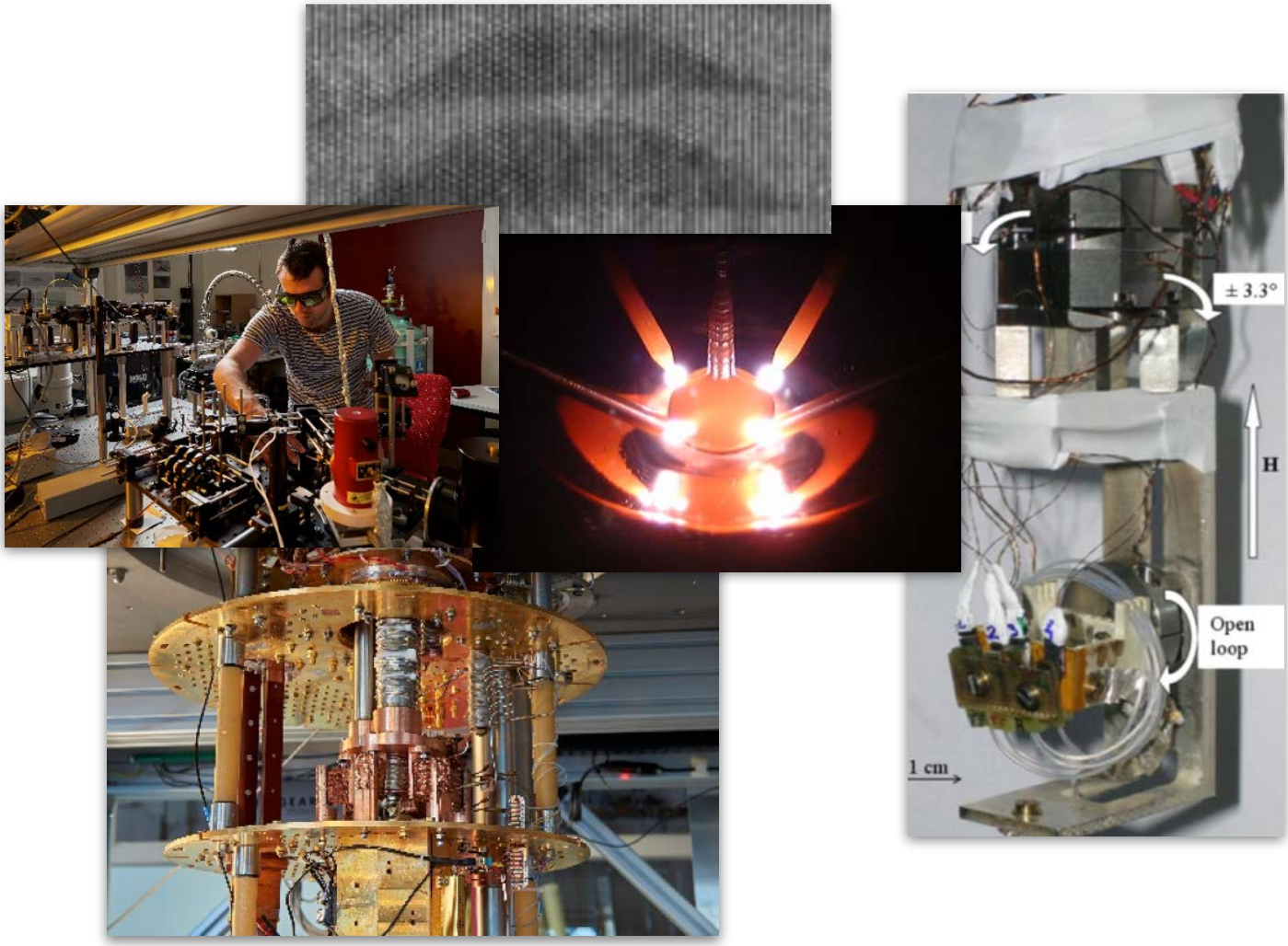
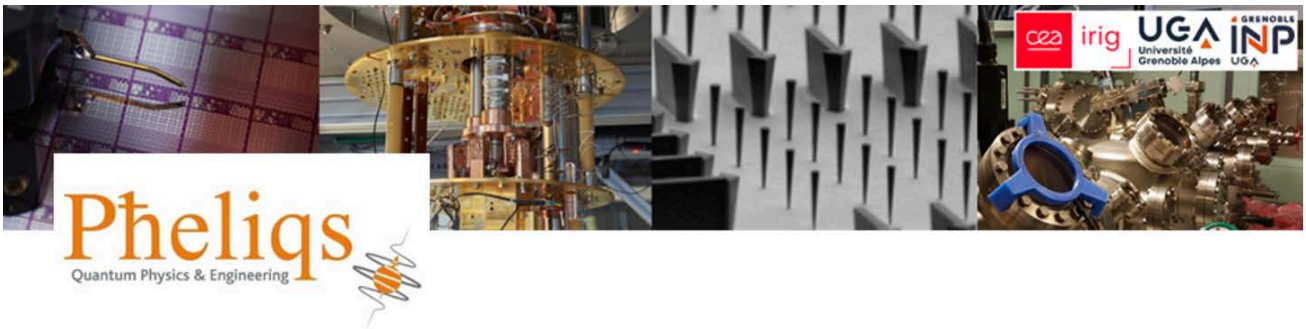
Master Thesis Projects 2024

Pheliqs

Quantum Physics & Engineering





The Laboratory for Quantum Photonics, Electronics, and Engineering (PHELIQS) is a joint research unit of the CEA, the Univ. Grenoble Alpes (UGA), and Grenoble INP Graduate Schools of Engineering and Management, with strong links to neighboring CNRS laboratories. The laboratory comprises five teams with complementary expertise in the fields of quantum physics, nanostructures, and quantum materials. As of April 2023, PHELIQS has a permanent staff of 53 people, including 35 researchers and professors, 16 technicians and research engineers, and 2 administrative assistants. In addition, it hosts around 30 PhD students and 10 postdoctoral researchers.

PHELIQS conducts fundamental research activities in the fields of nanophysics and condensed matter physics, with potential mid- to long-term applications in information and communication technologies. The laboratory aims to understand and master the unique physical effects that appear in nanoscale solid-state systems and quantum materials, both experimentally and theoretically. To achieve these goals and develop application-oriented systems, PHELIQS maintains strong collaborations with a network of French and international pre-industrial and industrial partners, including CEA-LETI and companies like Aledia, Single Quantum, or EnWires.

PHELIQS has solid expertise in instrumentation and methods for the synthesis of innovative bulk materials (mainly crystals) and nanostructures (semiconductor nanowires and quantum dots, monolayers of graphene, high-mobility germanium heterostructures, and other two-dimensional materials). The laboratory also has access to advanced cleanroom technology for device fabrication. PHELIQS has developed customized high-performance instrumentation for physical measurements under extreme conditions (low temperature down to 10 mK, large magnetic field, high pressure) or requiring ultra-high sensitivity (optical studies at the single-photon level, scanning tunneling microscopy and spectroscopy, RF manipulation with arbitrary wave generation, and reflectometry readout at the single-shot level). PHELIQS also leverages its strong theoretical expertise in condensed matter physics (superconductivity, magnetism, strongly correlated electron systems) as well as in quantum and mesoscopic physics, and is at the forefront of the development of new codes for "computer-assisted" theory in quantum condensed matter physics.

This booklet presents 19 different Master 2 projects, most of which are designed for potential continuation as PhD research. We hope they will spark your curiosity, and we look forward to welcoming you to our lab!

Manuel Houzet, Xavier Jehl, Eva Monroy, Head and Deputy-heads of PHELIQS
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THEORY

NANOMATERIALS AND PHOTONICS

QUANTUM MATERIALS

QUANTUM NANOELECTRONICS AND ENGINEERING

Theory

Master thesis Project

Tensor networks and quantum physics with Rust

The product of a sequence of matrices can be represented as a linear chain, for example A × B × C. This concept can be generalized by replacing matrices, which are 2-dimensional tables of numbers, with "tensors", tables of numbers of arbitrary dimension. A product of tensors is no longer necessarily linear in shape. Instead, it may be represented as a graph where the vertices correspond to tensors, and the edges correspond to tensor multiplications (or contractions).

This simple formalism finds fruitful applications in quantum physics, in machine learning, and in numerical analysis in general. Notably, tensor networks provide compact representations for many-body wave functions that would be much too large (in fact exponentially so) to be stored directly. Intuitively, they prioritize the tiny but important regions of Hilbert space that correspond to states with local entanglement over the vastly larger rest.

In this project we set out to improve the state of the art in the diagonalization of tensor networks. The work combines theoretical quantum physics with a good dose of numerical programming involving the Rust programming language. Rust is a modern replacement of C/C++. Its unique properties allow to express high-performance parallel computations such that already the compiler can detect many problems. With other languages, similar problems can remain undetected and manifest themselves only later as difficult to find bugs.

This internship will take place in the theory group of Pheliqs at CEA Grenoble. A specialty of our group is the creation of open-source research software. See for example https://kwant-project.org/.

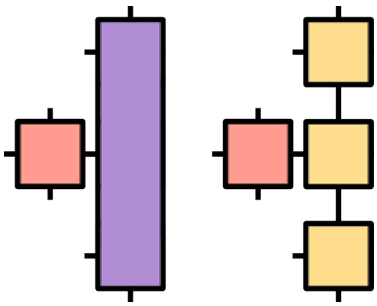

Image source: Wikipedia article "Tensor network"

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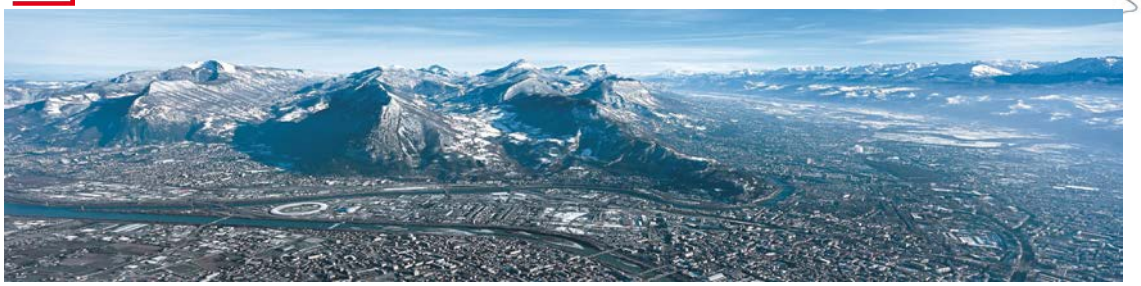

Master thesis Project

Superconducting spin-boson model for an Andreev qubit

Despite spectacular progress over the last 20 years, there seems to be an emerging consensus in the quantum technology community that current qubits are not sufficiently well protected against relaxation and dephasing mechanisms. Therefore, a lot is at stake in designing new types of qubits with inherent protection. A promising route, that is actively explored and that the master project inscribes itself in, is the combination of bosonic and fermionic degrees of freedom.

A Josephson junction formed by a weak link between two superconductors can accommodate localized fermionic states, known as Andreev bound states, whose energy depends on the phase difference between the two superconductors. New types of qubits realized by coupling these Andreev bound states to a bosonic mode of the surrounding electromagnetic environment have been proposed recently. The general idea is to convert two possible occupations of an Andreev bound state into two logical states of the qubit encoded in well-separated regions of the space of superconducting phase differences near 0 and π (modulo 2π), respectively. Such a separation is expected to strongly suppress the relaxation between two qubit states and therefore protects the qubit. However, at the same time it makes it harder to address the qubit. The aim of the master project will be to assess theoretically the best compromise between the desire to reach good protection and the needs for qubit manipulation.

In spite of the complexity of the circuit, a phenomenological model that contains the basic ingredients to describe such qubits involves a quite limited number of degrees of freedom: a spin, which accounts for the Andreev bound state occupation, and an oscillating mode of the environment. Their coupling is provided by the quantum fluctuations of the phase difference across the Josephson junction, which are driven by the displacement of the oscillator. As a first step, we will evaluate the performance of a qubit described by the resulting Hamiltonian and identify observables that allow one to assess the proper functioning of the qubit. Despite the apparent simplicity of the model, we expect that the interplay of various energy scales (Andreev gap, charging and inductive energy) and external control parameters (magnetic flux, electrostatic gate) can result in a broad variety of regimes. Our study will provide a useful guidance for the qualitative effects to be expected in realistic devices.

Analysis of the phenomenological Hamiltonian will rely on standard methods of theoretical condensed matter physics, such as analytical methods based on the Born-Oppenheimer picture of a spin degree of freedom coupled to a quantum oscillator. We will benchmark the results from the emerging physical picture with numerical evaluations based on exact numerical diagonalization.

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The internship will be supervised jointly with Benoit Douçot (LPTHE, Paris). A possible extension for a PhD project will be to explore more complex models needed for a quantitative description of the experiments. The focus will be, e.g., on the role of the quasiparticle continuum and the effect of additional Andreev bound states. The main issue here lies in the precise correspondence between theory and experiments. We will constrain the theoretical models by fitting their spectroscopic predictions with actual experiments performed in the Quantronics group in Saclay.

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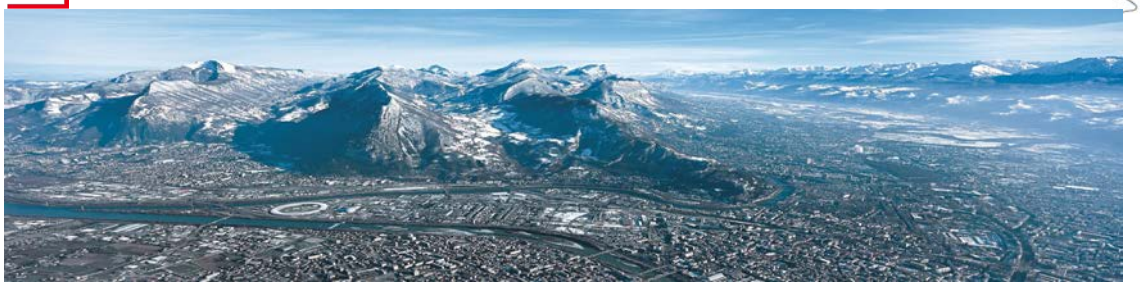
Nanomaterials and photonics



Master thesis Project

Topological-superconductor group IV nanomaterials

Progress in quantum computing stems from major advances in materials science and engineering, and their integration into novel fabrication techniques to develop scalable solid-state qubits architectures. Over the last decade, a plethora of solid-state quantum devices have been developed by combining multiple materials with inherently different properties within the same device - *heterogeneous integration*. This is a significant challenge in materials science, where quantum device operation with high performance requires a very high purity of the interface between two different materials. Any structural defect and roughness at the interface could compromise the ability to detect and manipulate quantum states in solid-state devices.

The goal of this internship is to develop a scalable material platform where quantum properties can be engineered simply by tailoring the crystal structure of a single atomic element – *Tin (Sn)* – and achieve interfaces with the highest quality. Topological insulator/semimetal phases can be tailored in diamond cubic α-Sn by controlling strain,[1] while body-centered tetragonal β-Sn behaves as a superconductor at temperatures below 4 K.[2] Currently, a controlled switch between α/β-Sn phases is out of reach in a conventional thin film geometry.

The student will establish the growth of one-dimensional (1D) Sn nanowires (NWs) on a Silicon wafer in a molecular beam epitaxy (MBE) system. In NWs a precise control over the growth of α/β-Sn phases (*i.e.* topological/superconductor phases) becomes possible, resulting in defect-free atomically-sharp interfaces with the highest purity. This will provide a truly *homogeneous integration* of multiple states of matter in solid-state quantum devices, paving the way to explore the fundamental processes in topological quantum computation,[3] spintronics,[4] and quantum photonics.[5]

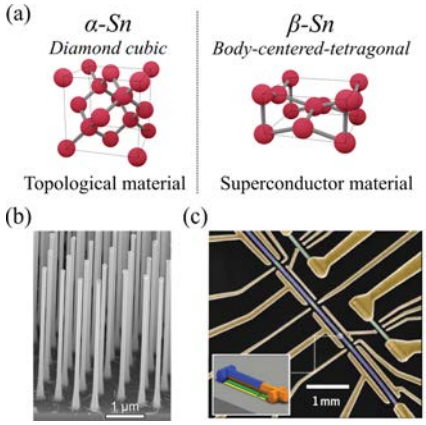


Figure: (a) Allotropes of Sn. (b) Vertical NW array. (c) Single NW quantum device.

For more information on this topic please read these recent publications (available on demand):

[1]. A. Barfuss *et al.*, Phys Rev Lett. 111, 157205 (2013). [2]. Y. Zhang *et al.*, Sci Rep. 6, 32963 (2016). [3]. A. Stern, N. H. Lindner, Science (1979). 339, 1179-1184 (2013). [4]. J. Ding *et al.*, Advanced Materials. 33, 2005909 (2021). [5]. E. D. Walsh *et al.*, Science (1979). 372, 409-412 (2021).

Possible collaborations and networking. Collaborations with Canada (Polytechnique Montréal), Italy (University of Milano Bicocca), Singapore (Nanyang Technological University), Denmark (University of Copenhagen), and U.S. (University of Pittsburgh) for atomic-level characterization of materials and devices, strain engineering, and quantum transport measurements.

Possible extension as a PhD: Yes.

Required skills: Interest in performing collaborative experiments in the lab (materials growth, fabrication of devices and quantum optoelectronic measurements), background in solid-state physics.

Starting date: Spring 2024.

Contact. Simone Assali (IRIG/PHELIQS, Grenoble).

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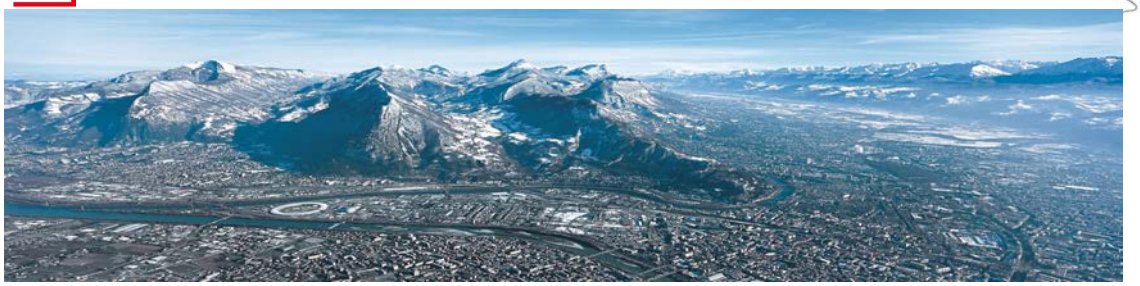

Master thesis Project

Selective area growth of GeSn infrared photonic devices

Developing all-group IV semiconductor infrared light emitters and detectors is an attractive approach towards the monolithic integration of photonics and electronics on the same platform.[1] This long sought- for silicon photonics has recently gained revived interest motivated by pressing needs for ultrafast data transfer and low-power electronics. With this perspective, direct bandgap GeSn semiconductors have been attracting great interest for a Si-compatible processing. Over the last decade, tremendous progress was made in the epitaxial growth of GeSn semiconductors grown on a Si wafer, resulting in a direct band gap material (*i.e.* high efficiency for the optical emission) when the incorporation of Sn increases above ~9 at.%. Photodetectors, lasers, and LEDs operating from short-wave infrared (SWIR: 1.5-3 µm) to mid-wave infrared (MWIR: 3-8 µm) are now available using direct band gap GeSn semiconductors.[2,3] However, GeSn material quality is the main limiting factor in the efficiency of optoelectronic devices. The growth of GeSn is commonly performed on Si using Ge as an interlayer, and the resulting lattice-mismatch with the Ge/Si substrate leads to compressive strain in GeSn. When the critical thickness is exceeded, plastic relaxation takes place and structural defects are formed in GeSn. Defects are a source of nonradiative recombination and largely contribute to the dark current of GeSn photonic devices, in turn strongly reducing efficiency.

The goal of this internship is to overcome the boundaries of the current epitaxial growth of GeSn by developing selective area growth (SAG) from patterned SiO_2 trenches on a Si wafer. The SAG has proven to be a highly valuable approach for the integration of III-V semiconductors on Si,[4] with similar results that are now being explored in Ge.[5] By tailoring the dimensions of SiO_2 trenches that are patterned using electron beam lithography, the student will develop the SAG of GeSn and evaluate its structural properties using a variety of characterization techniques down to the atomic-level.

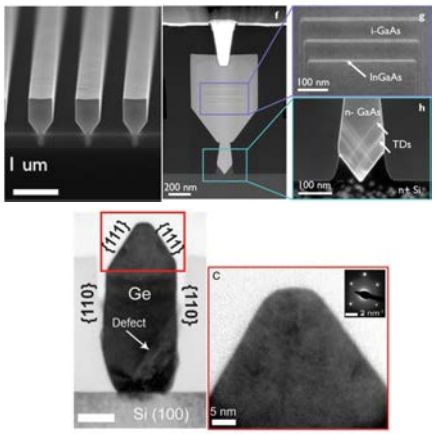

Figure: SAG of III-V (a)[4] and Ge (b)[5] semiconductors on a Si wafer.

For more information on this topic please read these recent publications (available on demand):

[1]. O. Moutanabbir *et al.*, Appl Phys Lett. 118, 110502 (2021).
[2] M.R.M. Atalla *et al.*, ACS Photonics 9 (2022). [3] Y. Zhou *et al.*, Phot. Res. 10 (2022). [4] Y. De Koninck *et al.*, https://www.researchsquare.com/article/rs-3187756/v1 (2023).
[5]. S. P. Ramanandan *et al.*, Nano Lett. 22 (2022).

Possible collaborations and networking. Collaborations with CEA-Leti, Canada (Polytechnique Montréal), Singapore (Nanyang Technological University), for atomic-level characterization of materials and optoelectronic measurements of the infrared photonic devices.

Possible extension as a PhD. Yes.

Required skills. Interest in performing collaborative experiments in the lab (materials growth, fabrication of photonic devices, optoelectronic measurements), background in solid-state physics.

Starting date. Spring 2024.

Contact. Simone Assali (IRIG/PHELIQS, Grenoble).

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Master M2 thesis Project

Growth of efficient nanowire-based single-photon emitters for free-space communication

General Scope: Single-photon sources are a key component in the framework of quantum communication and computing. In particular, they are required for the transmission of a secret decryption key, intrinsically secured by the laws of quantum physics. Our group develops the growth and optical studies of CdSe quantum dots (QDs) embedded in bottom-up core-shell ZnSe nanowires (NWs), all grown by molecular beam epitaxy (MBE). We have shown that these QDs are able to emit single-photons up to room temperature. Moreover, their emission in the blue-green spectral range is particularly appropriate for both free air-space and underwater communication.

Subject: The master internship aims at controlling the growth of these CdSe/ZnSe NW-QDs in order to enhance their efficiency as single-photon emitters. That means: (i) optimizing the growth of core-shell type nanowire heterostructures in order to enhance the emission quantum yield, (ii) acquiring the control of the QD shape and purity to permit the emission of entangled photons.
The internship combines MBE growth, structural characterization (scanning electron microscopy) as well as optical characterization. It offers the opportunity to explore a broad range of basic physical phenomena (growth mechanisms, optical properties, etc.) at the nanometric scale, while contributing to the development of a device essential for the field of quantum communication and quantum information processing.

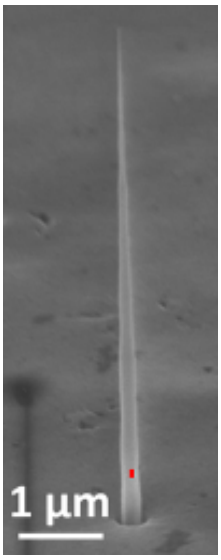

Fig. : CdSe QD (sketched in red) in a ZnSe nanowire.

Environment and collaborations: Our group "NanoPhysics and Semiconductors" is a joint CEA/CNRS team and the intern will interact closely with researchers of our group both in CEA-IRIG and in CNRS-NEEL.

Required skills: Nanosciences, material science, semiconductor physics, with interest for experiment and work in collaboration.

Starting date: February or March 2024
Duration: 4-5 months

Laboratory: CEA-Grenoble/PHELIQS/NPSC: www.pheliqs.fr/Pages/NPSC/Presentation.aspx

Contact: send your application (including CV) by e-mail to:

- Dr. Edith BELLET-AMALRIC: edith.bellet-amalric@cea.fr
- Prof. Kuntheak KHENG: kkheng@cea.fr

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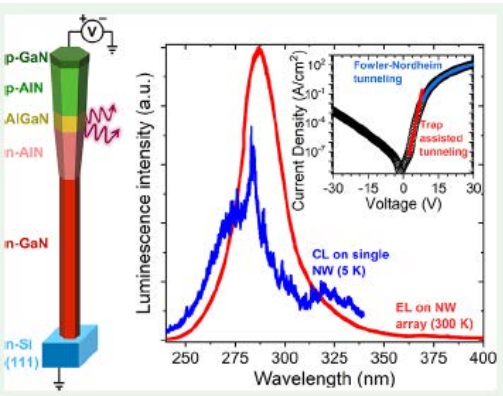
Master thesis Project

p-type doping of AlN nanowires for UV-C LEDs realization

The realization of efficient UV-C (200-280 nm) ligth emitting diodes (LEDs) is a current challenge to meet the requirements of numerous applications ranging from water, air and surface disinfection to short distance encrypted communication. However the efficiency of conventional UV-C LEDs is still low due to poor p-type doping and limited light extraction. In this context, the CEA/CNRS consortium involved in the realization of such emitters is developing a new strategy by using AlN nanowires (NWs). As a matter of fact, the absence of extended defects in NWs, the higher limit solubility of both Si (n-type) and Mg (p-type) electrical dopants, the eased light extraction intrinsically related to the large "roughness" of an ensemble of NWs make them particularly suitable to the realization of efficient UV emitters.



A scheme of such LEDs is shown in the figure. The inset shows the current-voltage characteristics which assesses the rectifying character of the device. Finally, an electroluminescence (EL) spectrum is shown assessing the successful realization of a UV-C LED. However, efficiency improvement now requires optimization of p-type doping, which will be the core of the present project, i.e. the growth, structural, optical and electrical characterization of p-type AlN nanowires.

The growth of the structures will be performed by plasma-assisted molecular beam epitaxy in CEA-Grenoble IRIG/PHELIQS-NPSC. Electrical characterization will be made in Institut Néel following NW processing in clean room environment. The optical characterization will be made in collaboration between CEA and Institut Néel.

This project requires a strong interest in experimental science (Nanoscience, Nanophysics academic background) and could be extended into a PhD.

APPLY

To apply for this position, send your application (including CV) by e-mail to: bruno.daudin@cea.fr, bruno.gayral@cea.fr or gwenole.jacopin@neel.cnrs.fr

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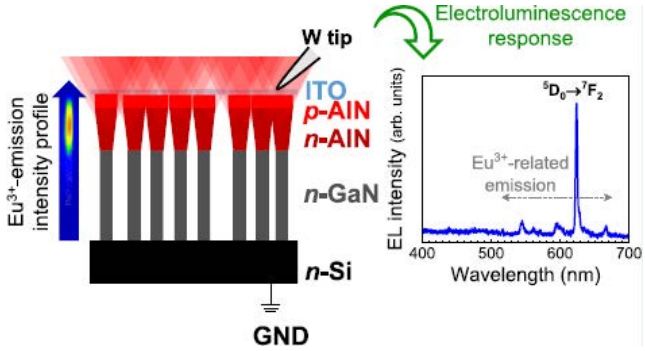
Master thesis Project

Eu- doped InGaN quantum disks in GaN and AlN nanowires for efficient red LEDs realization

The realization of red/green/blue (RGB) micro-LEDs is a current industrial challenge for micro-display applications. While the efficiency of InGaN/GaN-based blue LEDs (and to a large extent green ones) is very high, there is still room for improvement as concerns red LEDs, which are still far from meeting the requirements for integration in devices. The difficulties met, namely a high density of extended defects, an increased quantum confined Stark effect (QCSE) for increasing In content and a limited current injection on p-type side can be potentially overcome by using nanowire (NW) heterostructures. As a matter of fact, the absence of extended defects in NWs, the higher limit solubility of both Si (n-type) and Mg (p-type) electrical dopants, the eased light extraction intrinsically related to the large "roughness" of an ensemble of NWs make them particularly suitable to the realization of efficient red emitters. In this context, the CEA/PHELIQS laboratory has been collaborating for many years with Aledia company in view of realizing innovative, efficient NW-based LEDs grown by molecular beam epitaxy (MBE). Along these lines, the proposed project will consist in the MBE growth, structural and optical characterization of GaN/InGaN or AlnN/InGaN NW heterostructures containing Eu in the InGaN quantum disks. Preliminary results are shown in the schematics, where Eu was implanted in the depletion region of an AlN NW p-n junction. A sharp electro-emission peak is shown at 620 nm, assigned to Eu. The goal of the master internship will be to directly incorporate Eu in NW heterostructures during MBE growth, and subsequently to study the structural and optical properties of the grown nanostructures. This project requires a strong interest in experimental science (Nanoscience, Nanophysics academic background) and could be extended into a PhD.



APPLY

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Master M2 or M1 thesis Project

Characterization of polarization correlated and entangled photon pairs from a semiconductor quantum dot

General Scope: The 2022 Nobel Prize in Physics, awarded among others to Alain Aspect, recognizes the importance of entanglement for quantum technologies. Entangled states of light play a key-role to several quantum information applications: ultra-secure communication, quantum sensing and metrology, quantum networks, etc. Epitaxial semiconductor quantum dots (QDs) are considererd as promissing emitters that can lead to a scalable technology for triggered sources of entangled photons.

Subject: Our group develops the growth and optical studies of CdSe QDs embedded in bottom-up core-shell ZnSe nanowires (NWs). The NW is moreover embedded in a photonic wire acting as a waveguide to direct the QD emission and thus enhance the photon collection. A route to generating entangled photons is based on the radiative process called biexciton-exciton (XX–X) cascade in a single QD. These radiative cascades give rise to either polarization correlated photon pairs, or entangled photon pairs, depending on the structural symmetry of the QD system.

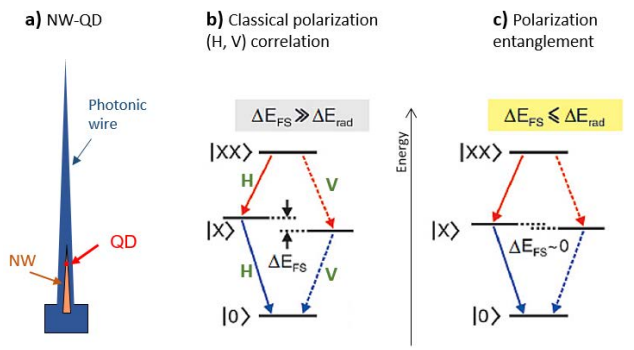

Fig : a) a QD in a NW with a photonic shell, (b) and (c) biexciton-exciton (XX–X) radiative cascades leading to Polarization Correlated or Entangled Photon Pairs.

The master internship aims at (i) setting up the optical experimental system that will allow us to study polarization correlation properties, (ii) investigating the polarization properties of biexciton-exciton photon pairs as well as the emission properties of the NW-QD structure.

Environment and collaborations: Our group "NanoPhysics and Semiconductors" is a joint CEA/CNRS team and the internship will take place both in CEA-IRIG and CNRS-NEEL. The intern will closely interact with the researchers who grow the NW-QD structure by Molecular Beam Epitaxy.

Required skills: Semiconductor physics, optics, photonics, with strong interest for experiment and work in collaboration.

Starting date: February-April 2024
Duration: 3-5 months

Laboratory: CEA-Grenoble/PHELIQS/NPSC : www.pheliqs.fr/Pages/NPSC/Presentation.aspx

Contact: send your application (including CV) by e-mail to Prof. Kuntheak KHENG : kkheng@cea.fr

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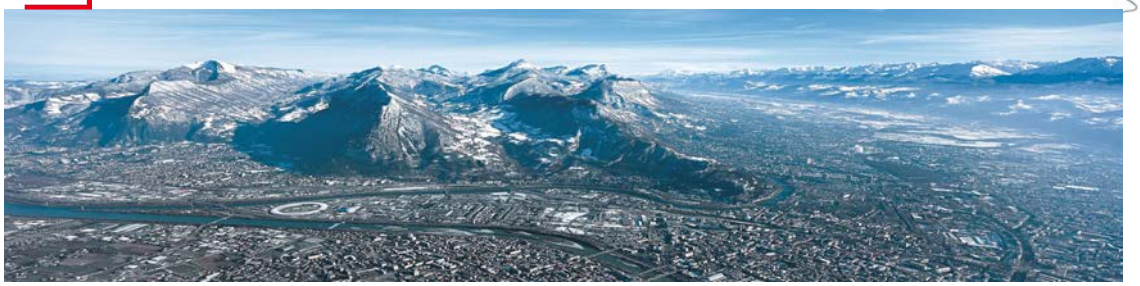

Master Thesis Project
Nm-Scale Characterization of the Electrical Properties of *p-n* Junctions by Transmission Electron Microscopy

General Scope: Semiconductor *p-n* junctions serve as fundamental building blocks in devices like solar cells, avalanche photodetectors or light emitting diodes. Nonetheless, the visualization of electrically active doping levels in semiconducting materials with nanometer precision remains a formidable challenge, particularly in wide bandgap materials characterized by high dopant activation energies..

Internship Objective: This internship aims to make a significant contribution to the investigation of p-n junction semiconducting materials, focusing specifically on their electrical properties at the nanometer scale. The selected student will become an integral part of a multi-institutional, interdisciplinary research team. Their primary responsibility will involve the fabrication of electrical contacts for p-n junction nanowires and thin films composed of various materials, including GaN and AlN. These p-n junctions will be electrically connected to membrane chips that are compatible with transmission electron microscopy (TEM) measurements. Additionally, the student will be responsible for conducting initial electrical characterization. By combining *in-situ* biasing techniques with 4D scanning TEM (4D-STEM) methods sensitive to electric fields, our goal is to achieve a precise quantitative description of the electrical properties of these objects at the nanometer scale.

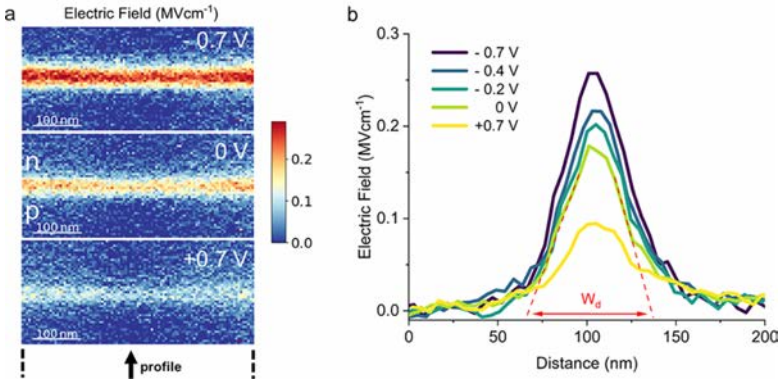

Figure 1. (a) 4D-STEM electric field maps of a silicon p–n junction. (b) Profiles of the electric field obtained from the maps in (a) by integration along the entire map. The measured depletion length for zero bias is indicated. [https://doi.org/10.1021/acs.nanolett.2c03684]

The student's work will involve:

- Nanowire contacting in a cleanroom environment. It implies nanowire dispersion, mapping using scanning electron microscopy, and assisting electron beam lithography.
- Current-voltage measurements to assess the electrical properties and performance
- The student will participate in the 4D-STEM characterization in a cutting-edge microscope.

Required skills: Interest in solid-state physics, electrical and optical properties of semiconductors and advanced characterization techniques like transmission electron microscopy.

Starting date: Jan/Feb/Mar 2023

Contact: Eva MONROY (eva.monroy@cea.fr) and Martien DEN HERTOG (martien.den-hertog@neel.cnrs.fr)

APPLY NOW!

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17 av. des Martyrs – 38054 Grenoble cedex 9 – France

Master Thesis Project
Nitride/Oxide Heterostructures for Power Electronics

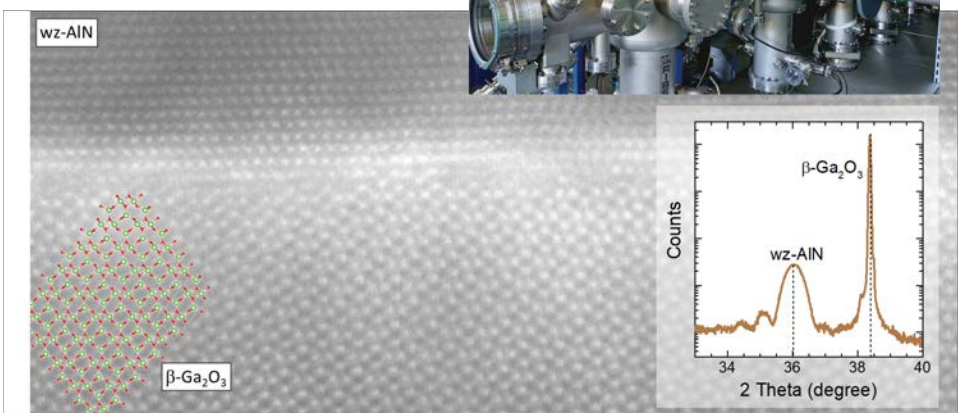
Context: The increasing demand of growth of electricity consumption, linked to the challenges of digital and ecological transition, is boosting the market for power electronics. With their high breakdown electric field, ultra-wide-bandgap semiconductors (UWBG) like gallium oxide (Ga_2O_3) and aluminum nitride (AlN) are promising competitors for the next generation of power electronics, surpassing not only traditional silicon-based materials but also GaN and SiC. UWBG materials can handle higher voltages, temperatures, and power densities. Nitride/oxide heterostructures hold great promise for power electronics by offering a compelling combination of UWBG properties, high breakdown voltage and fast switching capabilities.

Targets and strategy: The fabrication of an AlN/oxide device requires to address a number of material challenges, particularly the nucleation of epitaxial AlN on Ga_2O_3 managing the polarity of the AlN layer and the eventual activation of thermal interdiffusion. These phenomena can determine the electronic properties of the heterojunction. During this internship, we will optimize the AlN/Ga_2O_3 interface in terms of structural quality and electrical performance. Our ultimate goal is the fabrication of a chemically-sharp AlN/Ga_2O_3 heterostructructure hosting a polarization-induced two-dimensional electron gas at the interface.

The student will be trained in epitaxial growth of III-nitride semiconductors on gallium oxide. He/she will perform structural characterization of the samples using atomic force microscopy, scanning electron microscopy and x-ray diffraction. Transmission electron microscopy will also be accessible through in-place collaborations. Additionally, the student will be trained in cleanroom processing to perform basic electrical characterization of the material.

Required skills: Taste for experimental work. Interest in solid-state physics, semiconductors, epitaxy, structural and electrical characterization.

Starting date: Jan/Feb/Mar 2023



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Master thesis Project

Highly tunable single-photon sources emitting in the telecom bands

Context:

Efficient sources of non-classical light are key devices for photonic quantum technologies. Ideally, such sources should emit in telecom bands, be compatible with on-chip integration notably with the well-established silicon technologies. Monolithically integrated telecom-band single photon sources (SPSs) have been realized using III-V semiconductor quantum dots (QDs) and optically active defects in SiC or Si. Semiconductor quantum dot-nanowires (QD-NWs) constitute an appealing platform, with exceptional attributes: over 99% single photon purity, 0.72 collection efficiency, and a 1.2 ns coherence time. They are also capable of generating high-brightness entangled photon pairs and emit in the O and C telecom bands. Finally, QD-NWs offer tunable geometries for controlled photonic properties. However, a major challenge arises due to the inherent variations in emission wavelength among the QDs, hindering large-scale integration for quantum devices using photons as qubits.

We aim to address this very challenge by creating highly-tunable SPSs in the telecom band on silicon substrates. We propose to embed a III-V semiconductor QD-NW within a phase change material (PCM) shell. The concept relies on using PCM crystallization-induced volume changes to strain the QD-NW and adjust its emission energy in situ with a focused laser beam. This project focusses on the development of single photon sources using InGaAs/GaAs quantum dot nanowires grown by molecular beam epitaxy (MBE).

This research will explore two fabrication routes: the bottom-up approach (vapor-liquid-solid (VLS) growth) and the top-down approach (etching to define nanowires embedding a single or few QDs). On the one hand, the bottom-up fabrication route – more exploratory – features promising assets. On the other hand, the top-down approach has already demonstrated excellent results in terms of performance. To control the QD optical properties, we will apply a strain on the QD by controlling the phase change of a capping HfO2 shell.

Objectives and means available:

The primary objectives of this M2/PhD proposal are as follows:

- To develop single photon sources using GaAs/InAs QD nanowires, employing both bottom-up (VLS) and top-down (SK and etching) approaches.
- To investigate the optical properties and performance of the fabricated single photon sources, focusing on the brightness and linewidth of the emitted single photons.
- To evaluate the influence of strain on the optical emission characteristics of the QD nanowires by capping them with a layer of HfO2 and studying the resulting optical response.

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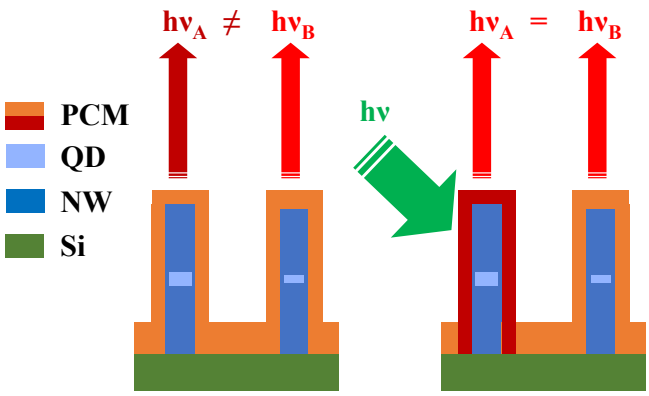

Figure 1: *Concept of the project: QD-NWs are grown on Si and capped with an amorphous PCM used as a shell. They emit single photon sources at two different wavelengths. The PCM crystallization state of one nanowire is controlled by heating with a laser light. Strain appears between the core and the shell of the nanowire due to the change in volume of the PCM. Consequently, the emission wavelength of the QD shifts. The amount of strain is tuned carefully to reach the desired wavelength.*

The available resources include a III-V molecular beam epitaxy (MBE) system for growing nanostructures, atomic layer deposition (ALD) equipment for depositing HfO2 shells, scanning electron microscopy (SEM), and access to cleanroom facilities. Optical characterizations will be conducted using micro-photoluminescence spectroscopy setups cooled to cryogenic temperatures. Additionally, the student will receive support from colleagues involved in the development of top-down structures in the cleanroom, which will help expedite the achievement of the project's goals.

The internship/PhD will take place within the ANR SONATE (granted in 2023). The different partners (material scientists, theoreticians and experimentalists) exchange regularly during meetings and research visits.

Possible collaboration and networking:
ANR SONATE partners: INL-Lyon, ILM-Lyon, IRIG-PHELIQS
Research Networks: GdR Matepi

Required profile:
We are looking for a student interested in experimental research. Knowledge in materials science and physics are mandatory. We are looking for a person curious with organizational skills and with ability to perform delicate experiments.

Possible extension as a PhD: yes, through the Quantalps PhD program (Spring 2024)

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moira.hocevar@cea.fr and julien.claudon@cea.fr

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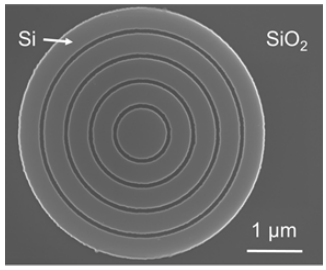
Master thesis Project

A deterministic source of single photons on a silicon chip

Applications of quantum photonics to quantum communications and quantum simulation or computing require a scalable, compact and low-cost technology for future widespread deployment. The silicon-on-insulator (SOI) platform is a highly attractive in this context, offering the possibility to implement a large panel of integrated devices for the coherent manipulation, encoding and detection of single photons. However, the lack of a source able to emit a well defined single photon increases the complexity and limits the performances of quantum photonic chips. The recent observation of photon antibunching for isolated color centers in implanted silicon, such as the G center [1] or the W center [2] is a game changing advance. It shows that the spontaneous emission of such a color center can be used to generate one and only one photon on demand. In view of practical applications, single photons must be prepared in a well defined quantum state. As shown for other single photon emitters such as quantum dots, this can be achieved by embedding the emitter inside an optical cavity, so as to harness quantum cavity effects and tailor spontaneous emission. In a highly encouraging preliminary experiment, we observed a strong enhancement of the zero-phonon emission of G centers embedded in SOI microrings [3].



In this context, this Master project will extend these studies to cavities containing a single color center. We will combine a single W center and a "Bull-eye" cavity such as the one shown in the figure. This choice is motivated by the high quantum efficiency of W centers and by the highly directive radiation pattern of Bull-eye cavities, enabling highly efficient off-chip collection in a normal-incidence geometry. We will then characterize fully the properties of these novel single-mode single photon sources, by measuring their efficiency, the purity and the degree of indistinguishability of emitted single photons.

The host team at CEA-PHELIQS has contributed to the first demonstrations of single photon emission by single color centers in silicon [1,2] and reported also the first observation of spontaneous emission enhancement for color centers in a SOI cavity [3]. These pioneering results provide solid ground for the Master project, which could be continued as a PhD project.

[1] W. Redjem et al, Nature Electron. 3, 738 (2020), A. Durand et al, Phys. Rev. Lett. 126, 083602 (2021) ; [2] Y. Baron et al, ACS Photonics 9, 2337 (2022) ; [3] B. Lefaucher et al, Appl. Phys. Lett. 122, 061109 (2023)

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Quantum Materials

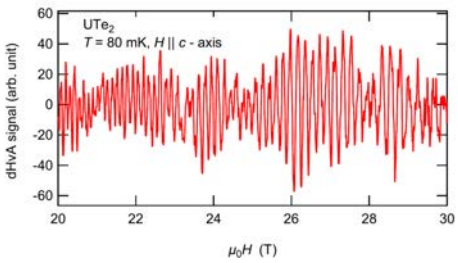
Master thesis Project

Topological superconductivity and Fermi Surface in UTe_2

General Scope: Topological superconductivity has become a subject of intense research due tc its potential for breakthrough in the field of quantum information. The key feature is the prediction of zero-energy excitations called "Majorana modes", present on the surface or in the vortex cores. However, despite intense research there is up to now no clear realization of a topological superconductor. Bulk systems are a promising possibility, with candidates found mainly among unconventional superconductors, which are also strongly correlated electron systems. More specifically, prominent systems for such topological superconducting states are superconductors with an odd parity superconducting order parameter, and their potential topological properties depend crucially from the topology of the Fermi surface. UTe_2 is one of the most prominent candidates for topological superconductivity.

Subject: UTe_2 is a strongly correlated electron system with very flat bands at the Fermi surface and thus the effective masses are expected to be very high. We propose a new approach to detect the quantum oscillations through the development of a new experimental technique (for IMAPEC), relying on a tunnel diode oscillator (TDO) circuit. The "TDO method" is a contact-less high frequency (10-50 kHz) ac susceptibility measurement, based on a resonance technique probing the electrical, magnetic and superconducting properties of a metal and has been shown to be very sensitive to quantum oscillations. This technique can also be used under high pressure.

Environment and collaborations: The study of topological superconductivity in strongly correlated uranium compounds is a central research activity of the IMAPEC team of PHELIQS with recently a strong focus on UTe_2. Fermi surface studies will be performed in the lab, but also in collaboration with the high magnetic field laboratories in Grenoble (static magnetic fields up to 36 T) and Toulouse (pulsed magnetic fields up to 70 T) where strong collaborations exist. High quality single crystals of UTe_2 are grown in IMAPEC lab and available. The candidate will further profit from strong theoretical support from the theory group of Pheliqs, and have the possibility to interact with groups in Japan where tight collaborations are well established.



Quantum oscillations in UTe_2 detected by the dHvA effect in high magnetic fields

Required skills: The candidate should have sound knowledge in solid state physics, good practical skills and strong interest in the development of instrumentation. The subject can be continued by a PhD thesis.

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Master / PhD Thesis Project

Exotic properties in magnetically frustrated superconductors

General Scope: Unveiling new physics from simple lattice models plays a vital role in modern condensed matter physics. One of these lattice models is the Kagome lattice (KL) formed by corner-sharing triangles, see Fig. 1. The KL contains geometric frustration for spin systems, which gives rise to extensively degenerate ground states in the nearest-neighbor antiferromagnetic Heisenberg model. Accordingly, the ground state of the Kagome spin model is the most promising candidate for the long-sought after quantum spin liquid state. Recently, fermionic models on KLs have also become an important platform for studying the interplay between electron-electron correlations, band topology and lattice geometry. The point group of the KL is the same as that of graphene, leading to similar Dirac cones in the electron excitations dispersion. Superconductivity also appears in some KL materials: it has been argued that the KLs can host a variety of unconventional pairing superconducting states, including chiral superconductivity (SC) and f-wave spin-triplet SC, among others. However, superconducting KL materials are rare in nature. Recently, the newly discovered KL material CsV_3Sb_5 was found to be a quasi-2D Kagome SC with a transition temperature Tc ≈ 2.3 K [2]. Subsequently, superconductivity was also found across the entire family of compounds KV_3Sb (Tc ≈ 0.93 K) [3] and RbV_3Sb_5 (Tc ≈ 0.75 K) [4]. This discovery has stimulated extensive research activity in this field, with the underlying the natural question: would the frustration, accompanied by large fluctuations, favors the magnetic mechanism for superconductivity?

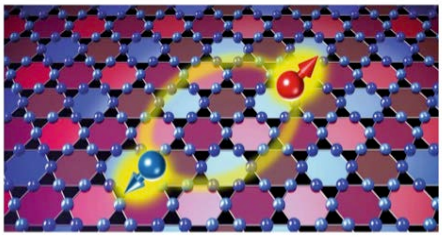

FIG. 1: Schematic of the charge order and superconductivity detected in Kagome superconductors AV_3Sb_5. The dark and light-blue spheres form the Kagome lattice. The shade of the colour represents the unusual distribution pattern of the charge order. The large red and blue spheres with arrows represent Cooper pairing of the superconductivity, from [1].

Subject: We propose an experimental and fundamental research project which will explore different types of frustrated superconductors among the AV_3Sb_5 (A = K, Rb, Cs) family. The goal is to use different transport (resistivity, thermoelectricity) and thermodynamic measurements (specific heat) under extreme conditions (low temperature, high magnetic field and high pressure), to characterize these materials, understand the different competing orders present and ultimately find new exotic orders.

Experimental environment: The candidate will benefit from a unique scientific environment: a dedicated dilution refrigerator (50mK-16T), a large range of experimental probes (resistivity, Hall effect, specific heat, thermal conductivity and thermoelectric effects…), the possibility to grow and characterize his own material in the laboratory, a strong interplay with theoreticians from the laboratory.

Possible collaboration and networking: The internship proposal is based on a long-term collaboration with the high magnetic field facility (LNCMI) in Grenoble and with close collaborators in Hong Kong and Japan.

Required skills: Master or Engineering degree. Skills on solid state physics or nanophysics will be appreciated. Motivation for experimental studies is needed.

The internship is aimed to be followed by a PhD.

[1] Yin, JX., *et al.* Nature **612**, 647 (2022)

[2] Ortiz BR, Phys. Rev. Mater. **3**, 094407 (2020)

[3] Ortiz BR, Phys. Rev. Mater. **5**, 034801 (2021)

[4] Yin Q, Chin. Phys. Lett. **38**, 037403 (2021)

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Quantum nanoelectronics and engineering

Master Project

Germanium bolometers for quantum information

In a bolometer, a small absorber heats up under photon absorption. Monitoring the absorber temperature in real time was shown to allow down to single-photon detection for high-energy radiation (X-ray). Quantum information processing in solid-state devices however is based on the exchange of microwave (MW) photons, which have several orders of magnitude lower energies. Extending the powerful bolometry method to the microwave range could be a formidable asset for future quantum technologies. Although the bolometric detection of a single microwave photon remains a challenge, promising steps have been achieved recently in this direction and new micro-bolometers have demonstrated impressive sensitivity [1], and even been used successfully to read a superconducting qubit state [2].

In this internship, we propose to develop novel micro-bolometers based on a two-dimensional hole gas in Germanium [3]. This novel 2D material holds promising perspectives for future quantum technologies, and its high-quality electrical interface to superconductors makes it suitable for novel bolometers development and integration with superconducting qubits.

The candidate will fabricate Ge-based superconducting Josephson junctions, basing on recipes already mastered in the team (fig.1), and characterize their potential as micro-bolometers in a dilution refrigerator. This internship can be pursued by a PhD thesis, during which the candidate will combine these novel detectors to Ge spin qubits and/or gate-based superconducting qubits already developed in the team, in order to reach unprecedented levels of qubit readout fidelities.

References :

[1] Kokkoniemi et al., *Nature* (2020)
[2] Gunyho et al., *arXiv* (2023)
[3] Scappucci, *Nature Rev. Mat.* (2021)

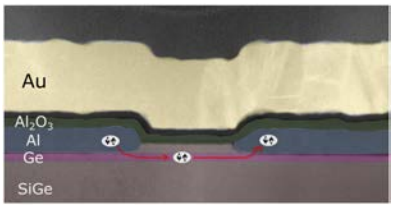

Fig.: Transmission Electron Micrograph of a Ge Josephson junction fabricated at the CEA clean room. (Courtesy of J. Labar, EK Budapest)

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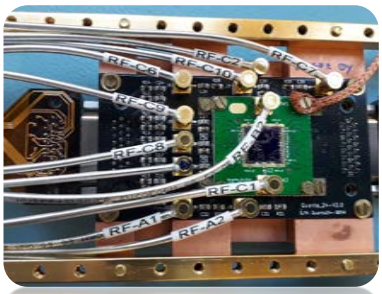
Master /PhD thesis Project

Silicon hole spin qubits hiding from the noise

Sample bonded and mounted, ready to be cooled to very low temperature



Quantum computing is currently pushing the frontier of information technology. Among other fields, solid-state hole-spin qubits in gate defined quantum dots are a promising research area. Recently, we have reached coherence times approaching 100 µs for a single hole spin in silicon, by decoupling the spin from electrical noise which is the main decoherence mechanism in these qubits [1].

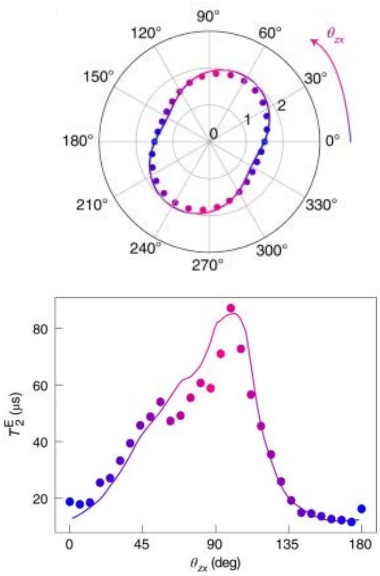
At the heart of this decoupling from electrical noise lies the anisotropic Zeeman interaction of the hole spin with an external magnetic field.

The aim of this master project is to characterize the anisotropic Zeeman interaction of a quantum dot containing three and five holes, going beyond the already well-known single occupied case. In doing so, possibly even longer coherence times might be found. The successful candidate will take over an experiment already running at 10mK and will perform measurements using state-of-the-art DC and RF techniques that will involve single spin manipulation and readout techniques.

Our research team is part of the French national "Plan Quantique" and is a founder member of the "Grenoble Quantum Silicon" group. A strong collaboration with the L-SIM group in the same building gives us a deep theoretical framework for our measurements.

This master project may continue as a PhD thesis, in order to answer open questions such as the origin of the remaining decoherence processes (possibly nuclear spins that can be removed by using isotopically purified ^{28}Si), the understanding of the energy relaxation times T1 of hole spin qubits, and the implementation of two qubit logic.

[1] Piot et al., Nature Nanotechnology 17, 1072, **2022**



Top: anisotropic Zeeman interaction of a single hole spin in a quantum dot as the magnetic field direction is varied in the plane of the device.
Bottom: Coherence time evolving with the magnetic field orientation approaching close to 100 µs. See Ref1 for more details.

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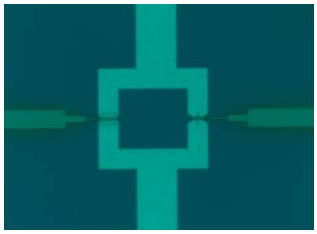
Master Project

Hybrid Superconductor – Semiconductor nanostructures

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 or injector. Second, from the semiconducting properties that allow changing the amount of carriers using an electrostatic gate – like in a field effect transistor (FET). New electronic properties and functionalities can appear from this unique combination which are revealed at very low temperature (typically below 1 K). The underlying mechanism that makes these nanostructures so appealing, is the proximity effect which describes how quantum coherence in the superconductor can leak into the semiconducting material and therefore strongly modify its electronic properties [1]. For example Al-Ge-Al based nanodevices with short Ge channel (~ few hundreds of nm) can exhibit a zero resistance state that can be controlled by a gate [2]. These devices have recently attracted a new interest with the possibility to realize reproducible high transparent S-Sm interface. Their potential for quantum technologies has been demonstrated with the realization of new types of superconducting qubits [3]
During this internship, the student will perform measurements at very low temperature of existing devices made from Si or Ge transistors with superconducting source and drain contacts. The objective is to characterize the S-Sm properties for the realization of more complex devices. He/She will acquire the experimental techniques related to electronic properties at very low temperature (T < 100 mK) and the physics of S-Sm interface. She/he will join the LaTEQS team (www.lateqs.fr) with 30 people including 15 PhD students and post-docs. The internship will take place at the CEA-Grenoble in the Minatec campus.

[1] Klapwijk, T.M.*J Supercond* **17**, 593–611 (2004)
[2] Vigneau et al. Nano Letters, **19**, 1023 (2019)
[3] Casparis et al. Nature Nano. **13**, 915 (2018)



SQUID geometry with two Al-Ge-Al superconducting transistors in a loop.

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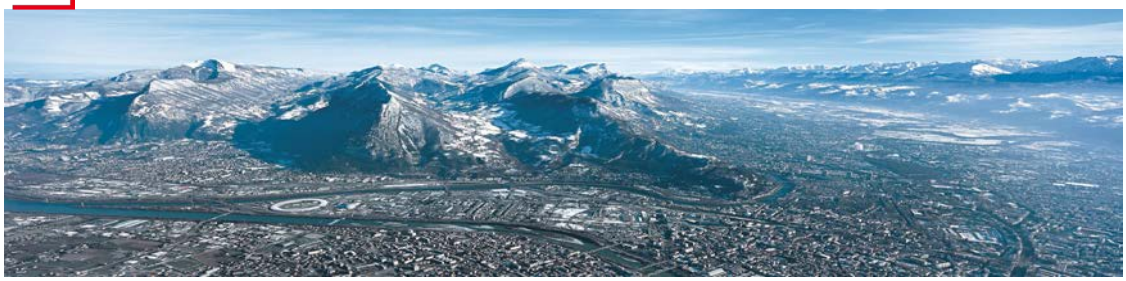
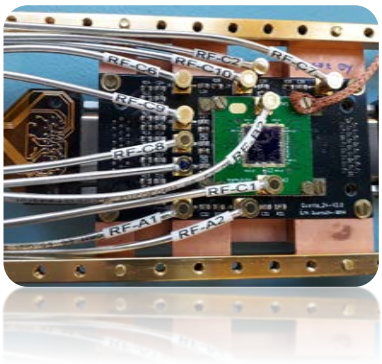


Master /PhD thesis Project

Hole spin and Circuit Quantum Electrodynamics

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.

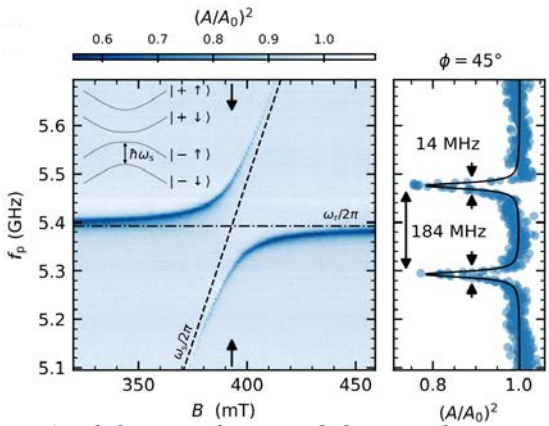
The aim of this project is to advance the field of spin cQED. First, we will probe the quantum state of the spin via the microwave photon through a quantum non-destructive protocol [2]. In parallel, we will study the spin coherence in such environment where its quantum properties may be strongly correlated to electro-magnetic noise.

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 two permanent researchers with one PostDoc and two 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.

[1] Nat. Nano 18, 741, **2023**

[2] Phys. Rev. A 75, 032329, **2007**



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

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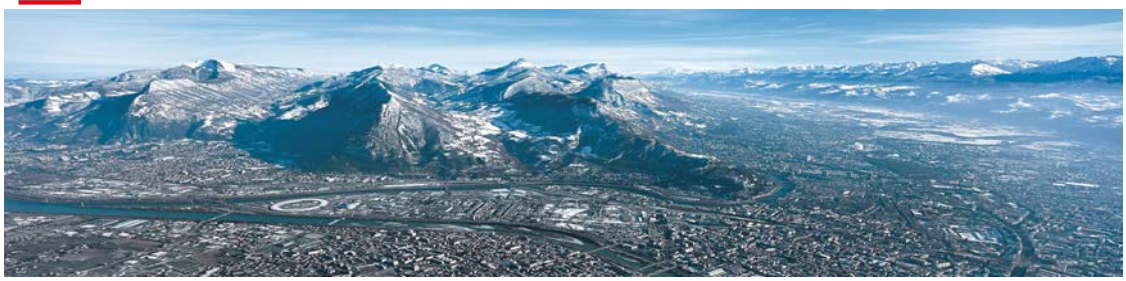
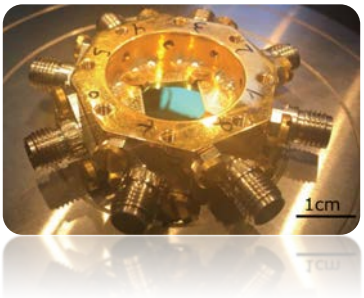


Master /PhD thesis Project

High quality superconducting resonators for spin circuit quantum electrodynamics

Measurement box containing a chip with superconducting resonators



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The aim of this project is to advance the field of spin cQED by improving the superconducting resonators, which are fabricated from superconducting thin films of NbN [3]. In order to achieve highly coherent spin-photon interfaces and high fidelity single-shot readout, superconducting resonators with quality factors reaching 10^5 to 10^6 are needed. 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 two permanent researchers with one PostDoc and two 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**

APPLY NOW!

To apply for this position, send your application (including CV) by e-mail to: simon.zihlmann@cea.fr & romain.maurand@cea.fr

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