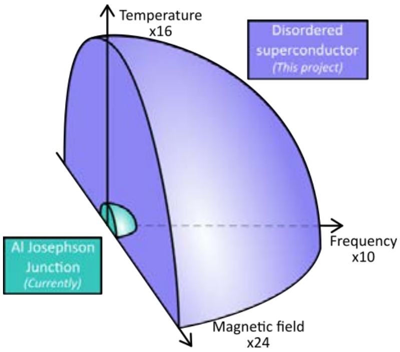

Fig. 1: Schematics of the working range improvement as function of magnetic field, frequency and temperature for lossless microwave components made from the disordered superconductors NbN compared to those based on aluminum Josephson Junctions.

During the last decades, superconducting quantum circuits have shown impressive results fueled by the so-called circuit Quantum ElectroDynamics (cQED) architecture where the quantum signal is carried by photons at microwave frequencies. cQED experiments often rely on the technology of aluminum Josephson Junctions (JJ's) which can be understood as non-linear inductors. This non-linearity allowed the development of numerous non-linear lossless microwave components (tunable resonators [1], low noise amplifier [2] ...) which became essential tools for state-of-the-art cQED experiments. Yet, as a consequence of being built upon aluminum JJ's, all of these components are restricted to low magnetic field $\lesssim$ 250mT, temperature $\lesssim$ 250mK and frequency $\lesssim$ 10 GHz, strongly limiting the range of their application. As illustrated in Fig. 1, the use of disordered superconductors with a large superconducting gap such as NbN would alleviate these constraints by one order of magnitude.

The goal of the project is to demonstrate that the non-linearity of large gap disordered superconductors, here NbN, can advantageously replace Al JJ's in order to offer lossless microwave components to research communities working at large magnetic field [3] ~ 6 T, temperature ~ 4 K and frequency ~ 100 GHz.

During the master project, you will collaborate on a daily basis with our entire team (www.lateqs.fr) with 30 people including 15 Ph.D. You will participate to the development of new samples that includes design, theory and nano-fabrication performed in our cleanroom facility. You will also learn to cool down samples to reach cryogenic temperatures and you will perform measurements using state-of-the-art DC and RF techniques.

This master project may continue as a PhD thesis.

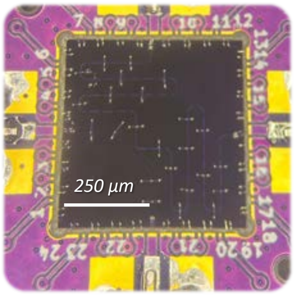

Fig. 2: Home-made PCB with a NbN circuit with two photonic–crystals, top-right, defining a microwave resonator, center, itself coupled to a feedline, bottom-left.

[1] Appl. Phys. Lett. 92, 203501, **2008**
[2] Appl. Phys. Lett. 118, 142601, **2021**
[3] Appl. Phys. Lett. 118, 054001, **2021**

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Master /PhD thesis Project

Hybrid superconductor-semiconductor for parity protected qubit

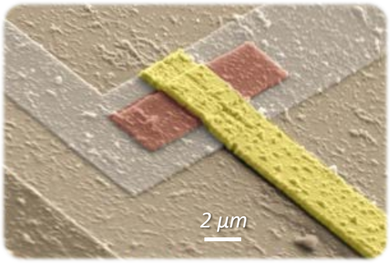

Fig. 1: Colorized SEM micrograph of a S-Sm nanostructure. Light gray shows superconducting Al, yellow normal metal Ti/Au gates and red semiconducting Ge.

Hybrid Superconductor – Semiconductor (S-Sm) nanostructures are nano-circuits which combine superconducting and semiconducting materials. Such devices take advantage, first from the superconductivity that is a macroscopic quantum effect and can be viewed here as a quantum coherence provider –needed ingredient to create a quantum bit or qubit. Second, from the semiconducting properties that allow changing the amount of carriers using an electrostatic gate – like in a field effect transistor (FET).

Our research focuses on hybrids made from aluminum-germanium nanostructure that we fabricate in our academic cleanroom, see Fig. 1. In a nutshell, our samples consist of a loop interupted by two hybrids nanostructures. By studying the multi-harmonicity of their current response to an applied magnetic field, we observed that only the transport of an even number of Cooper pair is allowed [1,2]. Such property is the building block to a type of protected qubit, the parity protected qubit [3].

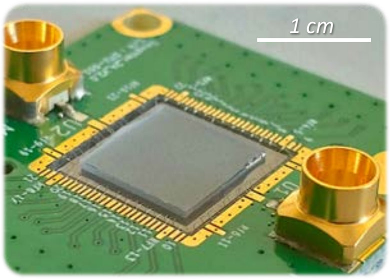

Fig. 2: Home-made PCB with a flip-chip sample micro-bonded in its center for microwave and DC measurement at cryogenic temperature.

The aim of this project is to incorporate our hybrid nanostructure in a circuit Quantum ElectroDynamics (cQED) architecture, a well-known and heavily used architecture in superconducting quantum information, to explore its properties as a qubit. For this integration, we leverage our long-term collaboration with the CEA - LETI and use advanced flip-chip integration, where two quantum chips of different nature are coupled together, see Fig. 2.

The final sample will be probed at cryogenics temperature in state-of-the-art DC and microwave measurement setup.

During the master project, you will collaborate on a daily basis with our entire team (www.lateqs.fr) with 30 people including 15 Ph.D. You will participate to the development of new samples that includes design, theory and nano-fabrication performed in our cleanroom facility. You will also learn to cool down samples to reach cryogenic temperatures and you will perform measurements using state-of-the-art DC and RF techniques.

This master project may continue as a PhD thesis.

[1] Phys. Rev. Research 6, 033281, **2024**

[2] arXiv:2405.14695, **2024**

[3] npj Quantum Information, 6, **2020**

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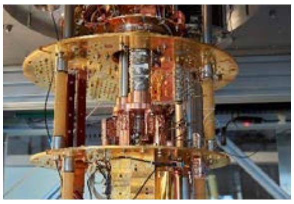
Master / PhD Thesis Project

Superconducting Devices in Silicon

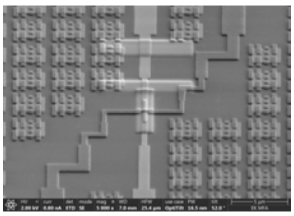


In the race towards building a quantum computer, there is clearly a need for a large scale integration of quantum devices. As silicon technology is by far the most advanced technology, the possibility to fabricate quantum devices based on silicon will provide a serious and may be determinant advantage to solid state qubits.

The project focuses on the study of superconducting devices with silicon as a semiconductor. Those include standard silicon transistors with superconducting source and drain contacts and superconducting resonators. The common properties is the superconducting material which is elaborated with the constrain of being compatible with the silicon CMOS technology.

In the actual situation of the project, devices with CoSi2, PtSi and Si:B superconducting contacts have been fabricated using the 300 mm clean room facility at the LETI and in collaboration with our partners at Uppsala university and C2N Paris Saclay. The main issue is now to characterize the electronic transport properties at very low temperature. Depending on the quality of the contact interface between the S/D contacts and the silicon channel, various behavior are expected. In the case of opaque contacts, the current at very low S/D bias is blocked due to the opening of the superconducting gap. In the opposite case, superconducting correlations extend in the channel and a gate-tunable non-dissipative supercurrent is expected to flow though the transistors. This situation, met for other materials like germanium (see other master project on protected qubit), is the ultimate goal of the project.

The master internship will focus on measurements at very low temperature of existing devices. Low frequency characterization will be performed on superconducting transistors and the effect of controlled parameters (gate voltage, S/D bias, temperature, magnetic field) will be explored. Radio-frequency measurements on superconducting transistors could also be addressed during the master thesis.



The candidate will be full time at the LaTEQS (IRIG/PHELIQS) at the CEA Grenoble. She or he will have full access to a dedicated dilution fridge equipped with rf lines.

This proposal is therefore at the frontier between state-of-the art technology and solid-state physics, applied technology and basic research, in the growing context of quantum technologies.

The candidate should have a strong interest for nanotechnology and experimental physics, together with a background in solid state physics.

This project is sponsored by a QUANTERA project SIQUOS and the European project JoGATE.

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Master Project

Dynamical nuclear polarization with hole spin qubits

Hole spin qubits in silicon quantum dots have emerged as promising candidates for quantum computation due to their long coherence times [1] and potential for scalability. These qubits leverage the spin states of holes confined in silicon nanostructures, offering advantages over electron spin qubits in certain aspects. However, the presence of ^{29}Si nuclear spins in natural silicon can introduce limitations through hyperfine interactions. These interactions can lead to decoherence and reduced qubit fidelity. While isotopically purified silicon (^{28}Si) can mitigate this issue, it is expensive and challenging to produce.

This internship project will focus on exploring a potential alternative solution: dynamical nuclear spin polarization (DNP). We will investigate the possibility of polarizing nuclear spins when the Rabi frequency of the hole spin qubit matches the Larmor frequency of the nuclear spin. This mechanism occurs when two different spin species are brought into resonance in the rotating frame. DNP for holes is yet an unexplored area, but theory predicts potentially very efficient polarization mechanism [2]. You will study the polarization rate and the subsequent effect on the hole spin qubit coherence times.

Practically, you will perform experiments in a dilution refrigerator at extremely low temperature (7 mK). You will learn how to manipulate spin qubits using microwave signals shaped on the nanosecond timescale. You will benefit from the fruitful environment of the Lateqs laboratory, that gathers 10 permanent researchers and 12 PhD students.

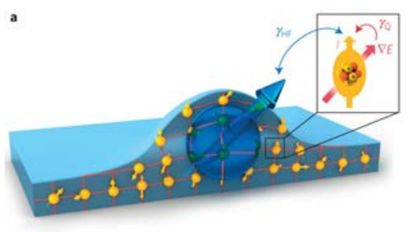

Figure 1: Artist view of the hyperfine interaction. A spin qubit (blue) interacts with the surrounding nuclei (yellow). Reproduced from [3]

References :

[1] N. Piot et al., Nature Nanotech. **17**, 1072 (2022)

[2] P. Stano et al. , Phys. Rev. B **108**, 155306 (2023)

[3] A. Bechtold et al., Nature Physics **11**, 1105 (2015)

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Master thesis Project

Protecting hole spin qubits from thermal decoherence

Solid-state qubits based on electron or hole spins are promising candidates for quantum computing applications. However, due to the fragile nature of quantum information, spin qubits need to be protected from any source of noise which can lead to decoherence. In principle, operating at very low temperatures, below 100 mK, provides good protection from thermal noise. However, recently several observations have challenged this naïve belief and shown that thermal fluctuations and overheating remain a significant issue even at mK temperatures that need to be tackled.Under proper operation conditions, a qubit must be driven resonantly by a microwave at the Larmor frequency f_L matching the energy difference between the two quantum states $hf_L = \Delta E$. A recent work reported the surprising result that ΔE (and therefore f_L) could still vary significantly with temperature (see Fig. 1) even below 100 mK [1], meaning that for a fixed drive frequency, temperature fluctuations will break the resonance condition and therefore lead to decoherence Although widely discussed in the qubit community, this unexpected behavior remains for now a puzzle.

In this internship, we propose to tackle this problem and provide not only a physical understanding of the temperature susceptibility $\partial(\Delta E)/\partial T$, but also a strategy for minimizing it. Our group was able to reproduce the results of [1] and found preliminary indications that this effect can be attributed to spin-orbit interactions, which are known to have a strong effect on hole spin states. The LATEQS groups has already a very strong expertise in mitigating spin qubit decoherence related to spin-orbit effects [2], building also on strong in-house theoretical support.

In practice, you will perform ultra-low temperature experiments using hole spin qubits and investigate in depth their temperature susceptibility. You will furthermore explore the correlation between the decoherence of spin qubits and the dissipation of MW signals, leveraging an already existing thermometry technique [3] to record temperature at the 100's of ns time scale. Finally, you will develop models to understand the temperature susceptibility, with the help of the local theory team.

This internship can be pursued with a PhD thesis.

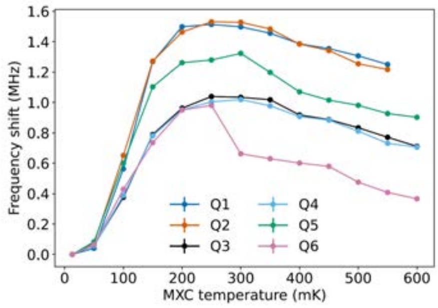

Figure 1: *Temperature dependence of the Larmor frequency (offset subtracted) of six spin qubits in a quantum processor. Reproduced from [1].*

[1] Undseth et al., Phys. Rev. X **13**, 041015 (2023)
[2] Piot et al., Nature Nanotech. **17**, 1072 (2022)
[3] Champain et al, Phys. Rev. App. **21**, 064039 (2024)

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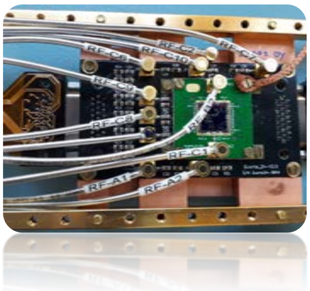
Master /PhD thesis Project

Ultra-strong coupling of a hole spin to a microwave photon

Bonded and mounted sample before cryogenic cooling.

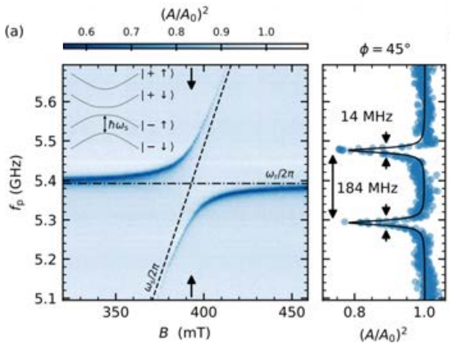


Quantum computing is currently pushing further the frontier of information technology. Among other fields, solid-state hole-spin qubits are a promising research area. Recently, we reached the strong-coupling regime between the spin of a single hole trapped inside the channel of a silicon transistor and a single microwave photon enclosed in a superconducting resonator [1]. This milestone paves the way to Circuit Quantum Electrodynamics (cQED) type experiments where we leverage such large spin-photon couplings to perform advance quantum information experiments.

The aim of this project is to further increase the coupling strength between the hole spin and the microwave photon to reach the ultra-strong coupling regime, a regime of light-matter interaction largely unexplored. First, we will probe this unique quantum system via microwave spectroscopy measurements [2]. In parallel, we will explore how time-domain experiments can unlock the peculiar physics of an ultra-strongly coupled spin to a microwave photon [3, 4].

Our research team is part of the French national “Plan Quantique” and is a founder member of the “Grenoble Quantum Silicon” group. We also strongly collaborate with the L-SIM group for theoretical support.

During the master project, you will collaborate on a daily basis with a lively team of three permanent researchers and three PhDs and take part in an exciting adventure to bring spin qubits to a new level. You will participate to the development of new samples that includes design, theory and nano-fabrication performed in our cleanroom facility. You will also learn to cool down samples to reach cryogenic temperatures and you will perform measurements using state-of-the-art DC and RF techniques. This master project may continue as a PhD thesis.



Avoided crossing between a hole spin and a microwave photon showing the strong coupling between them.

[1] Nat. Nano 18, 741, **2023**
[2] Phys. Rev. A 75, 032329, **2007**
[3] Nat. Rev Phys. 1, 19, **219**
[4] Rev. Mod. Phys. 91, 025005, **2019**

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Master /PhD thesis Project

High quality superconducting resonators arrays for spin circuit quantum electrodynamics

Measurement box containing a chip with superconducting resonators

Quantum computing is currently pushing further the frontier of information technology. Among other fields, solid-state hole-spin qubits are a promising research area. Recently, we reached the strong-coupling regime between the spin of a single hole trapped inside the channel of a silicon transistor and a single microwave photon enclosed in a superconducting resonator [1]. This milestone paves the way to Circuit Quantum Electrodynamics (cQED) type experiments [2] where we leverage such large spin-photon couplings to perform advance quantum information experiments.

The aim of this project is to advance the field of spin cQED by fabricating superconducting resonator arrays made of superconducting thin films of NbN [3,4]. These arrays should allow to study the interaction between one spin and several microwave photonic modes, a first step toward quantum simulation. During the master project, you will participate to the development of new high quality resonators. This includes their design, modelling and their nanofabrication in our cleanroom facility as well as their characterization at cryogenic temperatures to reach the quantum mechanical ground state. You will also learn how to use high frequency measurement electronics as well as modern data acquisition and analysis software packages.

Our research team is part of the French national “Plan Quantique” and is a founder member of the “Grenoble Quantum Silicon” group. We also strongly collaborate with the L-SIM group for theoretical support.

During the master project, you will collaborate on a daily basis with a lively team of three permanent researchers and three PhDs and take part in an exciting adventure to bring spin qubits to a new level. This master project may continue as a PhD thesis.

[1] Nat. Nano 18, 741, **2023**
[2] Phys. Rev. A 75, 032329, **2007**
[3] Appl. Phys. Lett. 118, 054001, **2021**
[4] arXiv:2403.18150**, 2024**

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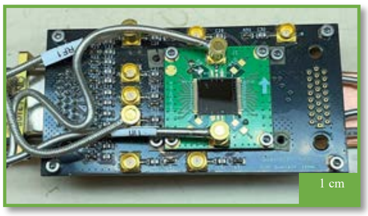
Master /PhD thesis Project

Quantum Dots in Germanium Heterostructures



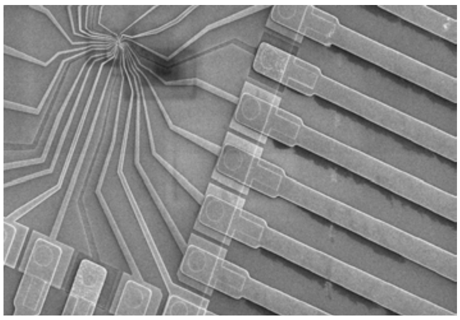
Wired sample before cryogenic cooling

Quantum computing (QC) is currently pushing further the frontier of information technology. Among other fields, solid-state spin qubits are promising for QC. Recently our laboratory is focusing on heterostructures embedding a high mobility hole germanium quantum well. In our cleanroom, we are a developing state-of-the-art nanofabrication to create arrays of quantum dots based on this quantum well. After fabrication such devices a cooled down to 10mK for electrical measurements. A low temperature, we manage to have an exquisite level of control giving us access to single charge and spin which can be used a quantum bits[1].

During the master project, you will collaborate on a daily basis with a lively team of three permanent researchers and two PhDs. You will participate to the development of the samples that includes design, theory and nano-fabrication done in our cleanroom facility.

Based on new theoretical predictions, the landé g-factor of the spins leaving in the quantum well could be modified by strain engineering. For this master project, we propose to focus on this prediction and try to design, fabricate and measure devices to reveal this new effect. This master project may continue as a PhD thesis.

[1] The germanium quantum information route, Scappucci, G. et al. Nat Rev Mater 6, 926–943 (2021)



Scanning electron micrograph of a device fabricated in our laboratory.

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Master thesis Project

Josephson physics of high-transparency quantum conduction channels in 2D Germanium

Two-dimensional (2D) Ge-based heterostructures have recently been put to the forefront of quantum technologies in particular for their high mobility and as a platform for hole spin qubit architectures. Additionally, 2D-Ge forms high transparency contacts to superconductors (S), offering a promising platform for hybrid superconductor / semiconductor physics [1]. This could have promising applications for combining superconducting with spin-based qubits.

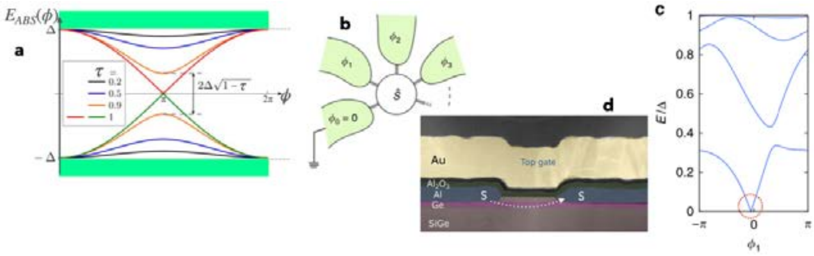

Figure 1: (a) ABS energies versus phase for different transparencies. As $\tau \to 1$, the Andreev gap closes at $\phi = \pi$.(b) Schematics of a multiterminal Josephson junction with relative phases applied and (c) ABS energies which can be driven to a topological ground state transition (red circle) (from [2]). (d) Transverse cut of a S-Ge-S junction, with length of bout 200 nm.

In short (few 100 nm long) S-Ge-S junction, the Josephson effect (dissipationless current flow) can be realized. Electronic transport is governed by only few conduction channels with conductance $G=\tau\, G_Q$, where $G_Q=2e^2/h$ is the quantum of conductance and $0<\tau<1$ is the channel transmission. In the superconducting state, each channel leads to a so-called Andreev bound state (ABS), which carries the supercurrent. In ballistic junctions with transparencies $\tau \to 1$, the ABSs can have intriguing properties which are the object of this project. So far, Al/Ge contacts have been successfully realized at the laboratory but the transmission seems to be limited to ~ 0.7.

The first step of this Master project will consist in fabricating and investigating 2D-Ge Josephson junctions based on new superconducting materials which form contacts to Ge with $\tau \to 1$. The next step consists in moving to 3- and 4-terminal Josephson junctions in 2D-Ge. Here, the ABS are more complex and can be varied by the quantum phases in each superconducting lead, which can lead to topologically distinct ground states [2]. You will study the dc transport properties of multi-terminal junctions and confront the results to theory [3].

This internship can be pursued with a PhD thesis in the frame of which the above-described structures will be investigated using microwave rather than dc transport techniques.

[1] Leblanc *et al.,* arXiv:2405.14695 (2024)., [2] Riwar *et al.,* Nature Commun. **7,** 11167 (2016)., [3] Mélin *et al.,* Phys. Rev. Research 5, 033124 (2023).

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