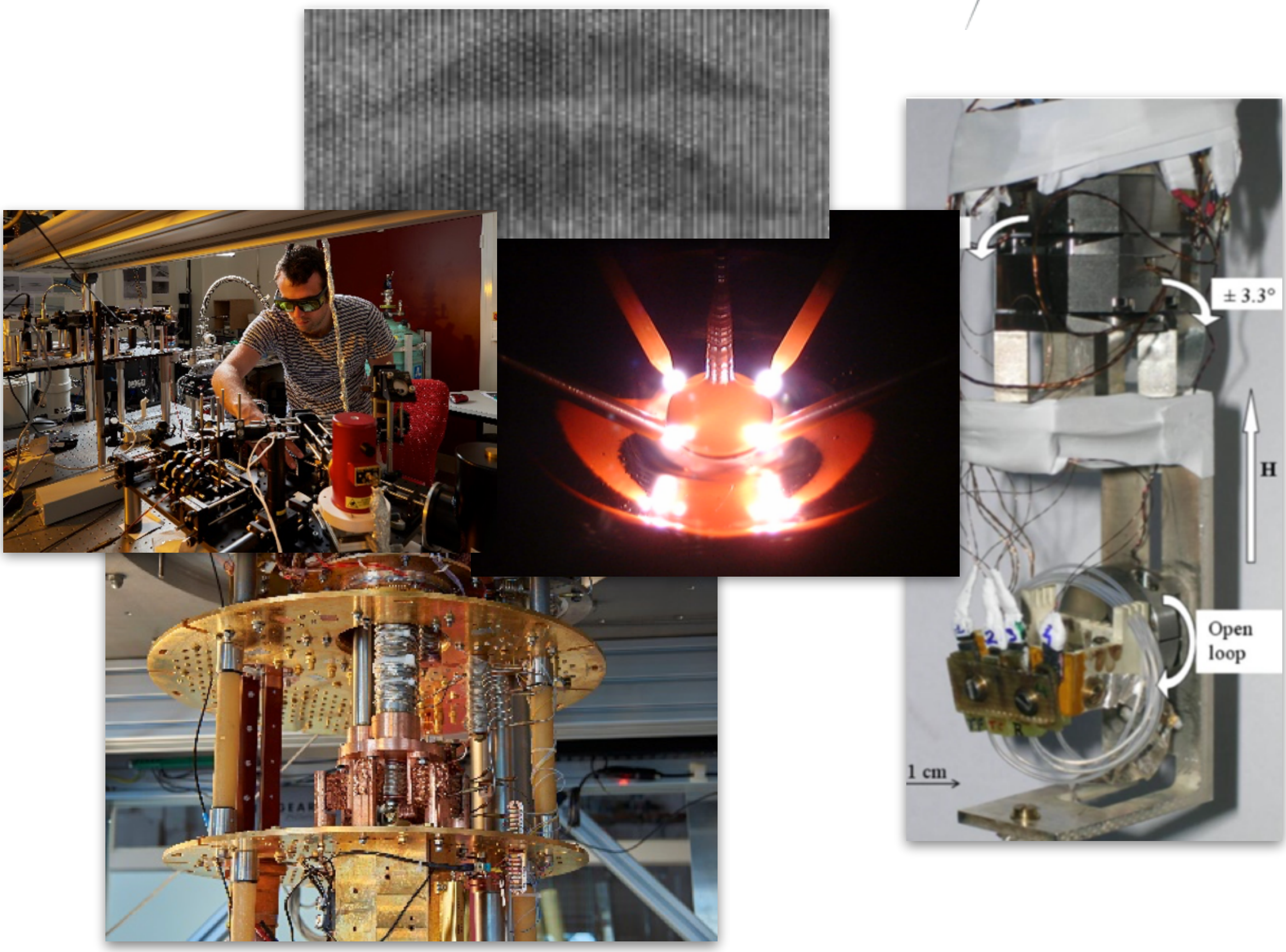
Master Thesis Projects 2022

Pheliqs

Quantum Physics & Engineering



The laboratory for Quantum Photonics, Electronics and Engineering (PHELIQS) is a joint research unit of CEA, the Univ. Grenoble Alpes (UGA), and Grenoble INP Graduate Schools of Engineering and Management, with strong links to neighboring CNRS laboratories. It brings together five teams with complementary expertise in the fields of quantum physics, nanostructures and quantum materials. As of Sept. 2021, PHELIQS has a permanent staff of 52 persons (36 researchers, 14 technicians and research engineers, 2 administrative assistants) and hosts 21 PhD students and 7 postdoctoral researchers.

PHELIQS is a fundamental research laboratory with activities in the fields of nanophysics and condensed matter physics, with potential mid or long-term application prospects for information and communication technologies. Our goal is to understand and master the unique physical effects (in most cases of quantum origin) that appear in nanoscale solid-state systems and in quantum materials, both experimentally and theoretically. With these targets in mind and with a view to developing application-oriented systems, PHELIQS maintains strong collaborations with a network of French and international pre-industrial and industrial partners, including laboratories of the Technological Research Division of CEA such as CEA-LETI, as well as companies like Aledia, Single Quantum, EnWires…

The scientific activities of PHELIQS are based on a solid know-how on 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), as well as access to advance cleanroom technology for device fabrication. We have developed custom 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 waves generation and reflectometry readout at the single shot level). PHELIQS also builds upon 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 17 different Master 2 projects, most of which are aimed at a continuation as PhD work. We hope that they will stimulate your curiosity, and we are looking forward to welcoming you to our lab!

Manuel Houzet, Xavier Jehl, Eva Monroy, Head and Deputy-heads of PHELIQS
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Theory projects are highlighted with an asterix in front of the title *

Photonics

Master / PhD Thesis Project

Tailoring superconductivity in two-shells superconductor-semiconductor nanowires

General Scope :

Controlling and manipulating topological superconductivity[1] can lead to the creation of a new generation of quantum bits, called topological quantum bits, that are more robust to decoherence than traditional quantum bits. One solution to create topological superconductivity is to combine a superconductor with a one-dimensional semiconductor having a large spin-orbit coupling. Superconductivity in the semiconductor appears via the proximity effect and so far, the most studied systems have been Al/InAs and Al/InSb core-shell nanowires. Yet, magnetic fields are necessary to create topological quantum bits and because of its low critical field, Al is not a good choice. New combinations of materials[2] are currently emerging including Sn and Pb. Yet, induced superconductivity in the semiconductor can be too strong with Sn and Pb. In order to mitigate this effect, high quality tunnel barriers are envisaged, preferentially lattice matched with the semiconductor nanowire.

Research topic and facilities available :

The objective of the internship is to explore the properties of two-shells superconductor-semiconductor nanowires using the InAs-ZnTe(CdSe)-superconductor system. Two-shells nanowires are very novel, as previously only one-shell nanowires were explored. This will be realized through (1) the preparation of InAs nanowires wrapped with ZnTe(CdSe) shells using a molecular beam epitaxy reactor and (2) the fabrication and transport characterization of two-shells nanowire devices in a low temperature setup. The work consisting in growing the nanowires will take place at CEA-IRIG-PHELIQS where molecular beam epitaxy reactors are available within the joint CEA/CNRS NPSC team. Fabrication of the devices will take place at Institut Néel at the Epitaxy platform and the Nanofab cleanroom facility. Transport measurements in a dilution fridge will take place in collaboration with the QNES team at Institut Néel.

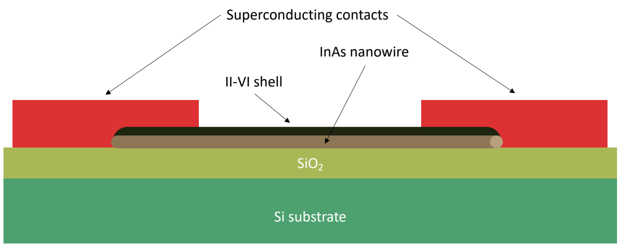

Figure : Example of a two-shells nanowire device designed for the study of topological superconductivity

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Possible collaboration and networking :

Collaboration with USA (University of Pittsburgh, Carnegie Mellon University, UCSB) and The Netherlands (TU/Eindhoven) via the NSF/ANR HYBRID project. The intern will work closely with the PhD students of the international collaboration through its participation in regular online meetings and discussions.

Possible extension as a PhD : Yes

Required skills:

Interest in performing experiments in the lab (materials growth, fabrication of devices and measurement), background in solid-state physics and nanotechnologies.

Starting date : Beginning of 2022

Contact :

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Phone : ++33438784604 and +33438783513

e-mail : edith.bellet-amalric@cea.fr and moira.hocevar@neel.cnrs.fr

[1]S.M. Frolov, M.J. Manfra, J.D. Sau *Topological superconductivity in hybrid devices* Nat. Phys. 16, 718–724 (2020)

[2]M. Pendharkar, B. Zhang, H. Wu, A. Zarassi, P. Zhang, C. P. Dempsey, J. S. Lee, S. D. Harrington, G. Badawy, M. Rossi, R. op het Veld, S. Gazibegovic, J. Jung, A. -H. Chen, M. A. Verheijen, M. Hocevar, E. P. A. M. Bakkers, C. J. Palmstrøm, S. M. Frolov. *Parity-preserving and magnetic field resilient superconductivity in indium antimonide nanowires with tin shells* Science 372 508 (2021)

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Master / PhD Thesis Project

Al-polar AlN nanowires grown by molecular beam epitaxy for efficient UV-C LEDs realization

The Minamata Convention entered into force on 16 August 2017, with the purpose of progressively banning mercury use and mercury-using devices. This directly concerns mercury lamps, which are the current source of UV light for a wide range of applications including -but not limited to- water processing, disinfection, air sanitization, psoriasis bleaching, wireless short range communication, banknote counterfeiting detection, agriculture, etc…. This political framework is boosting the rapidly growing market of UV light emitting diodes (LEDs) and stimulates even more the active research and development activities in the field.

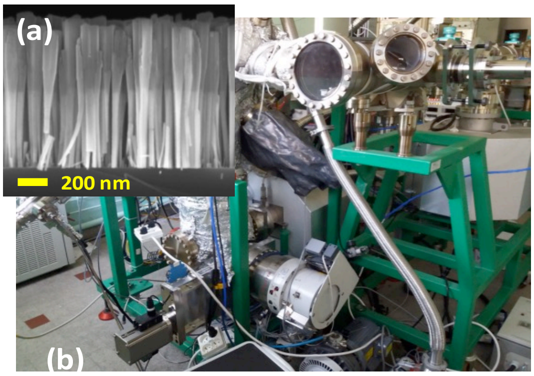

Figure: (a) SEM cross section view of AlN nanowires (b) partial view of a molecular beam epitaxy machine

In this context, IRIG and CNRS-Néel are collaborating for long on a joined research program targeting at the realization of disruptive UV-C LEDs using AlN nanowires (NWs), grown by molecular beam epitaxy (MBE) on Si. Due to the lack of symmetry center in wurtzite AlN, this material may be either N- or Al-terminated, depending on substrate and growth technique: indeed using Si substrate leads to Al-terminated NWs –in other words Al-polar NWs-. As this orientation tends to favour the incorporation of point defects detrimental to LED performances, it is desirable to revert it from N- to Al-termination: accordingly, the purpose of the internship is to develop Al-polar, AlN NW-based UVC LEDs, by polarity inversion using transitory O exposure in the growth chamber[1]. The material growth and structural characterization will be performed in CEA while the electrical characterizations will be carried out in Institut Néel in strong interaction with a PhD student. This internship requires a marked interest for material growth and the physics of semiconductors. Continuation in PhD will be possible.

[1]*A. Concordel et al,* **Appl. Phys. Lett. 114, 172101 (2019); doi: 10.1063/1.5094627**

APPLY

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irig Institut de Recherche Interdisciplinaire de Grenoble

Pheliqs Quantum Physics & Engineering

Master / PhD Thesis Project

(In)GaN microdomains on graphene for flexible LEDs

Nitride semiconductors (GaN, AlN, InN) are known for their exceptional light emitting properties. Nitrides are daily employed for lighting (blue/white LEDs) thanks to embedded InGaN quantum wells, which emit intense blue light with excellent efficiencies (>80%). Our laboratory is known for the pioneer work on novel LED based on nanowires with core-shell InGaN quantum wells. Indeed, we achieved the fabrication of flexible LEDs using such nanowires able to emit blue, green and white light [1-3]. We aims to go further in flexible LEDs by developing the growth of defect-free ordered (In)GaN microdomains on amorphous SiO_2 substrates thanks to the Van-der Waal epitaxy on graphene in order to improve efficiency and get red emission.
The project aims to grow organized and transferable GaN or InGaN micro-templates by apply Van Der Waals epitaxy on graphene and to use these templates for the fabrication of micro-LEDs transferable on flexible substrates. The initial substrate consists of nanoscale graphene patterns on an amorphous SiO_2 support. Growth proceeds in three steps, combining MBE and MOCVD methods to benefit from their respective specificities: (1) selective growth of GaN seeds on the graphene patches; (2) lateral growth around these seeds to form defect-free GaN domains of a few tens of µm; (3) growth of the active structure of the LED on the top facet of these micro-domains. Processing the LEDs includes their separation from the original substrate and their collective transfer onto a flexible support. This technology opens a path to all-nitride flexible displays with high brightness, high resolution and long-term stability.
The work is essentially experimental (epitaxy, advanced structural and optical characterization). It will be carried out in close collaboration with the C2N of Paris-Saclay for the ordered MBE seed nucleation on graphene and for flexible LED fabrication in the framework of the FLAGG project.

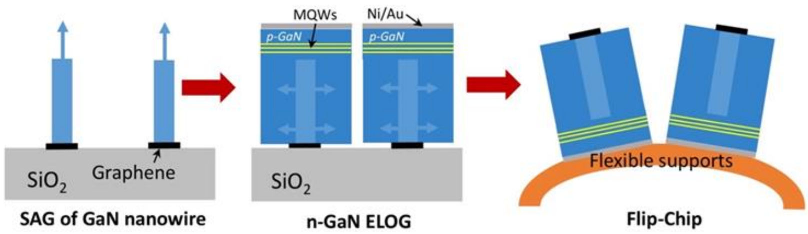

Figure: Schematic of the different fabrication steps of the flexible LEDs.

[1] Dai et al., Nano Lett. 15, 6958 (2015) ; [2] Guan et al., ACS Photonics 3, 597 (2016)
[3] Kapoor et al., Adv. Photonics Res. 3, 2000148 (2021)

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Pheliqs Quantum Physics & Engineering

Master 2 Project **2021-2022**

Integration of a semiconductor quantum dot single photon emitter to a quantum photonic circuit

General Scope:

Single-photons as flying quantum bits (qubits) are required for ultimately secure communication or quantum computing. Integration of quantum sources with photonic waveguides is crucial for the development of "plug and play" sources for secure quantum communication as well as for experiments requiring complex photonic circuits such as linear optics quantum computing. Single-photon sources based on semiconductor quantum dots (QDs) are particularly interesting because of their possibility of integration into conventional optoelectronics devices.

Research topic and facilities available:

Our group develops the growth of CdSe QDs inserted in ZnSe nanowire (NW), covered by a thick ZnMgSe shell acting as a photonic wire helping to guide photons emitted by the QD. These NW-QDs emit single-photons in the visible domain and have shown the possibility of single-photon emission up to room temperature. The NW-QD geometry offers several advantages, such as the control of the optical dipole orientation and nano-maniplulation of single emitters. In this internship, we propose to explore the integration of a NW-QD single-photon emitter to a waveguide and a photonic circuit. The goal of the internship will be: (i) to optically characterize the NW-QDs grown in our group, (ii) to design, fabricate and characterize waveguides for the optimal guiding of single photons, (iii) to study the coupling of the NW-QD to the waveguide.

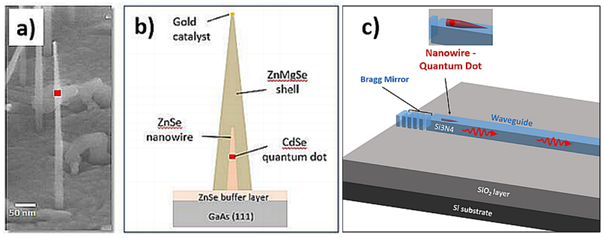

Figure: a) a ZnSe/CdSe NW-QD on the as-grown sample; b) a similar NW-QD in a photonic wire ; c) Evanescent coupling of a NW-QD to a wave guide.

Possible collaboration and networking:

Our group "NanoPhysics and Semiconductors" is a joint CEA/CNRS team and the internship will take place both in CEA-IRIG and CNRS-NEEL, with collaboration with LETI-DOPT. This internship will allow tackling different topics in nanociences and optics: NW-QD grown by Molecular Beam Epitaxy, nano-fabrication in clean room, spectroscopic (micro-photoluminescence) studies, light-matter interaction at the nanometer scale studies supported by numerical simulations.

Possible extension as a PhD: Yes

Required skills: Semiconductor physics, optics, photonics, nanotechnology, with strong interest for experiment.

Starting date: February 2022

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Master / PhD Thesis Project

Contribution to the development of InGaN-based solar cells

Context: Our target is the integration of various recently developed multi-purpose technologies with the aim of developing low-cost, high-efficiency, multi-junction solar cells using InGaN alloys, and following a fabrication process fully compatible with conventional integrated circuit production. The final multi-junction will present a nanopyramid structure, exploiting the capability of these nano-objects to release strain, and hence improve the indium incorporation without introducing structural defects. The conductivity of the *p*-type layers will be improved by a combination of MOVPE and MBE growth techniques, and the p-contact resistance will be reduced using p+/n+ tunnel junctions.

Objectives and available means: The student will work on the fabrication and characterization of the p-type region of nanopyramid InGaN solar cells. The tasks of the student will be:

- The student will grow the *p*-type (Mg-doped) InGaN layers by plasma-assisted MBE.
- He/she will design, grow and characterize the contact structure for the *p*-layer, which includes an n+/p+ tunnel junction, using either Ge or Si as n+ dopant.
- He/she will be in charge of the electro-optical characterization of the structures (I-V characteristics, C-V measurements, optical transmission, photoluminescence).

The internship implies training in epitaxy of III-nitride semiconductors, as well as electrical and optical characterization techniques. For each of these tasks, the student will be trained and supported by specialists in the field.

The team: The student will integrate a research team of the Nanophysics and Semiconductor Lab. (NPSC) Have a look at our webpage:
http://www.pheliqs.fr/en/Pages/Eva-Monroy.aspx

Collaboration and networking: This program develops in the framework of the **ANR project "INMOST"**, in close collaboration with Georgia Tech Lorraine and Institut Néel. We have access to advanced structural characterization techniques (transmission electron microscopy, atom probe tomography) in partnership with the CEA Nanocharacterization Platform at Minatec.

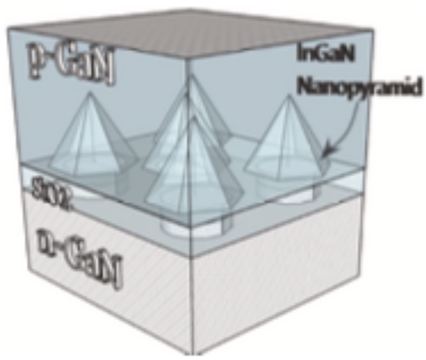

Fig: New solar cell design based on InGaN nanopyramids.

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Master / PhD Thesis Project

Semiconductor nanowire photodetectors

Context: Semiconductor nanowires constitute the ultimate miniaturization limit for a number of electronic and optoelectronic devices. In the field of photodetectors, the low electrical cross-section of nanowires implies low electrical capacitance, and this comes without degradation of total light absorption due to antenna effects. Indeed, nanowire arrays should exhibit higher absorption than a thin film of the equivalent thickness. Another interesting feature of nanowire photodetectors is their compatibility with silicon technology, either as growth support or carrier wafer with easy transfer procedures, which opens interesting possibilities of integrating the detector and readout. It is also particularly attractive the possibility of growth or transfer into flexible materials, which opens perspectives for the development of wearable devices.

Our target is to assess experimentally these theoretical advantages of a nanowire photodetectors. Our team has experience in the fabrication and characterization of single-nanowire devices, and here we will study the evolution of the performance in a device based on a nanowire array. We are interested in the potential application of such devices as telecom detectors and as biosensors, after functionalization.

Objectives and available means: The student will work on the fabrication and characterization of photodetectors based on GaN and GaAs nanowire arrays, which implies training in device fabrication technologies and electrical and optical characterization setups.

The team: The student will integrate a research team of the Nanophysics and Semiconductor Lab. (NPSC)
Have a look at our webpage: http://www.pheliqs.fr/en/Pages/Eva-Monroy.aspx
For more information on our work, please read our recent publications (available on demand):

[1] "Effect of Bias on the Response of GaN Axial p–n Junction Single-Nanowire Photodetectors", S. Cuesta, *et al. Nano Letters 19 (8), 5506-5514 (2019)*

[2] "Nanowire photodetectors based on wurtzite semiconductor heterostructures", M. Spies and E. Monroy, *Semiconductor Science and Technology 34, 053002 (2019)*

Collaboration and networking: The research will develop in collaboration with Institut Néel (transmission electron microscopy, comparison with single nanowire devices) and LETI (application as biosensors).

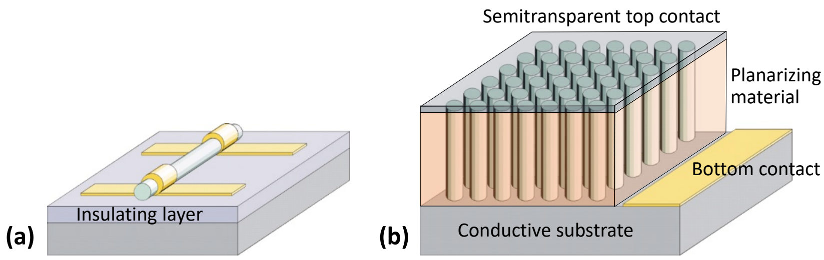

Fig: Schematics of (a) a single-nanowire device and (b) a photodetector based on a nanowire array.

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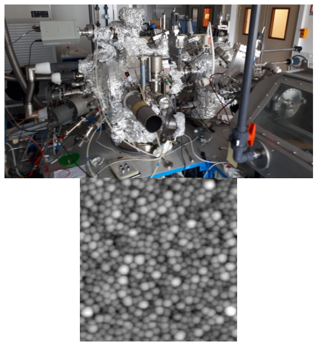
Master / PhD Thesis Project

Synthesis and study of GeSn/Si quantum dots

The optical information processing by the silicon technologies has been facing a major obstacle for many years: the availability of a bright and CMOS compatible light source. The recent discovery of the laser effect in thick layers of the $Ge_{1-x}Sn_x$ alloy makes this perspective a viable route owing to the real integrative potential of GeSn (which is an all group IV alloy). However, the today encountered thick layers of GeSn are infra red emitters, typically in the 2.2-5 µm range [1], and do not fit with the current telecom standard, in the 1.3-1.6 µm range. To give GeSn a broader applicative impact, tailoring the photon emission energy to higher values can be considered by taking advantage of the electronic confinement in GeSn/Si quantum dots. Based on this, the first objective of this experimental internship is to refine our knowledge on the synthesis of GeSn/Si quantum dots grown in our Molecular Beam Epitxy (MBE) tool. This topic, for this alloy, is still underexplored at the international level. In particular, the candidate will focus his (her) growth activities towards a better understanding of the parameters governing the Sn incorporation in the Ge matrix, the size and density of the dots, as well as strategies for layer capping, with the aid of structural characterization tools (SEM, AFM, Raman spectroscopy, and TEM in the frame of a collaboration). The second objective, that is no less necessary for qualifying these objects, and still little discussed in the literature, is drawing a detailed view of the potential barriers at the Si (Ge) and $Ge_{1-x}Sn_x$ interface. This point will be the subject of a complementary study by means of optical and electrical spectroscopy techniques (photocurrent and electrical impedance), carried out on standard $Ge_{1-x}Sn_x$ samples comprising well determined thin layers of known tin content and crystal stress state (collaboration with the CEA-LETI and the growth team regarding the synthesis of GeSn layers via the CVD approach). To that end, an introductory microfabrication activity will be proposed and will give the candidate the opportunity to fabricate his (her) own study-oriented devices.



IV-IV molecular beam epitaxy tool and example of uncapped GeSn dots on Si grown in our equipment (AFM, field of view 500 nm)

Continuation in a PhD is possible, with a view to studying the electronic states of these objects, as well as integrating them in optical resonators. For this work, collaborative in nature, the candidate must have skills in solid state physics and physics of semiconductors and appreciate the experimental work.

[1] J. Chrétien et al, ACS Photonics 2019, 6, 10, 2462–2469 (2019)

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Quantum Materials

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Master / PhD Thesis Project

Squeezing the superconducting secrets out of UTe_2

Three years ago, a highly unusual superconducting state was found in the compound UTe_2, triggering a lot of excitement. Indeed, this superconductivity appeared to be extremely robust in an applied magnetic field, demonstrating that it is a rare spin-triplet superconductor, where Cooper pairs are formed by electrons having the same spin direction. This implied that it could also be a topological superconductor, an exciting prospect with possible applications in quantum computing. Superconductivity in UTe_2 is not only robust under magnetic field, it can even be induced by a magnetic field applied in specific directions of the crystal lattice. Moreover, under pressure we discovered that multiple superconducting phases appear, of different symmetries, an extremely rare phenomenon. UTe_2 can be considered as a prototype quantum material, where physical properties are governed by electronic correlations, emerging among flat bands at the Fermi level, and topological effects.

Left: a standard diamond anvil pressure cell. Right: our new ultra-compact cell.

With this Master 2 project, we will further explore the superconducting properties of UTe_2 under pressure. Indeed, putting solids under pressure squeezes the atoms closer together and can completely change the properties of a material. It is particularly effective for quantum matter, which often lies close to instabilities toward new quantum states: pressure can reveal and help understand these new states. However, these are challenging experiments, requiring a pressure cell able to generate pressures of typically $10^4 – 10^5$ bars, often associated with other extreme conditions of low temperature and high magnetic field. Hence, the size of the pressure cell is often a limiting factor. To overcome these limits, we have designed a tiny pressure cell, smaller than a 1 cent coin, using diamond anvils, making it possible to orient the sample in any field direction under pressure and at low temperatures.

During the Master project, we will perform the first measurements in this new pressure cell, and notably electrical transport, suitable to probe the field-induced superconducting phases of UTe_2. This Master project can be followed by a PhD, where extensive studies using this cell are planned, including rotating the sample *in-situ* at low temperature and high magnetic field, in order to understand the interplay of magnetic fields, and more generally of magnetism, with the superconductivity of UTe_2.

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To apply for this position, or just to discuss further, contact by e-mail (including your CV): daniel.braithwaite@cea.fr

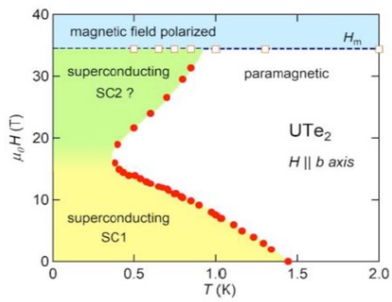
Institut de Recherche Interdisciplinaire de Grenoble

Pheliqs Quantum Physics & Engineering

Master / PhD Thesis Project

Enlightening Spin-Triplet Superconductivity in UTe_2

Superconductivity is one of the most dynamic fields of research in solid-state physics, thanks to the continuous discovery of new superconductors, challenging our understanding of this phenomenon. Notably, in **quantum materials** like the high-Tc cuprate superconductors, the iron pnictides, or the heavy fermion systems, completely new mechanisms are involved for the building of Cooper pairs, leading to a so-called unconventional pairing, and novel physical properties.
The recently discovered superconductor UTe_2 is an extreme example of the surprises brought by unconventional superconductors: it shows magnetic field reinforced superconductivity, leading to an exceptionally high (for such a low T_c superconductor) superconducting critical field (see Figure below). Under pressure, we also discovered transitions between different superconducting phases, and yet another completely anomalous behaviour of the upper critical field. Most of these properties remain unexplained today, but are certainly closely connected to the fact that UTe_2 is a "**spin-triplet/p-wave**" **superconductor,** or even a mixed singlet/triplet superconductor under pressure! Spin-triplet superconductivity has been found only in a handful of compounds; however, it is presently highly sought-after for its intrinsic **topological properties**.



In this Master 2 project, we will notably explore the high-field phase (green state on the figure) of UTe_2, which seems to be governed by completely new physics. Few measurements can probe the superconducting state in such high-field, low temperature conditions. Our new high precision dilatometer, able to detect length changes of 10^{-3}nm on a mm-size crystal, is an ideal probe. This is due to the strong interplay between lattice and electronic properties, arising from the dominant role of exchange in the electronic correlations. With thermal dilatation (change of length with temperature) or magnetostriction (change of length with field) measurements, down to very low temperatures (20 mK) and in high magnetic field, we will look for a potential field-induced phase transition between low and high fields, and measure the field-evolution of the superfluid density.

A PhD can follow this Master project, where in addition uniaxial stress experiments are planned to further explore this emergent quantum material. Strong coupling with theorists from the laboratory (two ongoing PhDs on this subject) should trigger clear progress in the understanding the exciting physics of UTe_2.

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Master / PhD Thesis Project

Quantum spin nematic and spin liquid states in magnets with competing exchanges

(contact Mike Zhitomirsky)

Geometrically frustrated magnets are at the forefront of fundamental research in modern magnetism. Strong quantum fluctuations in these materials can destroy conventional magnetic ordering and induce exotic quantum states: spin nematics that are only partially ordered and are similar to liquid crystals or completely disordered spin liquids, which may exhibit nontrivial topological properties. In this theoretical project we plan to investigate spin nematic states that result from condensation of bound magnon pairs. Magnon attraction can be induced by competing ferro- anf ferromagnetic interactions or by an easy-axis anisotropy. Recent experiments provide numerous examples for magnetic materials with required properties. In the beginning, we consider a Heisenberg honeycomb-lattice magnet with first-neighbor ferromagnetic J_1 and second-neighbor antioferromagnetic J_2 exchanges. In this case, spin flips (magnons) gain the interaction energy by occupying two adjacent sites. This may lead to formation of bound magnon pairs that are to some extent similar to the Cooper pairs of electrons in superconductors (see figure). The magnon pairs will undergo the Bose condensation transition resulting in the spin-nematic state. The primary task for the Master stage consists in developing an analytic theory for such a transition for non-Bravais honeycomb lattice by generalizing previous theoretical studies for Bravais lattices. Then we apply this approach to a closely related material $BaCdVO(PO_4)_2$, which may exhibit a spin nematic phase in high magnetic fields. Another direction to be pursued during the PhD thesis stage is an investigation of the nature of spin liquid state, which appears for J_1 and J_2 fcc antiferromagnet. We plan to develop an approximate theory for an RVB spin liquid state formed by local spin singlets (see figure) starting with the $SU(N)$ generalization of spin operators and performing calculations in the large-N limit. The possible extensions of these studies will include classical Monte Carlo simulations of these models.

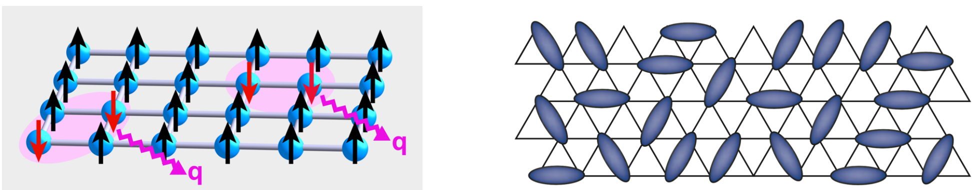

Figure: Cartoons of spin nematic (left) and an RVB spin liquid (right), each oval corresponds to a singlet spin pair.

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French Commission for Atomic Energy and Alternative Energies
Interdisciplinary Research Institute of Grenoble
Quantum Photonics, Electronics and Engineering Laboratory
17 av. des Martyrs – 38054 Grenoble cedex 9 – France

Quantum nanoelectronics and engineering

Master Project

Microwave photonic crystals
Toward quantum limited amplifier

1. The team

We are a large team studying quantum physics through various semiconductors quantum dots, hybrid and superconducting samples. Located inside the CEA-Grenoble, our researchers, postdocs and PhD students offer a rich and dynamic environment to work, see https://www.lateqs.fr/.

2. Overview

The internship project is the study of one of the key part of traveling wave amplifier, their **photonic crystal** [1]. Indeed, for traveling amplifiers to work, two conditions must be fulfilled: energy and **momentum conservation**. To achieve momentum conservation, we fabricate micro-designed photonic crystals to carefully bend the band structure of the amplifier resulting in a momentum conservation in a finite frequency band. The design of such crystals is complex and of critical importance to obtain wide band amplifier [2].

The student will **build his own microwave circuit** to measure the complex transmission through the photonic crystal and, through a **circuit model analysis**, build his own comprehension of the physics involved.

3. Perspectives

The project could be **followed by a PhD** to demonstrate near quantum limited amplification. Indeed while the photonic crystal offers momentum conservation, energy conservation is also require to obtain a traveling amplifier. The PhD will involve simulation, design, nano-fabrication, measurement and theory work.

[1] Ho Eom, et al, *Nat. Phys.*, **2012**, *8*, 623-627

[2] R. P. Erickson and D. P. Pappas, *Phys. Rev. B*, **2017**, *95*

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Master 2 Project

Quasiparticle-induced linewidth of the Josephson radiation

Josephson junctions are made of two superconductors separated by a tunnel barrier. Thanks to the coherent transfer of Cooper pairs across the barrier, these junctions realize a unique non-linear and non-dissipative dipole for electrical circuits. These properties also make Josephson junctions a useful block for quantum technological applications. An emblematic example are the superconducting qubits, which are basic components for building complex quantum machines.

A major reason for the reduced dissipation is the superconducting gap, which renders the equilibrium concentration of quasiparticles exponentially suppressed at low temperature. Recent progress has been made in order to characterize and quantify the detrimental effect of quasiparticles in a variety of Josephson devices [1]. A striking result of these studies was to show that many devices are affected by an excess concentration of quasiparticles, which may originate from electromagnetic, cosmic, or nuclear radiation. Because of their unclear origin and adverse effect, quasiparticles in superconductors remain a “hot” topic of research.

The aim of the Master 2 internship will be to investigate theoretically the role of quasiparticles on the linewidth of the Josephson radiation, that is, the generation of an AC current by a DC voltage biased Josephson junction. While the role of the junction’s electromagnetic environment was much discussed, little is known on the role of such quasiparticles. To make progress, the candidate will use a combination of quantum field theories (scattering formalism, Keldysh Green functions) for quantum transport.

A possible extension for a PhD project could be to address the yet unknown role of quasiparticles on the coherence properties of a recently investigated family of superconducting quantum bits, known as "cat codes", which have been shown to display an intrinsic protection against decoherence induced by photon losses.

Reference:

[1] *Bogoliubov quasiparticles in superconducting qubits*,
L. I. Glazman and G. Catelani, SciPost Phys. Lect. Notes **31** (2021).

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Master / PhD Thesis Project

Magnetic field effects in layered transition-metal dichalcogenide superconductors

Transition metal dichalcogenides (TMD) are layered materials with a hexagonal lattice structure similar to graphene, but with two inequivalent sites in the unit cell. Like graphene, these materials exhibit a valley degree of freedom. Unlike graphene, however the layers possess a very large intrinsic spin-orbit coupling (SOC), often called Ising SOC, which acts as an effective Zeeman field perpendicular to the plane of the material and with opposite directions in the two valleys (see figure). As a consequence, a large valley-dependent spin-splitting occurs, opening the door for novel applications of TMD monolayers in spintronics and so-called valleytronics.

A number of TMDs are superconductors down to monolayer thickness. The coupling between the spin and valley degrees of freedom has remarkable repercussions also for their superconducting properties. As shown in recent experiments [1], the in-plane upper critical field in TMD monolayers greatly surpasses the so-called Pauli limit due to the Ising SOC.

The internship aims at studying the effect of an in-plane magnetic field on quasi-2D layered structures. While in monolayers it is sufficient to consider the Zeeman effect of the magnetic field, in layered structures the orbital effect also plays an important role. In particular, the orbital effect drives a crossover from quasi-twodimensional to twodimensional superconductivity and may lead to re-entrant superconductivity [2]. During the internship, we will explore the interplay of this effect with the strong layer-dependent Ising SOC in TMDs [3], which by itself may lead to unconventional superconducting states.

The project will be performed mainly by using the analytical tools of condensed matter field theory. Interested candidates should have a good basis in quantum mechanics, statistical physics, and solid-state physics. A PhD may follow.

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References:

[1] J. Lu *et al.*, Science **350**, 1353 (2015) ; X. Xi *et al.*, Nat. Phys. **12**, 139 (2016) ; Y. Saito *et al.*, Nat. Phys. **12**, 144 (2016).
[2] A. G. Lebed and K. Yamaji, Phys. Rev. Lett. **80**, 2697 (1998).
[3] R. Masutomi, T. Okamoto, and Y. Yanase, Phys. Rev. B **101**, 184502 (2020).

Master Thesis Project

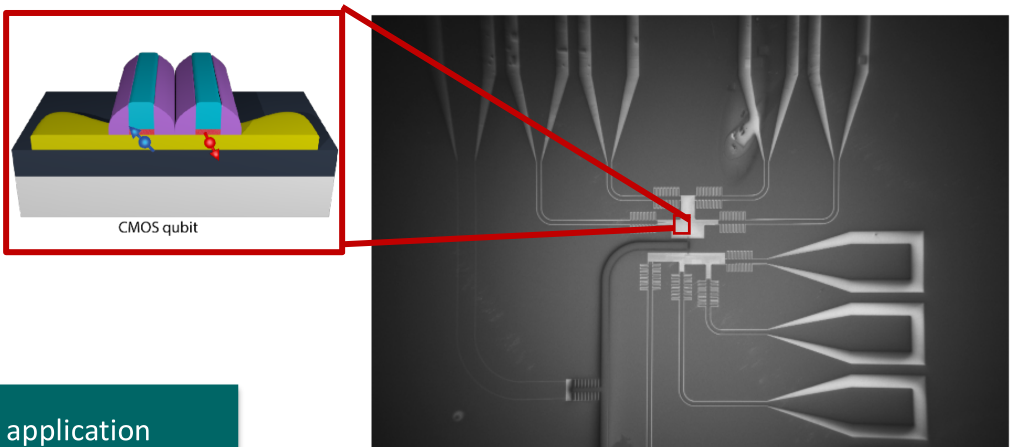
Spin and microwave photon speaking together

Quantum computing is a major new frontier in information technology with the potential for disruptive impact. Solid state implementations of qubits, especially spin qubits [1,2], are among the most promising ones. Diverting silicon technology is the approach explored in our Lab. The working principle of the qubit is to trap a spin inside the channel of a silicon transistor and to manipulate this spin via microwave signal applied on the gate electrode [3].

To go a step towards computing architecture, one may want to couple distant qubits. To take up this challenge a microwave photon can be used as a quantum mediator between the qubits. Practically, silicon transistors are embedded in a superconducting microwave resonator enabling the coupling between the spin and the microwave photons trapped in the resonator [4-6]. The figure below shows the chip fabricated in our laboratory for this spin/photon interaction to take place.

During the master project, you will take part of this exciting experiment in order to make spin and microwave photon speaking together. You will participate to the fabrication of the chip, with nano-fabrication steps done in our clean-room. You will also learn to cool down this chip in a dilution refrigerator to a base temperature of 10milliKelvin. Finally, you will perform the complex measurements of this hybrid physics at the interplay between spin qubit and microwave circuitry. For that, you will have to control the electrostatic gating of the silicon transistor in order to set the spin qubit working point while monitoring the microwave response of the photon cavity. Experimental results and new manipulation protocols will be widely discuss with theoreticians participating to this project. This master project may continue as a PhD thesis.

References:
[1] Hanson R. et al. Rev.Mod. Phys. (2007)
[2] Zwanenburg F. et al. Rev. Mod. Phys. (2013)
[3] Maurand et al. Nature Communications (2016)
[4] Landig, A. J. Nature (2018)
[5] Mi, X. et al. Nature (2018)
[6] Samkharadze, N. et al. Science (2017).



Photons and spin circuits on the same silicon chip!

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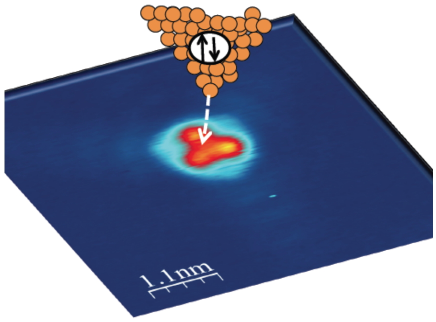
Master / PhD Thesis Project

Magnetic bound states in 2D superconductors

The presence of a nanoscale magnetic scatterer (a single atom, a molecule, a quantum dot etc.) on the surface of a superconductor can lead to the emergence of bound states with peculiar spatial and spectral properties within the superconducting gap. These states can be topologically trivial (the case of so-called Shiba states) or not (predicted Majorana zero modes).



Spatial map of a low-energy bound state around a Fe nanoisland on super-conducting Pb(111) and sketch of STM experiment.

In this project, we will investigate these states in two-dimensional superconductors. Here, the bound states can have a much longer spatial range, which will allow coupling several of them to engineer intriguing electronic properties. The superconducting substrate will consist of either (i) intrinsic superconductors in the single or few atomic layer limit, or (ii) single-layer graphene in which superconductivity is induced from a nearby superconductor. We will use a low-temperature Scanning Tunneling Microscope (STM), to track the signatures of the magnetic bound states and possible topological superconductivity with high spatial and energetic resolution.

The experimental work is at the interface between surface physics and quantum transport studies. The experiments will be performed using a milliKelvin STM available in the host group. The work encompasses collaboration between STM groups in Grenoble (both at Néel/CNRS and IRIG/CEA), together with FU Berlin. The work is further supported by strong interactions with theory groups. The student's work will include:

- Preparing and growing combinations of superconducting substrates and magnetic nanostructures, by self-assembly or single-atom manipulation.
- Performing low temperature scanning probe measurements, with a particular focus on quantum transport effects (Josephson effect, photon-assisted tunneling, …)
- Theoretical analysis and interpretation.

Collaboration and networking: The work bases on a strong experimental collaboration between Inst. Néel (J. Coraux, P. Mallet, J-Y Veuillen, C. Winkelmann), IRIG/CEA (V. Renard, C. Chapelier) and FU Berlin (K. Franke), as well as several theory groups.
Required skills: MSc level in Physics or Applied Physics. Prior experience in low temperature physics, surface science or nanoelectronics is a plus.

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Master project

Realistic modelling of quantum point contacts in integer quantum Hall effect

Quantum Hall effect is known for various exotic properties such as conductance quantisation to an astonishing precision or the existence quasiparticles having a fraction of the electron charge (for the fractional quantum Hall). One of the methods for observing this fractional charge is based on investigating tunnelling of the quasiparticles between two quantum Hall edges at a quantum point contact (QPC, Fig. 1a).

While this method is considered reliable with successful applications since 1997 (Fig. 1b), it produces a number of unexplained anomalies such as the fractional charge depending on the applied voltage (Fig. 1c). Similar, albeit less drastic, anomalies occur for integer quantum Hall effect.

In this project you will develop a realistic model of a QPC in integer quantum Hall and check whether it can explain the observed anomalies. You will perform analytic calculations (solving the Schrödinger equation for 1D systems, calculating current and noise within Landauer-Büttiker formalism) and numerical modelling (using Kwant).

Extra reading in case you want a deeper connection to the subject:
A review of quasiparticle tunnelling experiments
How to perform analytic calculations of tunnelling current and noise (read sections I and II only)

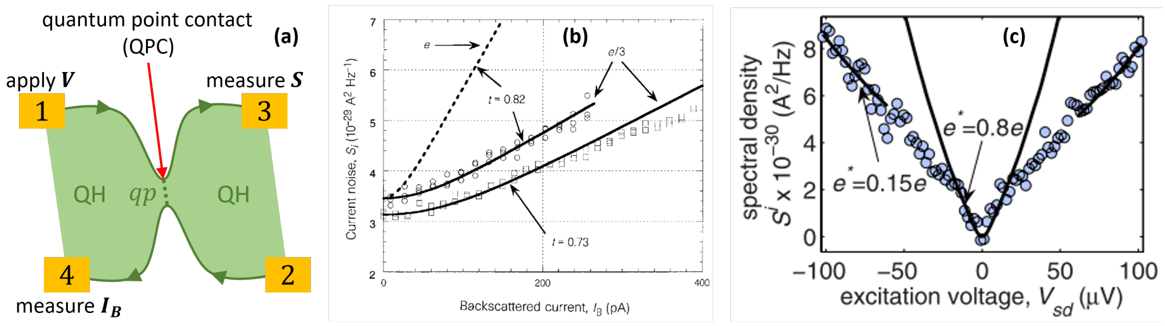

Figure 1. **(a)** QPC, where quasiparticles tunnel between quantum Hall edges. **(b)** Comparing the tunnelling current to its noise enables determining the charge of current carriers [source]. **(c)** Anomalies such as the dependence of the extracted charge on the applied voltage [source] remain unexplained.

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Pheliqs Quantum Physics & Engineering

Master / PhD Thesis Project

Simulations of anyons in topological quantum phases

Contact
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Title

Simulations of anyons in correlated topological quantum phases.

Simulations de particules anyonic (ni fermions ni bosons) dans des phases quantiques topologiques

Keywords
Quantum computing, quantum many-body problem, quantum simulations, Feynman diagrams.

Summary

Anyons are exotic particles that are neither fermions nor bosons. When one anyon makes a loop around another one the many-body wave function picks up a phase that is neither zero (bosons) nor pi (fermions) but that may take any value or even be a matrix (non-Abelian anyons). Anyons could be used for a new kind of quantum computers called "topological quantum computer". This is the route currently followed by Microsoft. Although these particles do not seem to exist in nature, quasi-particles with these characteristics can be stabilized in semiconducting heterostructures at low temperature and under high magnetic field. An experiment demonstrating unambiguously the anyonic behavior for the first time has been performed earlier this year: https://www.nature.com/articles/s41567-020-1021-7 . The physics of anyons is fascinating but also very complex. In particular it is very difficult to study them from microscopic models and usual approaches are restricted to effective models.

In this internship, we will build a microscopic description of the propagating edge states of anyons in the fractional quantum Hall effect phase 1/3. Our group develop state-of-the-art numerical tools for addressing quantum transport both in

the stationary (see http://kwant-project.org) and time-resolved (http://tkwant.kwant-project.org) domain.
We will adapt the traditional approach to use the so-called "composite fermion" framework where the electrons have captured quantum of flux. With this approach, we shall be able to study how the anyons edge states are reconstructed by the topological terms that arise in their field theoretical description. The internship could be extended into a PhD where one would study the dynamics of these anyons and propose actual experiments to be performed. The project would culminate with a study on how anyons could pair to form a topological superconductor harboring Majorana fermions (particles that are their own anti-particles). The fractional quantum Hall effect phase 5/2 is believed to harbor such a phase. The master project could naturally be extended into a PhD thesis where the modeling would be extended to account of anyons dynamics by incorporating the Chern-Simon gauge fields generated by the anyons into a self-consistent T-Kwant simulation.

Good mathematical skills as well as scientific programming are necessary for the success of the project. The work will involve theoretical / formalism aspects as well as numerics. The Internship/PhD will take place within the theory group of CEA Grenoble, IRIG, PHELIQS (Photonics NanoElectronics and Quantum engineering). Our group contains 15-20 researchers working on nanoelectronics, superconductivity, magnetism and electronic correlations in close collaboration with experimental groups. The project itself will be done under the direction of Xavier Waintal and co-supervised by Christoph Groth and Thomas Kloss.

We seek highly motivated students with a strong background in theoretical physics, quantum nanoelectronics and/or numerical simulations.

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