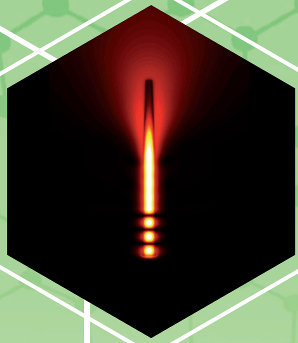

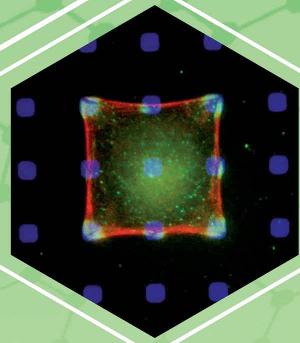

LANEF in 2018

lanef
Laboratoire d'Alliances Nanosciences-Energies du Futur

www.grenoble-lanef.fr

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LANEF in 2018

LANEF, Lab Alliances on Nanosciences - Energies for the Future, is a «Labex» (*Laboratoire d'Excellence*) funded in 2011 in the frame of the French *Plan d'Investissements d'Avenir*. LANEF associates five fundamental research labs, and it identifies common objectives between these labs in the domains of nanoscience, energies for the future and nanosensors for healthcare. It enhances the synergy between the different teams working towards these objectives, and makes connections with R&D.

It offers funding for students and scientists to join these activities.

Our five laboratories are engaged in forefront basic research with an emphasis on physics - condensed matter and nanosciences - and electrical engineering. There are very few places worldwide which combine such an expertise in basic multidisciplinary research, integrated in a larger campus for research and innovation such as the Grenoble *Presqu'île*.

THE FIVE LABS ARE:

- **Institut Néel (NEEL),** focused on basic research in condensed matter physics and nanosciences and supportive of the creation of intellectual property,

- **Institut Nanosciences & Cryogénie (INAC),** well balanced between basic research in nanosciences and the creation of intellectual property with strong links with R&D labs,

- **Grenoble Electrical Engineering Lab (G2ELab),** on electrical engineering with a strong focus on electrical energy,

- **Grenoble High Magnetic Field Lab (LNCMI),** with also a national and European mission for the production and use of high magnetic fields,

- **Laboratoire de Physique et Modélisation des Milieux Condensés (LPMMC)** on condensed matter theory.

In addition, the Grenoble environment is particularly suitable to establish links with R&D labs and industry. Our labs have strong interactions with LETI and LITEN, as well as industry, and one of the objectives of LANEF is to enhance these links.

One main eligibility criterion for the funding of a project by the Labex LANEF is thus that it reinforces the synergy either between at least two of our five laboratories, or between one of them and relevant R&D.

At the beginning of the Labex, we identified **three major economical and societal challenges**: information and communication technologies, energy, and healthcare. Within this frame, we identify **nine major research fields** where our labs, thanks to a long-standing tradition of working together, provide a critical mass and fore-front expertise to produce significant breakthroughs through specific **alliances** (Fig.1).

More information is available on the web site (http://grenoble-lanef.fr) and in the descriptive booklet to be uploaded at the same address. Our steering committee ("comité de pilotage") is composed by members of the Labex who represent these alliances, together with specific actions (international, education, exploitation of results).

OUR TOOLS COMPRISE:

- Scientific events organized by the members of the Labex: this goes from weekly seminars to thematic scientific meetings of half-a-day or one day. This is described on page 5.
- Specific actions to enhance international collaborations, with EPFL (Ecole Polytechnique Fédérale, Lausanne), Tsukuba (AIST, NIMS, Tsukuba University), Singapore, and Kalrsruhe. They are described on page 5.
- Education at the pre-doctoral and doctoral level, with practicals in-lab, European schools, pre-doctoral grants, and a diploma ceremony. They are described on page 6.
- Exploitation of results: favored at different levels and along different axes, in particular thanks to the work accomplished by our business development engineer; in short, this comprises actions toward the private sector and European funding projects; this is described on page 7. In addition, we are proud that 4 start-up companies acknowledge a significant input from our Labex, see page 41 to 43 and 45.
- Three types of projects submitted to specific calls and evaluated for funding (calls and panels have been organized jointly with the Nanosciences Foundation, http://www.fondation-nanosciences.fr/ , and our Quantum Engineering programs, https://quantum.univ-grenoble-alpes.fr/):
  - 2 specific calls have been launched for equipment projects; the projects which have been funded range from mutualized equipment (acquisition of commercially available pieces of equipment to be used jointly by several teams), to innovative instrumentation (development of specific instruments exploiting the unique expertise of the LANEF labs).
  - 8 "chairs of excellence" have been recruited; for each of them one (or two) PhD student or postdoctoral fellow benefits from a common supervision by the holder of the chair and the Grenoble contact.
  - 35 projects for which PhD students have been recruited thanks to two calls each year (Spring and Fall).

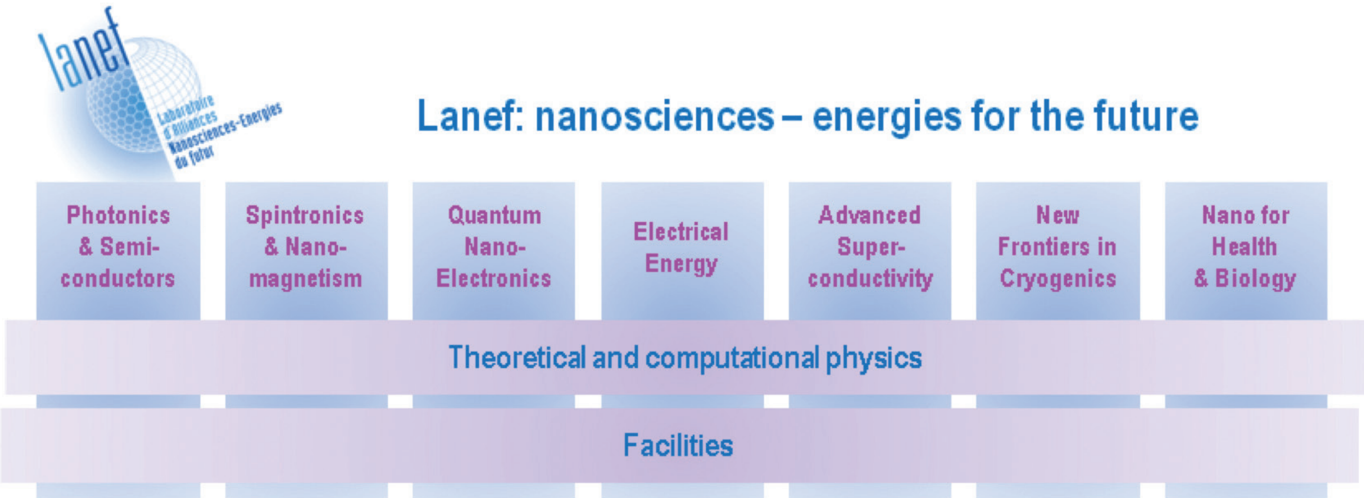

Fig. 1: the nine alliances of LANEF.

The present scientific achievements which result from these three types of calls and the four spin-off companies are described starting page 11. Their presentation is organized along **five scientific and societal challenges.** These five challenges emerged from the evolution of the Labex and its environment. They express a higher maturity of the different communities which contribute to the Labex and benefit from it. This ensemble is likely to form the new backbone of the Labex.

SCIENTIFIC EVENTS

Seminars and scientific workshops are organized by the different thematic alliances.

Regular seminars are a good opportunity for discussions and the initiation of collaborations and projects. Two series (>30 a year each), on quantum nanoelectronics each Tuesday, on condensed matter theory each Friday, are funded by our Labex, together with the Nanoscience Foundation and the Centre for Theoretical Physics Rhône-Alpes. Other thematic alliances have started seminar series but these are not yet as frequent and as regular.

Scientific workshops – half a day to 2-days – are another well appreciated opportunity to deepen interactions within the Labex, or with other organized communities. They cannot be detailed here: this comprises annual meetings (for instance, the annual day on spintronics and nanomagnetism), reciprocal visits of the labs (for instance in cryogenics), or thematic events (for instance, photovoltaics or quantum engineering). Particularly successful was the action towards quantum engineering, with several one-day workshops, actions to contribute to the brainstorming on the future European flagship, and the building of a dedicated community in Grenoble gathering physics, technology, mathematics and computer science, humanities. We obtained the funding of an IDEX Cross Disciplinary Project (see below) and a European MSCA Cofund project.

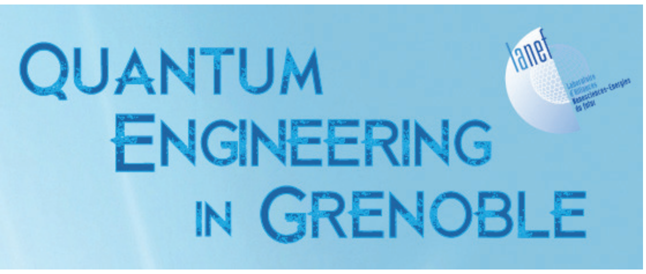

Fig. 2: booklet issued from the scientific day on quantum engineering in Grenoble.

In 2015, Antoine George gave his *Collège de France* lectures in Grenoble in the frame of our Labex. Other lectures were organized in cryogenics (A.T.A.M. de Waele, Eindhoven University of Technology, in 2017), and our *Chaires d'excellence* holders gave lectures in the frame of the relevant doctoral school.

INTERNATIONAL

There was a common agreement, that we should emphasize a sharing of our international networks much more than anticipated in the initial program of the Labex.

With the *Ecole Polytechnique Fédérale de Lausanne* (EPFL), we organized a 2-day workshop in 2012 in Grenoble, with >20 participants from Lausanne; the schedule was based on general presentations, and 3 specialized workshops run in parallel (quantum materials and nanophysics, nanobio, energy), with time to discuss possible collaborations; the content of the 3 workshops and the possible initiatives were subsequently presented in a plenary session - that helps a lot going to very concrete conclusions. Some of the projects received some funding from the Labex and from EPFL. A second workshop was organized in 2013 in Lausanne, with >20 Grenoble participants and the same general organization, the 3 specialized workshops being more focused, on neurobio, nanomechanics, solar cells. The support to exchanges of students and scientists has been continued for the following years.

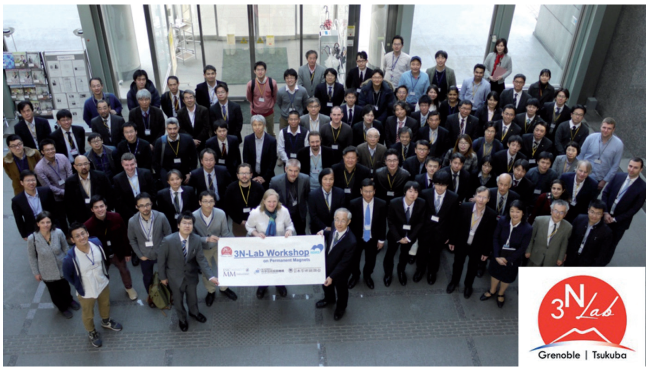

Fig.3 : one of the 3N-Lab workshops in Tsukuba.

With Tsukuba, the interaction was pushed to a very high level by Etienne Gheeraert, professor at UGA and scientist at NEEL. On the Japan side, it comprises the National Institute for Materials Science (NIMS), the National Institute of Advanced Industrial Science and Technology (AIST) and the University of Tsukuba. We thought it more efficient to start by sending and receiving delegations in association with other scientific (or politic) events which we could also support. The starting events were the 1st French-Japanese workshop on "Diamond power devices" (Grenoble 17-18 June, Chamonix 19-21 June 2013), a French delegation to Tsukuba (12-13 September 2013), another one joined to the 3rd French-Japanese High Field Research Collaboration Workshop, 14 November 2013 in Sendai, and a visit to Grenoble of two Japanese delegates in September 2013. The Chamonix workshop was the first of a series (Kyushu 2014, Nîmes 2015, Okinawa 2017, Aussois 2019), and other scientific delegations were organized between Grenoble and Tsukuba in the recent years. Several collaborations have been initiated and receive funding from the Labex - in average, 20 k€/y, mainly for exchanges of scientists. The first defense of a PhD thesis with a common Grenoble-Tsukuba supervision (by L. Besombes and S. Kuroda) took place in 2017: A. Lafuente worked on single magnetic atoms in CdTe quantum dots and benefitted from LANEF funding for travel expenses all along the PhD preparation. In addition, a PhD grant has been funded by LANEF and a Chaire d'excellence co-funded with AIST (H.Umezawa, see page 44). An International Lab (LIA) has been created in Tsukuba between CNRS and NIMS in 2016. This "3N-Lab" develops five active fields: wide bandgap semiconductors for advanced electronic devices, electronic properties of 2D materials (combining h-BN, MoS2 and WS2), low-rare-earth high-coercivity magnets (started with the 3N-Lab Workshop on Permanent Magnets on March 2017 at NIMS, see Fig. 3), high magnetic fields, and rare-earth intermetallics); it identifies new fields for future developments (multiferroics, high pressure, nanoscale electron-photon interaction). A common laboratory has been created at the University of Tsukuba (2016) on the technology of new semiconductor materials, essentially GaN and diamond in collaboration with NIMS and AIST; premises (50 m^2 of offices and 60 m^2 of experiment room) in Tsukuba welcome 3 invited professors from Grenoble each year (C. Vallée, E. Gheeraert, and H. Mariette, who are appointed Professors of the University of Tsukuba), with additional equipment funded by l'Air Liquide Japan; the team also comprises a full-time assistant professor, and a PhD thesis (C. You) co-funded by LANEF and l'Air Liquide (started 2017). Finally, let us mention also the creation of permanent offices of the Japanese labs in Grenoble.

An interaction, initiated by Alexia Auffèves (NEEL), was supported with the Centre for Quantum Technology, National University of Singapore, with the co-organization of an international summer school on «Strong light-matter coupling» and the successful application to the 2015 PHC Merlion call for further actions and exchanges. Two Merlion Projects were obtained in 2018: (1) "Towards scalable quantum error correction" with the Center for Quantum Technology (Dr. Hui Khoon Ng, UMI Majulab in Singapore and University of Yale), Alexia Auffèves at NEEL and ATOS-Bull as industrial partner; (2) "Hybrid quantum technology" (Wiebke Guichard at NEEL and Rainer Dumke at NTU). The Grenoble-Singapore collaborations comprise several scientific fields, such as hybrid quantum systems, quantum thermodynamics, noise in quantum information processing, low temperature atomic scale investigations for next generation high-temperature superconductors, atomtronics and mesoscopic physics (involving one of our Chairs of Excellence, Luigi Amico, see page 23, who is also half-time at the Centre for Quantum Technology in Singapore), Anderson localization and photons in disordered media, 2D materials, magnetoptics of atoms, strong correlations, many-body localization and entanglement in quantum systems, and exciton polaritons.

With Karlsruhe, the relations were intensified in 2017, starting with a workshop in Grenoble (first GREKIT meeting on "Superconductivity, from fundamentals to applications" - April 3rd-4th 2017, organized by Nicolas Roch and Serge Florens in Grenoble, Mathieu Le Tacon and Wolfgang Wernsdorfer in Karlsruhe). A second one took place in Karlsruhe (October 2017) with the support of the French Embassy in Berlin. An International Lab (LIA) has started in 2018, headed by Serge Florens, between CNRS and KIT.

Our international initiatives with Tsukuba, EPF-Lausanne, Karlsruhe match several objectives of the Grenoble-Alpes IDEX. For instance, developing the interactions with Tsukuba is a clearly identified objective of the IDEX as well as the Grenoble city and the Région. Our Labex initiative gave a significant, early impulse to the scientific and education aspects of these interactions.

EDUCATION

International schools receive funding from the Labex:

- Several already existing European schools such as ESONN (European School on Nanosciences and Nanotechnology, http://esonn.fr/), the European School of Magnetism (http://magnetism.eu/35-support.htm) and the International Doctoral Training Session on Frontiers of Condensed Matter organized with two other European centers (Casimir Research School of Delft-Leiden, and Donostia Physics Center of San Sebastian);

- New schools, such as the Introductory course on Magnetic Random Access Memory (http://www.inmram.com) which now gathers students, researchers and engineers from the industry on an annual basis.

Two are now in operation. **Advanced practicals in lab** have been created thanks to the work of an engineer hired by the Labex for two years, to equipment funding, and to the involvement of technical staff, scientists and academics from the CNRS and the Université Grenoble-Alpes (more than 20 contributors from NEEL) into the development of the set-ups and the supervision of the students. During the first academic year (2016-2017), about 130 students from the masters (*M1 physique, M2 matière quantique, énergétique physique, photonique et semiconducteurs, nanobiosciences and matière complexe / matière vivante*) were given the opportunity to access elaborated set-ups for experiments on Josephson effect, second sound, Kinetic Inductance Detectors (KIDs), Indium superconductivity, helium latent heat, non-linear optics, Hall effect, optical tweezers and ADN nanostructures. The sessions were open to small groups of students (generally 4) for a total of more than 300 hours. Further developments can be hosted in any of the five labs and they are now supported also by the Education and Research Department (UFR) PHITEM.

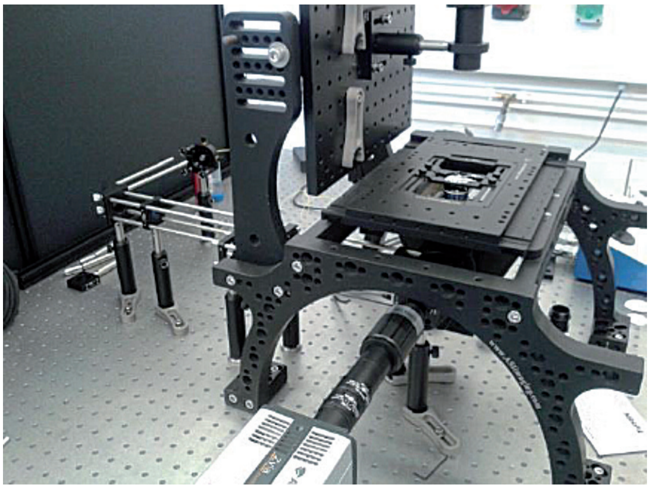

Fig. 4: Practicals in Lab on biophysics at NEEL.

Secondments of PhD students to private sector companies have been started in the frame of the GreQuE program (https://quantum.univ-grenoble-alpes.fr/). This is mandatory in the case of a GreQuE funding: this opportunity should be progressively opened to PhD students in other fields.

EXPLOITATION OF RESULTS

A business development manager, Xavier Thibault, has been hired on the LANEF budget in July 2013. The business development manager is fully immerged in the labs, and well aware of the strengths and the skills of the labs; he is able, and eager, to initiate and develop new links with other research centers, R&D labs, and private sector. His activity does not overlap with the technology transfer offices of the supervising institutes and universities: he works with these offices and favors the interaction of the scientists and engineers with them. One major role is to collect, filter and redirect towards the relevant teams, the various calls from the European Union and others: he initiates and helps to build the correct answer to these calls, once again without overlap with the technology transfer offices or private consulting offices. The role of the business development manager was progressively shifted towards the preparation of projects to be submitted to European calls, and particularly the MCSA calls.

Two recent successes are the Green Diamond Horizon2020 project on high power electronic devices with diamond (14 partners, €4 million) in 2015, and the MSCA Cofund project on Quantum Engineering (https://quantum.univ-grenoble-alpes.fr/) in 2016 (25 PhD grants with 70% funding from the MSCA program). Another project on Electrical Energy is submitted for MSCA funding: this domain is clearly broader than the LANEF area and includes the participation of other Labex's. Finally, two Innovative Training Networks (ITN) were successfully submitted: C. Bauerle participates to SAWTRAIN (https://www.sawtrain.eu/) , on Surface-Acoustic-Wave-related phononics, photonics, and electronics, and Hervé Courtois coordinates QuESTech (https://www.questech.org/) where seven leading European research laboratories, two high-tech companies and four partner organizations provide a challenging, state-of-the-art training for young researchers in the general field of experimental, applied, and theoretical quantum electronics.

Our Labex was very active in identifying **Quantum Engineering** as a mandatory perspective of at least 4 of our 5 labs, particularly timely in the European context, and fully supported by our competence in quantum physics and nanosciences, and the complementary competences of the Grenoble labs in microelectronics, computer sciences, pure and applied mathematics. A «cross disciplinary project» has been selected by the IDEX in December 2016 and receives a funding (10 PhD grants and 2 chairs of excellence) starting 2017. This is a timely complement to our MSCA cofund, started also in 2017 (September). The two programs (https://quantum.univ-grenoble-alpes.fr/) are coordinated by Alexia Auffèves and Jean-Philippe Poizat, respectively, in a tight coordination. Although well in line with some of our previous developments both scientifically (in the frame of four of our alliances) and methodologically (common calls are organized), these two programs offer us the opportunity to test several initiatives, such as the PhD secondments to the private sector and the Innovation Board. The secondments have been described above; the Innovation board gathers academics and industrials with the aim of promoting actions of common interest - at the first place educational initiatives in the field of quantum engineering, and improving the knowledge of the future PhDs to opportunities in the private sector.

The creation of a spin-off company is a long and difficult process and none can be attributed solely to the Labex. However 4 clearly acknowledge a support from LANEF and they are described on page 41 to 43 and 45.

Arryballe Technologies was created in 2014 to develop artificial noses (smart gas sensors) and tongues (liquid sensors). This subject benefitted from a PhD grant and an M2 grant. Magia was created in 2018 and develops portable, fast immunoassay based on micrometer sized magnet arrays, nanomagnetic particles, microfluidics, functionalization and medical tests; it benefitted from a PhD grant (the student contributed to the startup for a part time during the last year of her PhD work and works now full time for Magia) and a 3-month grant for a senior scientist (now the CEO of the company).

Two others are presently under maturation at the Grenoble technology transfer office Linksium. DiamFab, for diamond epitaxy for future power devices; the diamond program benefits from a chair of excellence, two PhD students, an equipment grant and the support to international collaboration with Tsukuba. Grapheal develops smart wound dressings based on graphene, aimed at curing difficult injuries; another facet of this program, dealing with graphene-coated brain implants, addresses common problems and was supported by a PhD grant and the international action towards EPFL.

Other contacts with industry are mentioned in the texts.

MagIA diagnostics

Grapheal

ARYBALLE Technologies

diAm fab

TABLE OF CONTENTS

PHD PROGRAMS, CHAIRS OF EXCELLENCE, EQUIPMENT, SPIN-OFF COMPANIES.

• Nanophysics and quantum engineering. Three alliances of our Labex deal with photonics, spintronics and nanoelectronics. These are domains where international networks are well developed: the Labex, together with the Nanoscience Foundation, allows us to efficiently attract excellent foreign students through these international networks. Several projects pertain to these fields, including our first chair of excellence on Iontronics.

• Quantum materials: Several projects are specifically devoted to the development and the understanding of new materials based on quantum properties, in particular superconducting ones.

• New frontiers in cryogenics and low temperature physics. The ability to develop new instrumentation at low temperature is recognized as a particular strength of several of the LANEF labs. Several projects have been funded either through the equipment calls, or through PhD grants. Note that PhD grants with a large part of instrumental development are risky and not easily supported by some doctoral schools. No need to say that our business development engineer follows these projects with a special care.

• Nano for healthcare and biology is another challenge of our Labex, with the aim of creating an alliance in this field. Several are involved in these fields, with an insufficient mutual knowledge at the beginning of the Labex. Collaborations are particularly needed; outside of LANEF, they involve Grenoble labs and EPFL. Specific equipment was acquired on the Labex budget: a digital holographic microscope (project TECNO), used in particular in the biophysical approach of cell volume described below, and inverted microscope for in-situ functionalization and photo-ablation of culture cells (Biophab project, starting now).

• Electrical energy is a major challenge of our Labex, and our strength is the presence of scientists working on a huge diversity of materials, nanostructures and mechanisms (4 of the 5 labs in LANEF), on electrical engineering (G2ELab in LANEF), and on devices and systems for new energy (CEA-LITEN). The different tools of the Labex were used to enhance the collaborations on photovoltaics, thermoelectricity, and power electronics.

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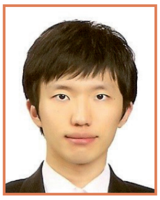


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DiSABloC - Directed Self-Assembly of Block Copolymers: Towards Smart Functional Surfaces for Nanoelectronics & Energy

LABORATORIES: LETI, INAC, CERMAV; UNIV. OF CHICAGO/IME & ARGONNE NATIONAL LABORATORY

PRINCIPAL INVESTIGATORS : Paul F. Nealey (Chair of excellence), Raluca Tiron (Grenoble Contact 1), Hammed Gharbi, **Tommaso J. Giammaria** (Postdoctoral Fellow), Patrice Rannou (Grenoble contact 2), Manuel Marechal, Said Sadki, **Gyuha Jo** (Postdoctoral Fellow), Redouane Borsali (Grenoble Contact 3), Sami Halila, Issei Otsuka, Christophe Travelet

Supported jointly by the Labex LANEF and the Grenoble Nanosciences Foundation, the collaborative research project DiSABloC is "high-risk high-gain" (Technology Readiness Level, TRL2-4) and multidisciplinary (chemistry, physics, biology, nano-science/technology). It aims at originally addressing two societal and technological, applied and basic research-oriented grand challenges: i) Ultimate nanoelectronics (ICTs) ii) Safer and more efficient electrochemical energy storage solutions.

At the heart of this project is the disruptive concept of the Directed Self-Assembly (DSA) of a new class of high-χ Block CoPolymers (BCPs), including carbohydrate-based ones. Thanks to 20 years of academic and industrial efforts, this concept is on the verge of achieving goals previously thought as being far

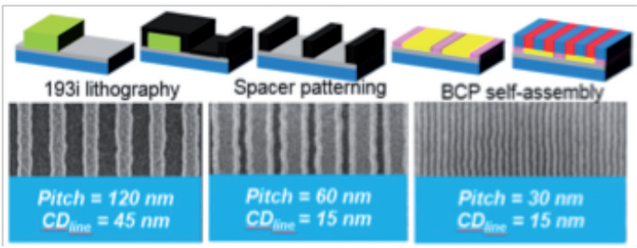

Fig. 1: ICTs: DiSABloC's BCP chemo-epitaxy flow based on spacer patterning leading to 30 nm pitch line patterns

from practical reach: mastering the quasi defect-free ordering of (soft) matter into a handful of morphologies and functions (e.g. nanomasks & ion conductivity) up to the 300 mm wafer scale with pattern resolution down sub-10 nm range.

This unprecedented joint effort to date, co-operated by a leading scientist for Directed Self-Assembly of Block CoPolymers and researchers of three Grenoble labs, is aiming at scientific and technology breakthroughs with transformative economical impacts in

• ICTs/Nanolithography (task 1), through enabling the generation of nanosmasks with sub-10 nm resolution via DSA (grapho/chemo-epitaxy) of BCPs (Fig. 1)

• Energy Storage/Block CoPolymer Electrolytes (task 2), through a fundamental understanding and mastering of the structure/property correlations existing within ion-conducting polymer thin films (Fig. 2)

• Life Sciences (task 3), with smart 2D substrates acting as stimuli responsive test beds for next generation (bio)sensors.

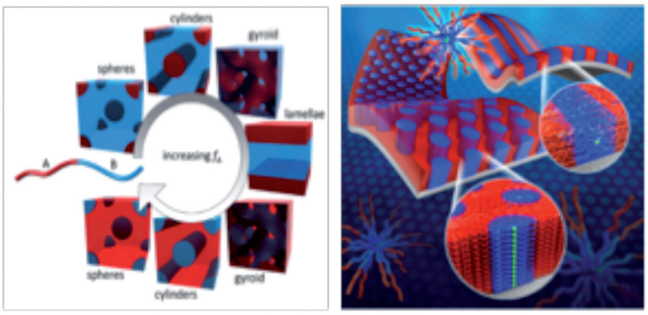

Fig. 2: Electrochemical Energy Storage: Encoding 1D, 2D & 3D ionic transport in DiSABloC's BCP Electrolytes

OUTCOMES

Oral presentations:

ILL-ESRF October 2017;

Bordeaux Polymer Conference, Bordeaux, France, 2018;

E-MRS Spring Meeting, Strasbourg, France, 2018;

4th International symposium on DSA, Sapporo, Japan, 2018.

Collaborations:

O.T. Ikkala, Academy of Finland & Aalto University, Finland. S. Patel, University of Chicago, USA

Awards:

Paul F. Nealey elected to the National Academy of Engineering (USA)

UHV-NEQ : Chambre Ultra-Vide de dépôts métalliques pour la Nano-Electronique Quantique

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EQUIPMENTS

LABORATORIES: NEEL, INAC, LPMMC

PRINCIPAL INVESTIGATORS : Olivier Buisson, Thierry Crozes, Hervé Courtois

The NEQ-UHV equipment has been developed to fabricate several original devices based on high quality superconducting and metal films. For example we optimize superconducting quantum interference devices (SQUID) based on Nb films in terms of sensitivity, ease of fabrication [1] and operation, or operating temperature and magnetic field range through a thorough understanding of their electro-thermal behaviour [2,3]. For the optimization of Nb nanobridge SQUID (Fig. 1), we demonstrated controlled nanoconstrictions using a sequential repetition of customized electro-annealing steps [4,5]. Superconducting vortex dynamics and its dissipation have also been studied in a Nb/insulator/metal multilayer structures [6]. Finally Nb microwave coplanar resonators patterned onto silicon nitride wafers are used as quantum-limited position detectors for the study of a nanomechanical (NEMS) beam at ultra-low temperature (Fig. 2).

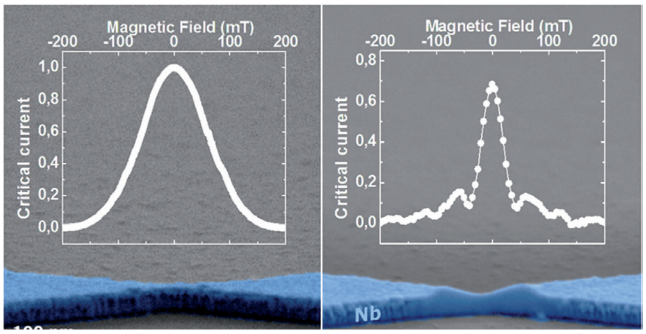

Fig1: Nb constriction before and after sequential electro-annealing [4]. Fraunhofer-like field dependence of the critical current indicates the formation of a weak link.

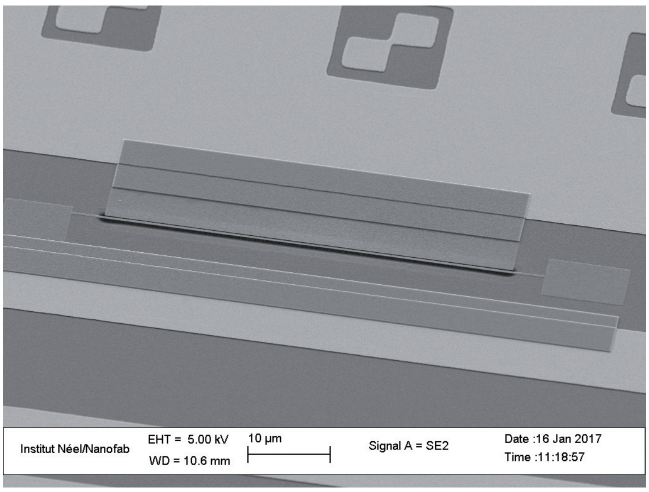

Fig2: Nanobeam NEMS inserted in a coplanar Nb microwave resonator.

We have also implemented the epitaxial growth of rhenium on a sapphire substrate in order to realize quantum circuits and quantum resonators with higher coherence time. Through X-ray diffraction, the Re films show an epitaxial relationship with the substrate and a narrow rocking curve. From these films we realized and studied nanowires down to 50 nm to characterize their superconducting properties and evaluate quantum effects.

OUTCOMES

Publications :

[1] "Niobium-based superconducting nano-device fabrication using all-metal suspended masks", Nanotechnology 24, 375304 (2013).

[2] "Reversibility Of Superconducting Nb Weak Links Driven By The Proximity Effect In A Quantum Interference Device", Phys. Rev. Lett. 114, 157003 (2015).

[3] "Controlling hysteresis in superconducting constrictions with a resistive shunt", Supercond. Sci. Technol. 28, 072003 (2015).

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[5] "In situ tailoring of superconducting junctions via electro-annealing," Nanoscale, 10, 4, (2018).

[6] "Imprinting superconducting vortex footsteps in a magnetic layer," Sci. Rep. 6, 27159 (2016)

[7] "Interplay between electron overheating and ac Josephson effect", Phys. Rev. B 93, 180505(R) (2016).

[8] "Magnetic flux penetration in Nb superconducting films with lithographically defined microindentations," Phys. Rev. B, 93, 054521 (2016).

[9] "Flux penetration in a superconducting film partially capped with a conducting layer," Phys. Rev. B, 95, 1 (2017)

[10] "Quantitative magneto-optical investigation of superconductor/ferromagnet hybrid structures," Review of Scientific Instruments, 89, 023705, (2018)

[11] "Josephson coupling in the dissipative state of a thermally hysteretic µ-SQUID", arXiv:1709.02569.

Leverage :

Indo-French project funded by CEFIPRA «Micro-SQUID magnetometry of nano-scale magnetic structures", in collaboration with A. K. Gupta

ANR "Optofluxonics", coordinated by B. Lounis (Bordeaux).
ANR "QPSNanoWires" ", coordinated by P. Joyez (CEA-SACLAY).

Collaboration :

Alejandro Silhanek (Université de Liège), B. Gilles (SIMAP), Xin Zhou (IEMN), B. Lounis (Bordeaux), D. Basko (LPMMC).

PhD & Internship :

PhD:

Alessandro de Cecco (2014-2018),

Jorge Nacenta (2015-2018),

Jovian Delaforce (2018-2021)

Master Internships: Akanksha Kapoor, Karthik Bharadwaj

Many-body quantum optics with superconducting circuits

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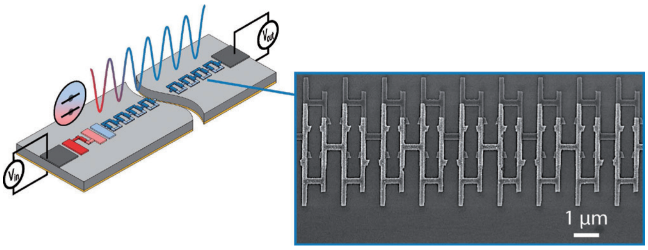
Javier Puertas Martínez (PhD student), Nicolas Roch (thesis supervisor), Nicolas Gheeraert, Serge Florens, Olivier Buisson

LABORATORY : NEEL

The use of superconducting circuits as building blocks for studying light matter interactions at the fundamental level was introduced more than a decade ago and is named Circuit Quantum ElectroDynamics (circuitQED). With this project we want to push these ideas to the next level and build circuits to explore many-body quantum optics. The key element of these circuits is the Josephson junction, two superconductors separated by a thin insulating barrier. Thanks to its huge non linear inductance it can be used for fabricating devices as: quantum two level systems (qubits), quantum limited amplifiers and high impedance transmission lines.



Artistic representation of the circuit. A transmon qubit (red) coupled to a chain of Josephson junctions (blue). In the inset an electronic microscope image of the array of Junctions is shown.

In this work we are interested in studying a qubit strongly coupled to an engineered environment containing many degrees of freedom. To enhance this coupling we need the impedance of the environment to be high. Using an array of 4700 Josephson junctions we can obtain such a high impedance.

We couple the qubit via coupling capacitors to the array and probe the system via microwave transmission measurements. We obtain a strong hybridization of the qubit levels with several modes of the environment obtaining a many-body system.

OUTCOMES

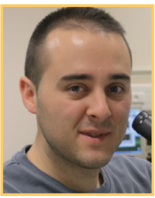
Publications: Probing a transmon qubit via the ultra-strong coupling to a Josephson waveguide. arXiv:1802.00633 (2018)

Oral presentations:

- GMD 26 2016 Groningen (Netherlands)
- APS March Meeting 2017 New Orleans (U.S.A)
- ICQSIM 2017 Paris (France).

Leverage: CLOUD (ANR-16-CE24-0005)
GEARED (ANR-14-CE26-0018)

Collaborations: Izak Snyman, University of the Witwatersrand, Johannesburg, South Africa



Spin-sensitive tunneling in Superconductor - Quantum Dot junctions

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Alvaro Garcia Corral (PhD student), Clemens Winkelmann (thesis supervisor), David van Zanten, Hervé Courtois, Denis Basko, Serge Florens

LABORATORIES : NEEL, LPMMC

When inserting a single quantum dot (QD, a molecule or a nanoparticle) between two superconducting (S) contacts, the resulting device has fascinating electronic conduction properties, which reflect the coupling of a discrete orbital quantum energy level to superconductivity. The host group has recently demonstrated applications of S-QD-S junctions as an on-chip and on-demand source of single monochromatic electrons. Building on these findings, the present PhD project explores in more depth the quantum dynamics at play in such devices, as well as the role of the spin degree of freedom.

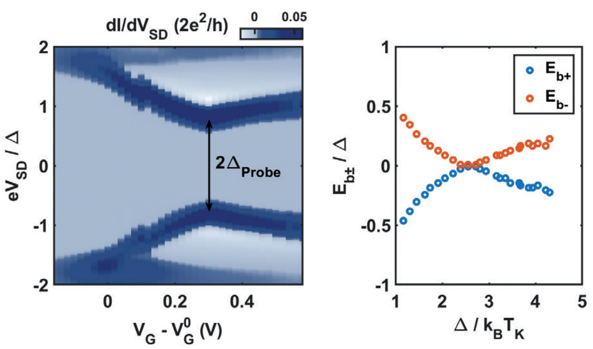

Fig. 1: (left) Mapping of sub-gap states versus gate voltage. (right) Extracted bound-state energy, displaying the phase transition for $\Delta/k_BT_K \approx 2.5$.

In the course of the above project, we have studied S-QD-S devices with stronger values of the tunnel coupling. These are not necessarily well suited for single electron injection, but give access to a rich physics: the competition of the leads' superconductivity and the magnetism of single unpaired electrons on the QD leads to bound sub-gap excitations in the superconductor. In particular, we are able to tune the S-QD hybrid precisely across the quantum phase transition between a magnetic and non-magnetic QD ground state (Fig1).

OUTCOMES

Oral presentation: LT28, Gothenborg, Sweden, 2017.

Collaborations: J. P. Pekola, Aalto University, Finland; K. J Franke, FU Berlin, Germany.

Awards: Best thesis presentation prize at Rencontres des Jeunes Physicien-ne-s for A. Garcia Corral, 2017.

Leverage: JOSPEC ANR (PRCI), 2017.

PHD GRANT

Topological Josephson junctions – Joule poisoning of Majorana modes

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Kévin Le Calvez (PhD student), Manuel Houzet, Julia Meyer, Hervé Courtois, Benjamin Sacépé (thesis supervisor)

LABORATORIES : NEEL, INAC

The new excitations called Majorana zero modes that can emerge in topological superconducting systems are attracting considerable attention for the prospect of topological quantum computing. In this work we have investigated topological Josephson junctions made by grafting the surface of the 3-dimensional topological insulator Bi_2Se_3 with superconducting electrodes: the surface states are predicted to host Majorana Bound States with an unusual 4π-periodicity in the superconducting phase difference across the junction, and the subsequent suppression of the odd Shapiro steps in the current-voltage characteristics.

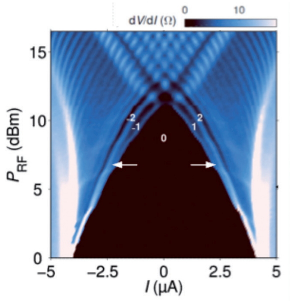

Fig. 1: Shapiro map of a topological Josephson junction; white numbers indicate Shapiro steps index. The white arrows mark the appearance of the Shapiro steps ±1 upon increasing the microwave power P_{rf}.

We have studied the response of the characteristics of our junctions to a microwave excitation. Our main experimental finding is the absence of the first Shapiro step at low microwave power (Fig. 1). By including electron overheating due to Joule dissipation in our theoretical analysis, we predict a poisoning of the 4π-periodic Majorana Bound States [1]. The numerical simulations compare very well with the experimental data and lend support to the Majorana origin of the partial suppression of the first Shapiro step [2].

OUTCOMES

[1] Interplay between electron overheating and ac Josephson effect, Phy. Rev. B 93, 180505(R) (2016).

[2] Joule overheating poisons the fractional ac Josephson effect in topological Josephson junctions, arxiv:1803.07674 (2018).

Oral presentations: Shybrids, Les Arcs (2018); Optima18, MPI Dresden (2018).

Leverage: Development of a fruitful collaboration between theory (INAC) and experiments (NEEL) on topological superconductivity.

PHD GRANT

Doping engineering and characterization in germanium nanowires using in-situ transmission electron microscopy

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Minh Anh Luong (PhD student), Martien den Hertog and Eric Robin (thesis supervisors)

LABORATORIES : NEEL, INAC

This PhD focuses on doping engineering and quantification using a metal phase propagation of aluminium in germanium nanowires (NWs), that can be performed in-situ in a transmission electron microscope (TEM). With this original approach, we expect to obtain exceptionally high doping levels in germanium, with concentrations beyond the limits imposed by the growth process of nanowires or thin films.

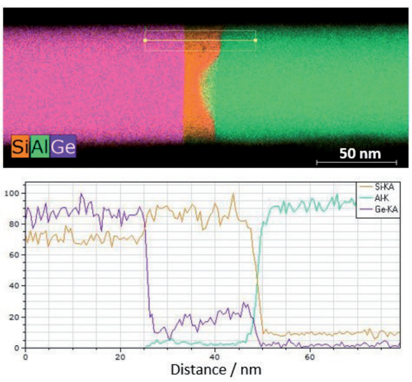

Fig. : Chemical map, and line-scan on the yellow rectangle, of fabricated heterostructure with SiGe NW, Si region and Al reacted part.

Minh Anh has improved the fabrication of contacted NWs on nitride membranes, a TEM compatible support. He uses energy dispersive X-ray spectroscopy to map the chemical composition and get more insight in the diffusion processes (figure), as well as TEM holography and electrical in-situ experiments to study the electrical properties of these nano-materials and potentially make a correlation with their composition. While we can't yet conclude on the doping engineering aspect, Minh Anh has obtained exciting results on propagating Al in SiGe alloy NWs. In these structures, a silicon rich region is created at the interface between the Al contact and the remaining SiGe alloy NWs. This is potentially a powerful method to fabricate contacted quantum dot heterostructures, and this will be explored in more detail.

OUTCOMES

Presentation to IMC conference, Sydney, Australia, 2018.

Collaboration: M. Sistani, A. Lugstein, Vienna Technical University, Austria.

Leverage: ANR project COSMOS and e-See, ERC project e-See.


Iontronics
Field effect study of nanodevices using ionic liquid gating

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LABORATORIES: NEEL, INAC, CENTRAL RESEARCH INST. OF ELECTRIC POWER INDUSTRY (JAPAN)

PRINCIPAL INVESTIGATORS : Shimpei Ono (Chair of excellence)**, Johanna Seidemann** (PhD student), Benjamin Sacépé (Grenoble contact), Thierry Klein, Christophe Marcenat

Ionic liquids (IL's) are non-volatile fluids, consisting of cations and anions, which are ionically conducting, but electrically insulating and nowadays widely used for high field-effect carrier injection. Allowing conformal surface doping, IL's are very suitable gate dielectrics for nanodevices such as nanotubes and nanowires. Good candidates are the atomically flat inorganic transition metal dichalcogenide nanotubes (TMDC INTs). Astonishingly, in spite of the considerable amount of work devoted to carbon nanotubes, the potential of TMDC INTs for electronic and optoelectronic device applications has been widely overlooked.

Other candidates are III-V semiconductor nanowires, where advanced field effect control represents a key aspect for both fundamental studies and technological application.

In this project, we realized high-quality ambipolar IL-gated field-effect transistors (FETs) based on multi-walled WS2 nanotubes (Fig. 1a). A FET transfer characteristic is displayed in Fig. 1b. The operation performances of our INT FETs are comparable to that of best electrical double layer gated WS2 thin flakes. We obtained mobility up to 80 $cm^2V^{-1}s^{-1}$ for both p- and n-type charge carriers and on-off current ratios exceeding 10^5. The IL-gate allowed us to establish a pn-junction in the INT, leading to a light-emitting diode. Fig. 1c shows the same device before the measurement and in the light emission regime. An electroluminescence (EL) spot appeared on the INT between drain and source electrodes.

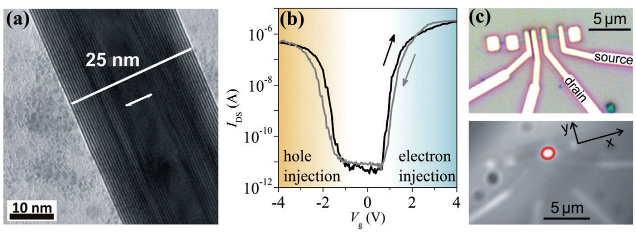

Fig. 1: WS2 NT's: a) TEM image of a WS2 nanotube. b) FET transfer characteristic. c) Optical image of a device before the measurement and in the light emission regime.

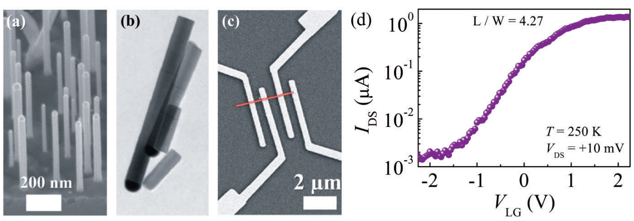

Fig. 2: InAs nanowires: a) and b) SEM and STEM image of individual InAs nanowires. c) SEM image of a NW device. d) FET transfer characteristic.

Additionally, we realized new IL-gated FETs based on single InAs nanowires (Fig. 2a–c). Fig. 2d displays a transistor transfer characteristic, showing an on-off current ratio of 10^3 when going from complete electron depletion to high electron injection. The nanowires undergo a transition from insulating to metallic at high electron doping levels. The promising performances resulting from the conformal doping open an avenue for new IL-gated III-V nanowire devices.

OUTCOMES

Publications:

[1] Electric-field assisted depinning and nucleation of magnetic domain walls in FePt/Al_2O_3/liquid gate structures, Appl. Phys. Lett. 104, 082413 (2014).

[2] High field termination of a Cooper-pair insulator , Phys. Rev. B 91, 220508(R) (2015).

[3] Electric field controlled domain wall dynamics and magnetic easy axis switching in liquid gated CoFeB/MgO films, J. Appl. Phys. 122 (2017) 0133907.

[4] Ionic-liquid gating of perpendicularly magnetised CoFeB/MgO thin films J. Appl. Phys. 120 (2016) 023901.

[5] Quantum meets classical phase transition: Low-temperature anomaly in disordered superconductors near B_{c2}, to appear in Nature Physics

Invited presentation:

- 2D Materials Worskhop, MINATEC, Nov. 2016
- International Workshop on Localization, Interactions and Superconductivity, Landau Institute for Theoretical Physics, June 2018

Collaborations:

Gilles Nogues, Christopher Bauerle, NEEL

David Le Boeuf and Marc-Henri Julien, LNCMI

Francesco Rossella, Stefan Heun, Scuola Normale, Pisa

Francesca Chiodi, C2N, Université Paris-Sud,

Liza Herrera Diez, CNRS-Université Paris Sud.

Zheng Vitto Han (Shenyang National Laboratory for Material Science, China)

Leverage: under discussion with CRIEPI for a continuation of the collaboration

EQUIPMENTS

Scanning probe microscopy stage for low temperature and high magnetic field imaging

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LABORATORIES: NEEL, LNCMI

PRINCIPAL INVESTIGATORS : Roman Kramer (equipment supervisor), Laurent Lévy, Klaus Hasselbach, Ilya Sheikin, Albin De Muer

A compact scanning probe microscope for low temperatures and high magnetic fields is constructed in SCANSET. The scanning microscope is equipped with two nanoscale probes, a Hall probe and a single electron transistor, in combination with high magnetic fields and extremely low temperatures: this makes it possible to investigate a variety of phenomena in condensed matter physics, related for instance to the quantum Hall effect, heavy fermions, superconductors or topological insulators.

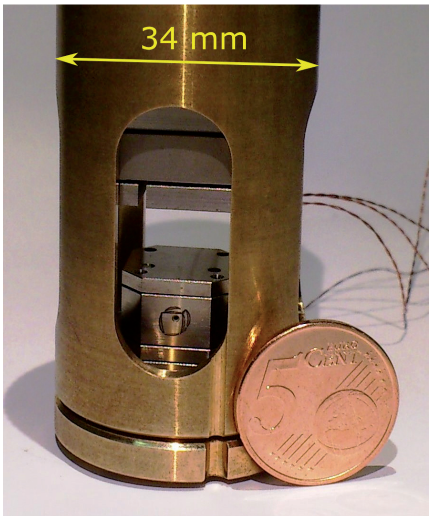

Fig.1: the compact scanning probe microscope.

We constructed an extremely compact scanning probe microscope (3.4 cm in diameter, Fig.1) with a rather large scan range (30x30 µm2) at low temperature. Due to this compact design the complete scan stage fits in the cold bore of an 18T superconducting magnet and is mounted on an Oxford dilution refrigerator (50 mK). We developped two different nanoscale scanning probes for the microscope in order to open a large spectrum of applications in the frame of LANEF.
First, we engineered micro-Hall probes at Néel (Fig. 2) which enables the microscope to map magnetic induction at the sample surface. Typical applications are the visualization of magnetic domains and the characterization of novel superconductors and superconductor/ferromagnet hybrid structures [1].
Second, a nanoscale scanning single electron transistor (SET), which is a very sensitive charge detector, was fabricated at Néel(Fig. 2). With the nanoscale SET on a tip we first mapped a well known charge distribution produced by electrostatic gates on a Si/SiO surface (Fig. 3b). Fig. 3a shows the SET current variations induced by these three gates measured in a distance of 200 nm. These measurements demonstrate a spatial resolution of the order of 200 nm and a very high electric field sensitivity.

The SET microscope is now used to probe locally the compressibility of electronic states in encapsulated graphene. Moreover we will investigate new compound superconductors, e.g. $PdTe_2$, with low critical temperatures (T_c<1.5 K) with the Hall probe option of the microscope.

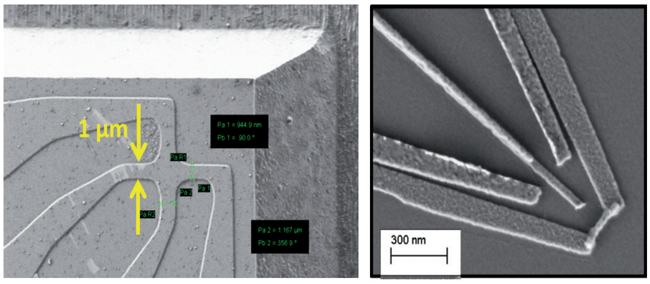

Fig 2: Micrometer sized Hall probe (left) and nanoscale single electron transistor (right) engineered close to a sharp edge of a substrate.

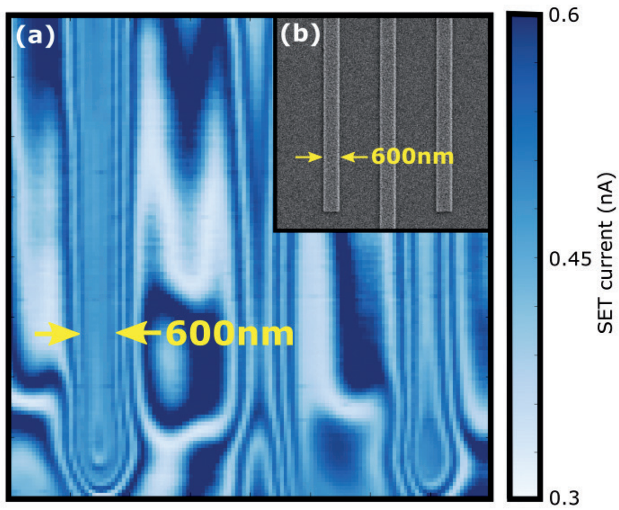

Fig. 3: (a) Map of the current through the SET measured in a distance of about 200 nm above three electrostatic gates (b).

OUTCOMES

[1] Quantitative magneto-optical investigation of superconductor/ferromagnet hybrid structures, Rev. Sci. Instrum 89, 023705 (2018).

Oral presentations: Roman Kramer at Vortex IX and X, Rhodes, Greece, 2015 and 2017.
Jorge Nacenta at C'Nano, Lyon, France, 2017

Poster presentation: Jorge Nacenta at Bienal de la Real Sociedad Española de Física, Santiago de Compostela, Spain, 2017

Collaboration: Prof. Alejandro Silhanek, Université de Liège, Liège, Belgium.

Leverage:

PhD: Jorge Nacenta (2015-2018) funded by Fondation Nanoscience.

3 year IUA chair for Roman Kramer.

Time Resolved E-beam Experiments (TREE)

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LABORATORIES: NEEL, INAC

PRINCIPAL INVESTIGATORS : Gilles Nogues (scientific supervisor), **Fabrice Donatini** (equipment supervisor), Christophe Hoarau, Laurent Del-Rey.

In the frame of condensed matter physics, an electron beam is a very convenient source to excite and probe wide-bandgap semiconductors at the nanometer scale, by measuring the cathodoluminescence or the electron beam induced current. Internal electric fields can be mapped and the diffusion of charge carriers can be measured. This is particularly interesting for the improvement of new lighting and power devices.

Furthermore, the dynamical study of excited carriers brings additional information such as carrier lifetime and mobility, which are key parameters for the realization of state-of-the-art devices. One available solution to achieve this at the nanometer scale is the use of a dedicated, very expensive system consisting of a specific scanning electron microscope (SEM) with a photocathode excited by a pulsed laser. A 10 ps temporal resolution is reported, which is often much shorter than our characteristic times, to the detriment of the energy per pulse.

Our project consisted in the use of an add-on solution on a conventional field effect SEM (FESEM). In this case, an electrostatic beam blanker system (Fig. 1) is inserted in the FESEM column. Under operation, the detrimental spatial deflection of the electron beam is overcome by column realignment. The core of our equipment is an in-house add-on system for a FEI Inspect F50 FESEM. It is a fast beam-blanking system with 150 ps intrinsic response time thanks to an ultra-high-speed pulse generator. However, when the device under study is smaller than the deflection length of the electron beam, a 35 ps resolution can be achieved. Both optical and electrical time-resolved electron beam experiments are possible using fast detectors associated with time-correlated single photon counting system and high bandwidth oscilloscope with RF connection, respectively.

The usefulness of such dynamical studies at the nanometer scale has been proven by this installation and that of comparable setups in several French laboratories. Our setup is currently used by different groups to study the luminescent and electrical characteristics of GaN, AlN and ZnO nanowires (Fig. 2), and on hybrid perovskites for luminescent and photovoltaic applications. We started time-of-flight experiments on diamond-based and perovskite-based x-ray detectors. Industrial companies, such as OSRAM and ALEDIA (using our equipment), have also seen the advantage of this technique to probe the quality of their lighting devices made of semiconductor nanorods.

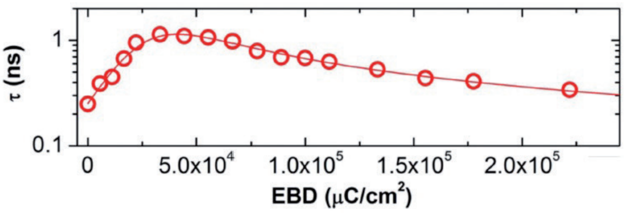

Fig. 2: Exciton lifetime τ in a ZnO nanowire exposed to an electron beam dose (EBD)

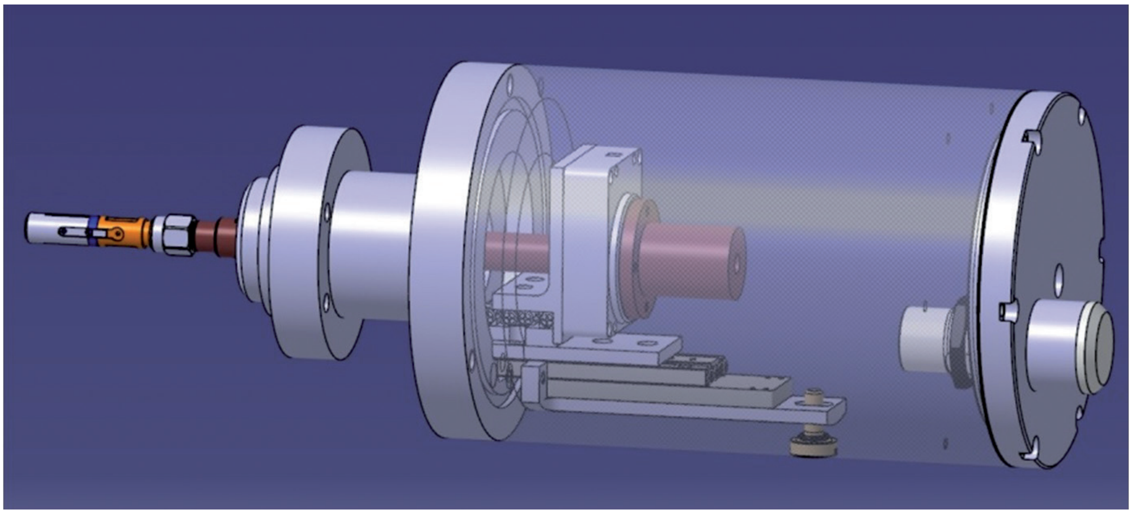

Fig. 1: 3D technical drawing of the beam blanker

OUTCOMES

[1] Exciton diffusion coefficient measurement in ZnO nanowires under electron beam irradiation, Nanotechnology 29, 105703 (2018).

Oral presentations: TWCSN, Berlin, Germany, 2018; J2N, Grenoble, 2017.

Main users : Bruno Gayral, Bruno Daudin, Julien Pernot and Gwénolé Jacopin.

Collaborations:

Denis Dauvergne, LPSC, Grenoble, 2018.

Pierre Tchoulfian, ALEDIA start-up company in Grenoble and Timothée Lassiaz, ALEDIA/NEEL Cifre PhD fellowship 2018-2021.

Recruitment: Gwénolé Jacopin, CNRS 2018, NEEL.

Leverage: ANR project ROLLER 2018-2021.

EQUIPMENTS

CryOptics – A dilution cryostat for nano-optics and nano-optomechanics

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LABORATORIES: NEEL

PRINCIPAL INVESTIGATORS : Olivier Arcizet and Laetitia Marty (equipment supervisors), Francesco Fogliano, Benjamin Besga, Julien Jarreau, Eric Eyraud, Wolfgang Wernsdorfer, Corinne Felix, Benjamin Pigeau.

The CRYOPTICS project aimed at developing a novel instrument capable of realizing ultrasensitive optical and optomechanical experiments with nanoscale samples at dilution temperatures. It is based on a 20 mK "sionludi" platform - an inverted dilution cryostat, with dimensions and operation modes compatible with ultrasensitive optical experiments, entirely developed at NEEL. Cryo-compatible optical elements were also developed internally, such as large numerical apertures (0.75) fibered objectives producing diffraction limited optical spot (400 nm) with interferometric imaging capability. They can be piezo-scanned for imaging.

A first nano-optomechanical experiment allowed us to validate the experimental developments (test of optics, thermalisation of the samples, vibration level). It consists in reading out optically the vibrations of a singly clamped, suspended silicon-carbide nanowire. Those nanoresonators with subwavelength-sized diameters and extreme aspect ratios (2000) represent ultrasensitive scanning vectorial force sensors, with 10 attonewton/$Hz^{1/2}$ sensitivities at 300K, only limited by the thermal noise. The latter can be much reduced at cryogenic temperatures, while benefiting from increased values of the mechanical quality factor. This requires an efficient thermalization of the nanowire, and avoiding optical heating. The thermal conductance becomes extremely weak (~10^{-14} WK^{-1} at 100mK), which lead us to develop optomechanical readout techniques operating in the photon counting regime using avalanche photodiodes. We could observe nanowires thermalized down to 40 mK while injecting only a picowatt of laser light, with a ~10 mK/pW heating rate. Force sensitivities of 40 zeptonewton/$Hz^{1/2}$ were reported, which represents a 10-fold improvement over existing experiments, and corresponds (in 1 s) to the Coulomb interaction between 2 electrons separated by ~100 µm.

Future developments are oriented towards the realisation of fluorescence imaging and improved optics, cavity nano-optomechanics and the incorporation of electrical transport.

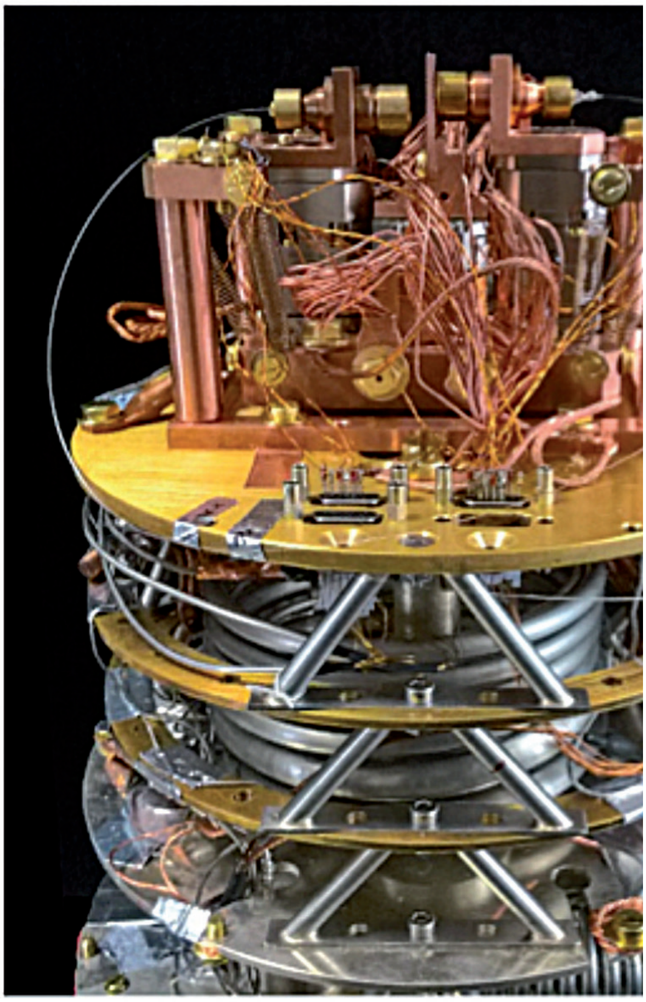

Fig. 1. The cryoptics experiment, built on top of a "sionludi" cryostat. Well visible are the optical fibers used to inject and collect light from the sample. The sample and the fibered interferometric objectives can be finely positioned with piezo-actuators. The experiment is suspended by 8 springs to isolate it from acoustic vibrations.

OUTCOMES

Publications:

[1] Eigenmode orthogonality breaking and anomalous dynamics in multimode nano-optomechanical systems under non-reciprocal coupling, Nature Commun. 9, 1401 (2018).
[2] Ultrasensitive nano-optomechanical force sensor at dilution temperatures (in preparation,2018).

Oral presentations :
GDR MecaQ, Paris 2017;
ENS Lyon 2017,
LOMA Bordeaux 2018;

Leverage:
ERC proof of concept, CARTOF, 2017.
ANR NC2 2016,
ANR QCFOrce 2016

Ultrasensitive nano-optomechanical force field sensor at dilution temperatures

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Francesco Fogliano (PhD student), Olivier Arcizet (thesis supervisor), Benjamin Pigeau, Benjamin Besga, Laure Mercier de Lépinay, Antoine Reigue, Philip Heringlake

LABORATORY : NEEL

An ultrasensitve force field sensor based on the optical readout of suspended vibrating nanowires has been successfully operated at dilution temperatures (Fig. 1). The development of measurements techniques operating in the photon counting regime, where less than one photon is detected per oscillation period, enabled to measure the thermal noise of a nanomechanical resonator thermalized to the base temperature of a dilution fridge. Realizing noise thermometry by varying optical readout powers permits to investigate the unexplored thermal and mechanical properties of the nanowire at dilution temperatures (Fig1.d).

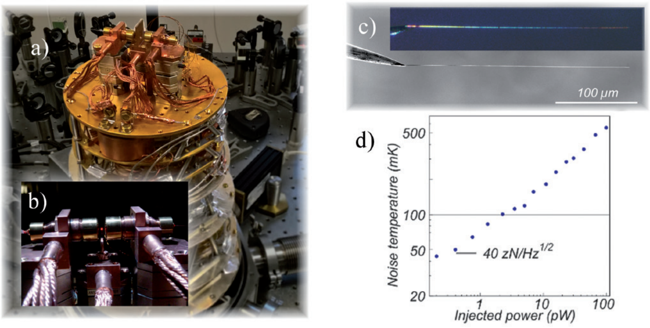

Fig. 1: a) Cryostat CRYOPTICS b) Optical element to inject light and perform the readout c) SiC Nanowire d) Effective temperature and force sensitivity of the sensor.

Despite the modest quality factors achieved, limited for the moment by residual amorphous defects contribution, this approach enables unprecedented force readout sensitivities, in the zeptonewton range. In parallel, a novel cavity nano-optomechanical experiment was developed at room temperature, consisting in inserting a nanowire in the middle of a high-finesse fiber-cavity. The combination of dilution temperatures and high-finesse microcavities opens the door towards unexplored regimes in cavity optomechanics, where optical non-linearity arises at the single photon level.

OUTCOMES

[1] Ultrasensitive nano-optomechanical force field sensor at dilution temperatures, in preparation, (2018)

Oral presentation: GDR MecaQ, Paris, France, 2017

Collaborations: W. Wernsdorfer, E. Eyraud, C. Felix, J. Reichel (ENS-Paris)

Development of Bragg coherent X-ray diffraction and ptychography methods

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Gaétan Girard (PhD student), Vincent Favre-Nicolin and Joël Eymery (thesis supervisors)

LABORATORIES : INAC, ESRF

Optimising the performance of semi-conductor nanostructures, developed for existing and future electronic and optoelectronic devices, relies on a precise control of the strain. This PhD topic focuses on the study and use of Coherent X-ray Imaging techniques, which allow to reconstruct single objects with a resolution of 5 to 10 nm. Beyond the results in terms of materials knowledge, the main motivation is to develop a technique expected to become a reference metrology method for the study of strained nanostructures, down to objects with a thickness of 10-20 nm. Therefore, three guidelines are identified: the development of 2D and 3D strain mapping using coherent X-rays, taking into account all the characteristics of the focused X-ray nano-beam; the quantitative study of objects, including non-isolated ones such as in a complex device; the application to axial and radial nanowire heterostructures grown at INAC and SiGe strained nanostructures, developed by a CEA-LETI/STMicroelectronics collaboration.

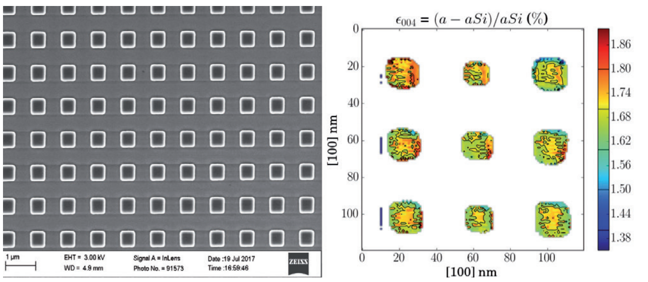

Fig.: Left: SEM image of strained SiGe islands; Right: Strain map relative to Si lattice parameter on a patterned zone of 2x2 µm² square islands

This PhD is co-financed by the European Synchrotron, with the prospect of the « Extremely Brilliant Source » upgrade, which will provide in 2019 a 100-fold increase of the coherent X-ray flux.

OUTCOMES

Software: PyNX python library, http://ftp.esrf.fr/pub/scisoft/PyNX/

Poster presentation: RX2017, Lille, France, 2017.

Collaboration: ESRF co-financing, XNP group, ID01 beamline.

PHD GRANT

Growth and structural characterizations of InAs/GaAs axial nanowires heterostructures

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Daria Beznasyuk (PhD student), Moïra Hocevar and Julien Claudon (thesis supervisors), Petr Stepanov, Martien Den Hertog, Jean-Luc Rouvière, Eric Robin

LABORATORIES : NEEL, INAC

Nanowires can host combinations of materials with very different lattice parameters: the mismatch strain is efficiently relaxed on the sidewalls, enabling the formation of dislocation-free interfaces out of reach with two dimensional thin films. It is important to understand how the strain distributes as it strongly influences the band structure, and consequently the electronic and optical properties of the final device. We grow GaAs-InAs nanowires by molecular beam epitaxy using the vapour-liquid-solid mechanism with gold catalysts. Nanowires diameter, length and density are readily controllable by adjusting the growth parameters and the catalyst diameter. We evaluate the strain and composition distribution by high-resolution scanning transmission electron microscopy (HRSTEM) together with Energy Dispersive X-ray spectroscopy. One of our important results is the observation of a 20 nm long strained region around the interface, where crystal planes bend close the sidewalls (Fig.1). Despite a 6% lattice mismatch, our structures show no dislocation when the diameter is less than 40 nm.

We are now working on the reverse structure, GaAs on InAs, in order to realize quantum dots integrated in nanowires, positioned on demand, for new photonic emitters.

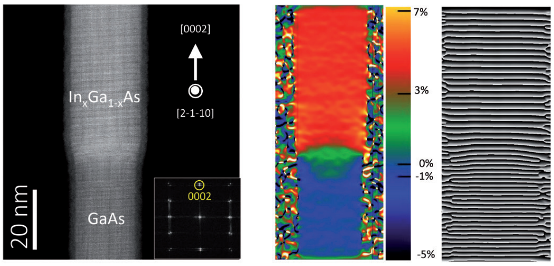

Fig. 1 : HRSTEM image of an InAs/GaAs axial heterostructure. Relative change in lattice parameter along the growth axis with respect to unstrained GaAs. HRSTEM image after Fourier filtering of the [0002] Bragg reflection.

OUTCOMES

Publications: Dislocation-free axial InAs-on-GaAs nanowires on silicon, Nanotechnology 28, 365602 (2017).

Oral presentations: Journées Nationales du GDR PULSE Paris, 2017 (invited) ; Journée Nationales Nanofils, Grenoble, 2017 ; MRS Fall Meeting, Boston, USA, 2016

Collaborations: Pierre Verlot, University of Notthingam, UK; Marcel Verheijen, Philips Research, Eindhoven, NL.

Leverage: AGIR pôle PEM 2015-2016

PHD GRANT

Semiconductor nanowires for Ultimate Magnetic Objects

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LABORATORIES : NEEL, INAC

A quantum dot inserted in a nanowire allows a versatile design of its shape and strain configuration, in order to tailor the orbital and spin anisotropy of confined holes. As a result, the optical selection rules can be adapted to the optical manipulation of the confined hole contemplated as a qu-bit. In addition one can adjust the magnetic anisotropy of the so-called magnetic polaron formed when magnetic impurities are oriented around a hole.

The PhD work was focused on four main steps: (1) the formation of the gold nanoparticle which induces the growth of the ZnTe nanowire, (2) the incorporation of CdTe quantum dots, supported by a model of growth taking into account the volatile character of Cd and CdTe; (3) the formation of a (Zn,Mg)Te shell with clean interfaces and smooth sidewall surfaces; (4) the p-type doping of the shell and the electrical characterization of a single nanowire. Optimizing and combining these processes allows us to grow nanowires with inserted quantum dot of variable length (Fig. 1) and good optical properties.
The study of the emission diagram and the formation of the magnetic polaron with tailored magnetic anisotropy is now pursued in the frame of an ANR project.

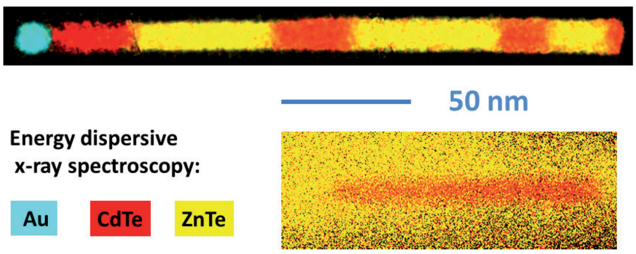


Fig.1: A ZnTe nanowire with CdTe insertions of various lengths (top) and a 80-nm long CdTe quantum dot in a ZnTe nanowire with its shell (bottom).

OUTCOMES

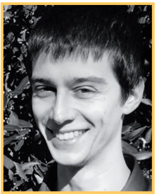
[1] Nanowire growth and sublimation: CdTe quantum dots in ZnTe nanowires, Phys. Rev. Materials 2, 043404 (2018)

[2] Control of the incubation time in the vapor-solid-solid growth of semiconductor nanowires, Appl. Phys. Lett. 110, 263107 (2017).

[3] Diffusion-driven growth of nanowires by low-temperature molecular beam epitaxy, J. Appl. Phys. 119, 164303 (2016).

Oral presentation: 19th. Int. Conf. MBE, Montpellier, 2016.

Leverage: ANR ESPADON, 2016.



Control of the emission of semiconducting nanowires using plasmonic nanoantennas

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Mathieu Jeannin (PhD student), Kuntheak Kheng (thesis supervisor), Gilles Nogues (thesis supervisor), Pamela Rueda-Fonseca, Edith Bellet-Amalric

PHD GRANT

LABORATORIES : NEEL, INAC

Semiconducting nanowires (NWs) offer the possibility to fabricate extremely high quality light-emitting structures for a wide range of applications, ranging from photovoltaics and optoelectronic displays to solid-state based sources of quantum light. However, because of their small size, studying and engineering their optical properties is a challenging task. Metallic nanostructures, on the other hand, provide the ability to control electromagnetic fields at length scales well below the wavelength. The main goal of this project is the control and enhancement of the emission properties of semiconductor quantum dots (QDs) inserted in NWs by modifying their dielectric environment using nano-antennas. For this purpose, we first developed a set of nanocharacterization techniques to correlate various measurements on the one and same NW, allowing a full characterization of its optical and electronic properties. We then implemented a novel nanofabrication technique to couple single QDs embedded in semiconducting NWs to metallic nanostructures. The resulting coupled systems show up to a twofold enhancement of their light emission properties.

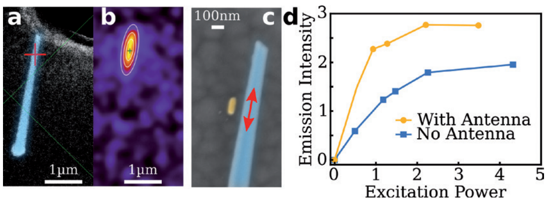

Fig. 1: a) Localization of a QD embedded inside a NW (red cross). b) using cathodoluminescence. (c) Hybrid system with antenna. (d) Enhanced luminescence.

OUTCOMES

[1] Deterministic radiative coupling between nanowire quantum dots and plasmonic nanoantennas, Nanotechnology 27, 185201 (2016).

[2] Optimized Wave-mixing in single and compact aluminium nanoantennas, ACS Photonics 3, 1840 (2016).

[3] Light-hole exciton in semiconducting nanowire quantum dot, Phys. Rev. B 95, 035305 (2017), editor's choice.

[4] Cathodoluminescence spectroscopy of patch plasmonic antennas: towards lower order and higher energies, Opt. Express 25, 5488 (2017).

[5] Enhanced photon extraction from a nanowire quantum dot using a bottom-up photonic shell, Phys. Rev. Appl. 8, 054022 (2017).

Oral presentation: JMC14MCD25, Paris, France, 2014

Collaborations: Alberto Artioli, Joël Cibert, David Ferrand, Guillaume Bachelier, NEEL. Yanxia Hou-Broutin, INAC.

Awards: Best poster award, Nanowires2015, Barcelona, Spain, 2015
Best poster Award, QCD2016, Jeju, South Korea, 2016
PhD award from the Nanoscience Foundation
Leverage: CEA DRF-Impulsion project Hybridimer.

From Sum Frequency Generation to Spontaneous Parametric Down Conversion in hybrid nonlinear plasmonic structures

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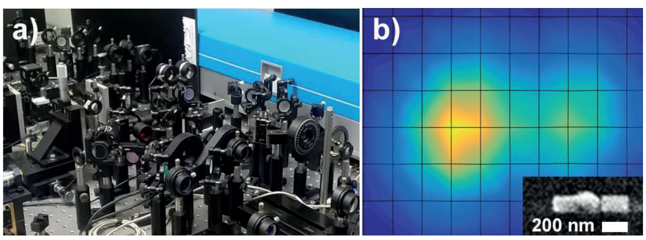
PHD GRANT

LABORATORY : NEEL

Nonlinear optical processes are the core of many technologies such as quantum cryptography or non-invasive multiphoton microscopy. However, the intrinsically weak response of bulk nonlinear materials prevents one from directly downsizing components to the nanoscale, making on-chip applications out-of-reach.
To overcome this issue, a possible path is to combine two complementary nanosized elements with specific properties into a single hybrid structure. In my thesis project, I have developed and used a versatile, computer-controlled setup (Fig.1a) to study homemade optimized hybrid nanostructures composed of plasmonic antennas for near-field enhancement, and a nonlinear KTP nanocrystal for nonlinear conversion efficiency (Fig.1a). We want to optimize two kinds of coherent processes: Sum Frequency Generation (2 photons merging into 1) and Spontaneous Parametric Down Conversion (1 photon splitting into 2). One possible objective is the entangled photon pair production with an individual nanostructure compatible with on-chip integration. Such a device based on entangled photon pairs is contemplated for the development of decision-making strategies algorithm with applications for resource allocating or deep learning algorithms.



a) Experimental setup developed. b) 2D Second Harmonic Generation cartography of a hybrid nanostructure (inset: corresponding SEM image).

OUTCOMES

[1] Wave-mixing origin and optimization in single and compact aluminum nanoantennas, ACS Photonics 3, 1840 (2016)

[2] Collective decision making based on entangled photons (submitted);

[3] Photon-pair production at the nanoscale with hybrid nonlinear/plasmonic antennas (submitted).

Invited oral presentations: COST NQO – GDR Ondes, Marseille, 2016; C2C symposium, Tokyo, 2018.

Collaboration: M. Naruse, NICT, Tokyo, Japan.

PHD GRANT

Differential ultrafast mode switching in micropillar cavities

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LABORATORIES : INAC, NEEL

The injection of free carriers can change the resonance frequency of a semiconductor optical microcavity reversibly within few ps. While cavity switching dynamics is commonly probed using pump-probe spectroscopy, we have introduced a novel approach using quantum dots as a broadband internal light source. The analysis of the cavity emission using a spectrometer and a streak camera (Fig.) probes the switching dynamics of all cavity modes in a single experiment. We have also studied the effect of a strongly inhomogeneous distribution of the injected electron/hole pairs. We observe drastically different switching amplitudes and dynamics for different cavity modes, that we quantitatively model through the different overlaps between free carriers and field intensity distributions.

Non-uniform free carrier switching appears as a powerful tool to tailor the modal structure of a cavity and the switching dynamics of each mode. This is an interesting novel feature in view of applications of cavity switching in quantum optics. For instance, it provides an additional degree of freedom for controlling in time the interaction between quantum dots and a microcavity mode, and it is currently used in our lab to generate ultrashort non-coherent pulses of spontaneous emission.

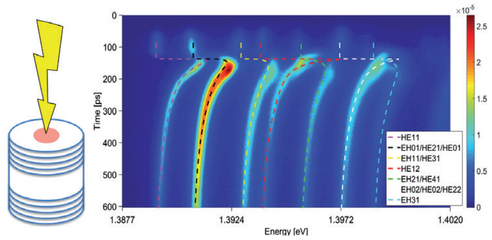

Fig: Streak camera image showing the temporal evolution of various cavity modes frequencies, after the localized injection of free carriers around the axis of a GaAs-AlAs micropillar at 130 ps. The result of numerical simulations is shown by dashed lines

OUTCOMES

[1] Cavity switching: A novel resource for solid-state quantum optics, Proceedings of ICTON 2017, IEEE Book series DOI10.1109/ICTON.2017.8025177

Invited oral presentations : ICNN, Yokohama (2016); SPIE10111 Photonics West, San Francisco (2017); ICTON, Girona, Spain (2017).

Collaboration: W. L. Vos, University of Twente, Netherlands.

Leverage: Novel collaboration with PUC Rio (Brazil) on frequency translation experiments in switched optical microcavities (joint PhD thesis G. Monteiro Torelly).

PHD GRANT

Phonon mediated conversion of exciton-polaritons Rabi oscillations into THz radiation

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Katharina Rojan (PhD student), Anna Minguzzi, Maxime Richard and Giovanna Morigi (thesis supervisors)

LABORATORIES : LPMMC, NEEL, JOINED SUPERVISION SAARLAND UNIVERSITY

Semiconductor microcavities in the strong-coupling regime exhibit an energy scale in the terahertz (THz) frequency range fixed by the Rabi splitting between the upper and lower exciton-polariton states. While this range can be tuned by several orders of magnitude using different excitonic media, the transition between both polaritonic states is dipole forbidden. In this project, we show that, in cadmium telluride microcavities, the Rabi-oscillation-driven THz radiation is actually active without the need for any change in the microcavity design. We propose a frequency down-conversion scheme to generate THz radiation based on a chain of interactions naturally present in a pumped semiconductor microcavity: optical photons strongly couple to excitons that weakly couple to transverse optical (TO) phonons (Fig.1 a). The TO phonons strongly couple to THz photons. We derive the crucial exciton-phonon coupling, starting from the electron-phonon interaction via the deformation potential, taking into account the crystal symmetry. We identify conditions necessary for THz emission, estimate the emission power (Fig.1 b) and show that the exciton-phonon interaction provides a second-order susceptibility. This should allow the experimental realization of a new THz source working at room temperature.

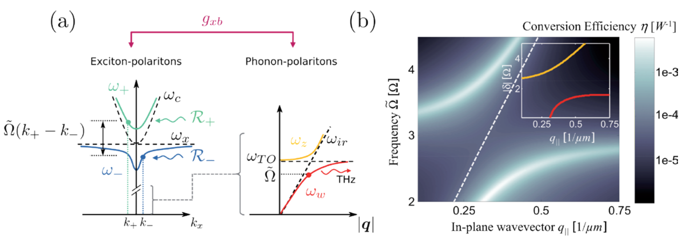


Fig.1: (a) Sketch of the conversion mechanism. (b) Power conversion efficiency of THz photons for resonant pumping

OUTCOMES

[1] Localization transition in the presence of cavity backaction, Phys. Rev. A 94, 013839 (2016)

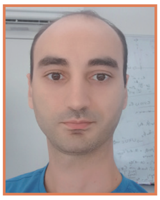
[2] Enhanced Second-Order Nonlinearity for THz Generation by Resonant Interaction of Exciton-Polariton Rabi Oscillations with Optical Phonons, Phys. Rev. Lett. 119, 127401 (2017)

PhD cofunding: Saarland University, with a support from Université Franco-Allemande - Deutsch-Französische Hochschule

Oral presentations: Journée de la matière condensée, Août 2016, Bordeaux ; Deutsche Physikalische Gesellschaft (2016 and 2017) ; 66th Lindau Nobel Laureate meeting (2016)
ANR «Quantum fluids of light» 2016-2020

Collaborations: Régis André (NEEL); Yoan Léger, INSA-Rennes CNRS; Jérôme Tignon, Emmanuel Baudin, LPA Paris.





Quantum technologies with correlated matter at mesoscopic scales

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LABORATORIES: LPMMC, NEEL, INAC, UNIVERSITÀ DI CATANIA & NATIONAL UNIVERSITY OF SINGAPORE

PRINCIPAL INVESTIGATORS : Luigi Amico (Chair of excellence), Anna Minguzzi (Grenoble contact), Denis Feinberg (Neel), **Piero Naldesi** (Post-doc fellow), **Enrico Compagno** (Post-doc fellow), Juan Polo

In this project, we study key issues in mesoscopic physics inspired both by quantum electronics and by the emerging field provided by atomtronics: ultra-cold atoms manipulated in micro-magnetic or laser-generated micro-optical circuits.

In our research, mesoscopic physics have been studied by integrating quantum electronics and atomtronics in a direct way. With this approach, we could explore physical regimes that are hard, if not impossible to access with more standard views. As starting point, we considered specific ultracold matter-wave-analog of known quantum electronic systems. In line with such a program, bosonic networks confined in ring lattices, the simplest atomtronic circuit perhaps, can define the so-called Atomtronics Quantum Interference Devices (AQUIDs), in analogy with SQUID's (Fig. 1). This way, we have disclosed new aspects of defining issues in quantum science, like interference, entanglement, and macroscopic quantum coherence. In particular, preparation and read-out protocols to study coherent states in AQUID have been devised.

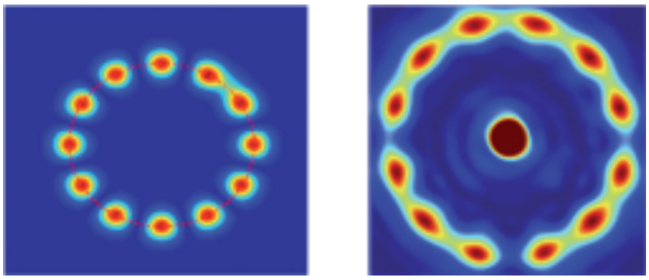

Fig. 1: The Atomtronics Quantum Interference Device (AQUID). Ring-shaped lattice of condensates interrupted by a single weak link mimicking the rf-SQUID (left) or by three weak links with flux qubits dynamics (right). Such systems can sustain macroscopic quantum coherence and quantum phase slips with experimentally feasible protocols [3].

Again inspired by quantum electronics, we have studied transport. The specific features of quantum optical systems allow us to study the problem with a new twist (Fig. 2). At the same time, standard views and methods well established in quantum electronics, like quantum phase dynamics in Josephson junctions arrays, Luttinger liquids effective theories etc., have been employed to study basic questions of atomic and molecular physics of Bose-Einstein condensates.

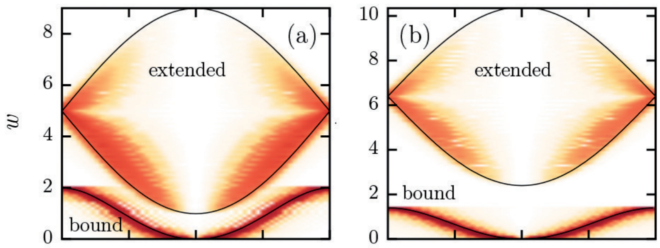

Fig. 2: Quantum solitons in optical lattices. The dynamical structure factor of quantum solitons obtained by a specific microscopic theory with two different system parameters [1].

It appears very likely that our integrated approach will trigger breakthroughs both in basic research and technology developments in the years to come. Specifically, the scope of quantum simulators is expected to be considerably enlarged. At the same time, we put the basis for new devices in quantum technology with enhanced coherence, flexibility and control.

OUTCOMES

Publications:

[1] 'Raise and fall of a bright soliton in an optical lattice', arXiv:1804.10133;

[2]'Mesoscopic Vortex-Meissner currents in ring ladders', Quant. Sci. Tech. (2018);

[3]'Readout of the atomtronic quantum interference device', Phys. Rev. A 97, 013633 (2018).

Oral presentations:

'The many facets of non-equilibrium physics: from many body theory to quantum thermodynamics', Mazara del Vallo, (Italy) 2017.

'Conference on statistical field theory and applications', Trieste 2107.

'Physics of Quantum, Electronics', USA 2018 ; Frank Hekking Memorial workshop', Les Houches 2018.

PhD: Niolas Victorin (201?-20??)

Collaborations: R. Dumke, L.-C. Kwek, Centre for quantum technologies (Singapore); C. Miniatura CNRS-MajuLab (Singapore).

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PHENIX - mesures dans le Plan et Haute rEsolution de Nanostructures par dIffraction X

LABORATORIES: INAC, NEEL

PRINCIPAL INVESTIGATORS : Edith Bellet-Amalric and **Stephane Grenier** (INAC and NEEL contacts), Bernard Mongellaz and Christophe Bouchard (INAC and NEEL technical contacts), **Stephanie Pouget** (INAC)

At the end of March 2015, we welcomed a Smartlab x-ray diffractometer by Rigaku. Hosting a powerful x-ray source and offering a high measurement versatility, it is well-adapted to the diversity of samples and problems specific to crystalline layers of high structural quality and even crystalline nanoobjects. This project was jointly supported by NEEL and INAC with a co-financing of the Labex LANEF. It is jointly managed by the two institutes.

The main characterics of this equipment are: i) a 9 kW rotating Cu anode with high flux, ii) a versatile diffraction geometry, adaptable to sample morphologies, in particular for thin fims, with precise alignments of the diffraction vector either normal to the sample surface or in the plane of the sample (Fig. 1), iii) the ability to completely explore the reciprocal space, the detector having two independent movements, all angles guided by a powerful simulation and all-automated control software, iv) a modular design which enables powder diffraction, medium or high resolution diffraction, v) an oven reaching 1100°C (by Anton Paar).

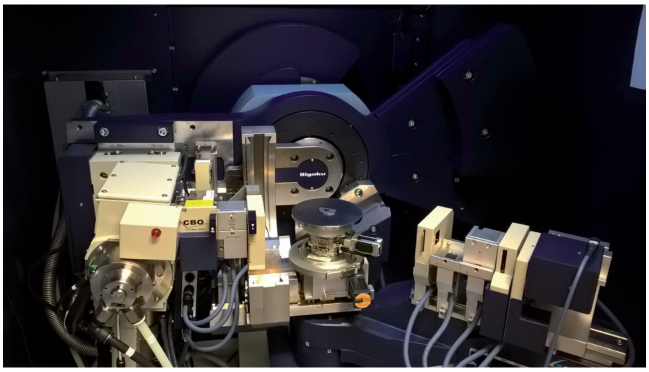

Fig.1: The equipment in the in-plane configuration mode.

A broad range of materials were studied:
- Nanostructures of nitrides semiconductors (c and m-plane growth, planar or nanowire geometry) for inter-band (UV) and intra-band (THz) emission: structural quality, strain and composition, using the high-resolution mode [1].
- II-VI semiconductors heterostructures: strain, detailed interface profile, epitaxial relation on (111) axis (fig 2).

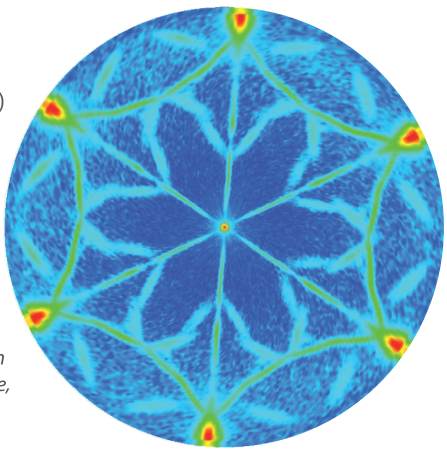

Fig. 2: Pole figure around the (1000) wurtzite reflection of a CdSe layer grown on a GaAs (111) substrate, showing an axiotaxy phenomena.

- PEDOT, organic nanometer-thick layers with very high conductivity for thermoelectric applications: in-plane and out of plane orientation of the PEDOT chains according to the type of doping molecules [2].
- Hybrid perovskite films for photovoltaic applications: crystal structure and microstructure (orientation, in-plane and out-of-plane domain size).
- Transition metal dichalcogenides, a new class of semiconducting two-dimensional materials, one to a few monolayers in thickness: crystal orientation, strain and grain size thanks to the in-plane measurements (Fig. 3) [3].
- VO_2, dependence of the electric properties of thin films on substrates, growth conditions, microstructure orientation and quality: reciprocal space mapping, in-plane measurements, dependence with temperature.

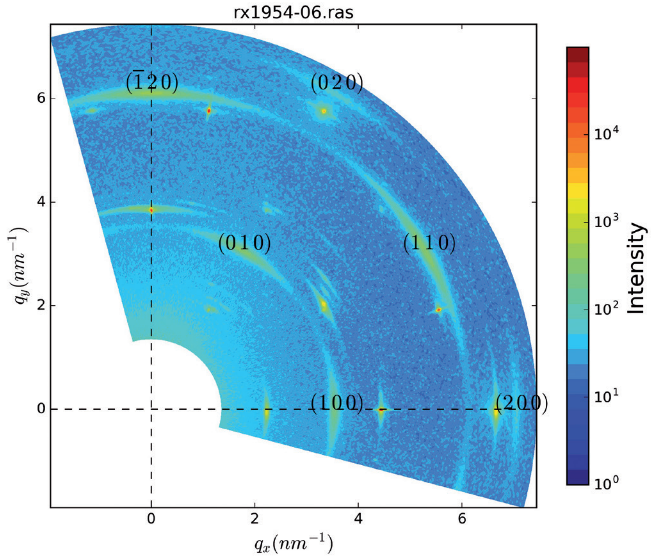

Fig.3: In plane reciprocal space map of WSe_2, 1.5 monolayer thick, epitaxially grown on mica.

OUTCOMES

[1] Effect of Ge-doping on the short-wave, mid- and far-infrared intersubband transitions in GaN/AlGaN heterostructures", Semicond. Sci. Technol. 32, 125002 (2017)

[2] Structure and Dopant Engineering in PEDOT Thin Films: Practical Tools for a Dramatic Conductivity Enhancement, Chem. Mater. 28, 3462 (2016)

[3] Millimeter-scale layered $MoSe_2$ grown on sapphire and evidence for negative magnetoresistance, Appl. Phys. Lett. 110, 011909 (2017)

Main users: Alain Marty and Eva Monroy (INAC), Aude Bailly and Laetitia Laversenne (NEEL)

Leverage: ANR Harvesters, 2017.

EQUIPMENTS

Nanostructures for the electrical measurement of the Spin Hall effect and the detection of domain walls

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Van Tuong Pham (PhD student), Jean-Philippe Attané and Laurent Vila (thesis supervisors), Alain Marty, Gilles Zahnd, Paul Noël

LABORATORY : INAC

Spin–orbitronics is based on the ability of spin–orbit interactions to achieve the conversion between charge currents and pure spin currents. As the precise evaluation of the conversion efficiency becomes a crucial issue, the need for straightforward ways to observe this conversion has emerged as one of the main challenges in spintronics. This thesis focused on the study of a new electrical device to characterize the spin Hall effect, and on the detection of magnetic DWs in nanowires using the direct or the inverse spin Hall effect. A new ferromagnetic/nonmagnetic nanostructure has been proposed, in which it is possible to realize the spin-charge interconversion (Fig. 1).

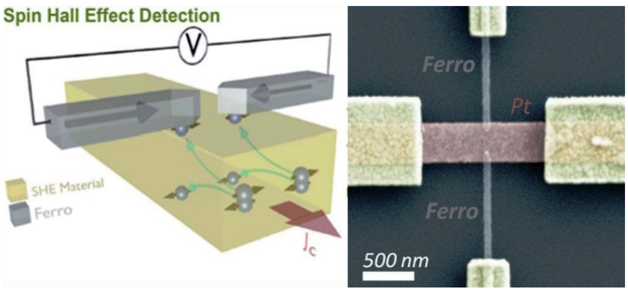

Fig. 1: Scheme and SEM image of a nanodevice allowing transforming charge currents into spin currents.

This nanostructure can be used to quantify the spin Hall angle and the spin diffusion length of Pt. The same technique can then be used to characterize the spin Hall effect in different metals and Au-based alloys. Tuong Van Pham also studied the role of the ferromagnetic/nonmagnetic interface, which is in particular found to be very important in the NiFe/Pt system. Finally, he developped a new method to detect electrically magnetic domain walls by the direct or the inverse spin Hall effect.

OUTCOMES

[1] Ferromagnetic/nonmagnetic nanostructures for the electrical measurement of the Spin Hall effect. Nano Lett. 16, 6755 (2016)

[2] Electrical detection of magnetic domain walls by inverse and direct spin Hall effect.» Appl. Phys. Lett. 109, 192401 (2016)

[3] Giant magnetoresistance in lateral metallic nanostructures for spintronic applications.» Sci. Rep. 7, 9553. (2017)

6 additionnal publications : 1 Phys. Rev. B, 1 Nanotech., 1 Appl. Phys. Lett., 1 J.M.M.M. (+2 submitted papers)
28 conference communications
Collaboration Unité Mixte CNRS/Thales.

Leverage : ANR SOspin

PHD GRANT

Spin-charge conversion studied by spin pumping in spin-orbit materials

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Paul Noël (PhD student), Jean-Philippe Attané & Laurent Vila (thesis supervisors)

LABORATORIES : INAC, NEEL

Spin-charge conversion is one of the main current challenges of spintronics. Our project focuses on its study in gold alloy systems (AuW and AuTa) and in HgTe. Other systems (Ge, STO / metal, BiSbTe, α-Sn), whose physics is close to the above-mentioned systems, are also studied. The growth of these complex systems is carried out within our laboratory or through national and international collaborations. The main method of characterization used is spin pumping by ferromagnetic resonance (Fig.). These measurements are complemented by magnetotransport studies.

Our main results concern:
• the observation of a strong spin-charge conversion up to room temperature, by direct spin pumping into the Fe/Ge(111) interface states, with implications on how to take advantage of the spin–orbit coupling in spin field-effect transistor [1]

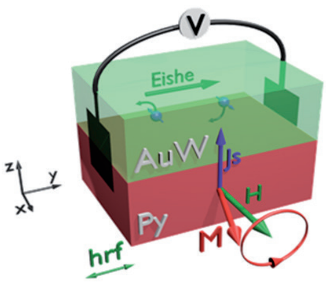

Fig.: The spin pumping technique, here from permalloy to AuW

• an increase of the Hall angle up to 0.5 in AuTa, attributed to the sidejump mechanism on the Ta impurities [2]
• the observation of a very high conversion rate in strained HgTe layers at room temperature, with a non-trivial thickness dependence, which indicates that the conversion mechanism in this topological insulator is very different from those in the spin Hall effect materials [3].

OUTCOMES

[1] Evidence for spin-to-charge conversion by Rashba coupling in metallic states at the Fe/Ge(111) interface, Nat. Commun. 7, 13857 (2016).

[2] Large enhancement of the spin Hall effect in Au by side-jump scattering on Ta impurities, Phys. Rev. B 96, 140405 [R] (2017)

[3] Highly Efficient Spin-to-Charge Current Conversion in Strained HgTe Surface States Protected by a HgCdTe Layer, Phys. Rev. Lett. 120, 167201 (2018)

Oral presentations: 10 oral contributions
best poster prize at Intermag 2017.

Main collaborations: UMP CNRS-Thales (AuTa, AuW, α-Sn and STO / LAO), LETI and NEEL (HgTe), Catalan Institute of Nanosciences and Nanotechnologies (BiSbTe).

Leverage: ANR TOPRISE, ANR OISO

PHD GRANT

PHD GRANT

Magnetic Microscopy of Domains and Domain Walls in Ferromagnetic Nanotubes

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Michal Stano (PhD student), Olivier Fruchart (PhD supervisor)

LABORATORIES : NEEL, INAC

The project was concerned with exploration of magnetic domains and domain walls (DWs) in magnetic nanotubes and more complex geometries such as multilayered core-shell nanotubes and diameter modulated nanowires. Upon miniaturization, arrays of such structures could open the way for 3D spintronics: tubular synthetic antiferromagnets, novel sensors and non-volatile solid state memories.

The project involved the synthesis, numerical modelling and advanced magnetic microscopies. We considered multilayered tubes with magnetic (Ni, NiCo, CoNiB, NiFeB) and non-magnetic layers. We provided the first magnetic microscopy images of well-defined domains and DWs in magnetic nanotubes. In core-shell structures we could probe selectively the magnetic domains in different layers using element sensitive X-ray microscopy (see fig. 1). By exploiting the shadow created by partially absorbed X-rays with low angle of incidence, we obtained images of magnified (by a factor of 3.6 along the beam) projection of magnetic domains. We also observed the evolution of domains when subject to an applied magnetic field.

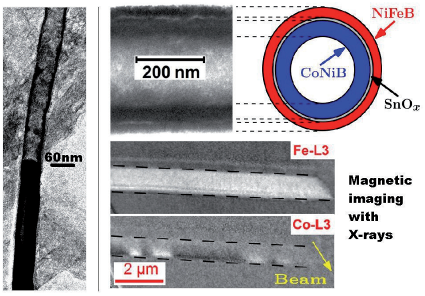


Fig.1 : Left: Wire-tube element; Right: multilayered tube with layered-resolved magnetic images using the shadow of X-rays.

OUTCOMES

[1] Probing domain walls in cylindrical magnetic nanowires with electron holography, J. Phys. Conf. Ser. 903, 012055 (2017).

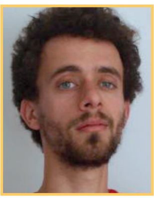
[2] Imaging magnetic flux-closure domains and domain walls in electroless-deposited CoNiB nanotubes, arXiv:1704.06614 (2017).

Oral presentations: EMS 2016, Glasgow, United Kingdom, 2016. Intermag, Dublin, Ireland, 2017. CLN2017, Paris, France, 2017. JEMS 2017, Mainz, Germany, 2016.

Collaboration: Sandra Schaefer, Wolfgang Ensinger, TU Darmstadt, Germany. Andrea Locatelli, Elettra Sincrotrone Trieste, Italy. Rachid Belkhou, Synchrotron Soleil, Saint-Aubin, France. Aurélien Masseboeuf, Christophe Gatel, CEMES Toulouse, France.

Leverage: ANR-DFG project proposal with TU Darmstadt and FAU Erlangen (Germany), under review.

PHD GRANT



Topological magnetic solitons in thin epitaxial films with reduced symmetry

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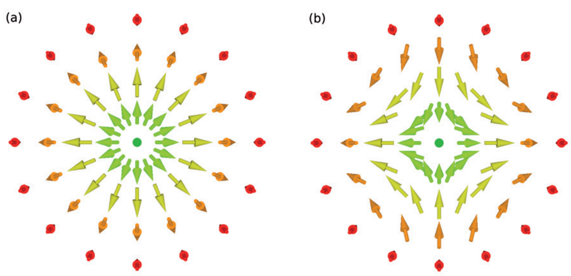
LABORATORIES : NEEL, INAC

In my thesis, I used a combined theoretical and experimental approach to study the relationship between the crystal symmetry, the magnetic interactions and topological solitons in epitaxial magnetic thin films.

Solitons are field solutions that evolve without perturbing their configurations, to which one can associate particle properties like a charge. For topological magnetic solitons the considered field is the magnetization field and the charge is the topological charge.

I studied how the anisotropic magnetic interactions allow stabilizing domain walls and skyrmions, respectively 1D and 2D magnetic solitons, with different symmetries and topological charges. Theoretically, I developed a continuous model to characterize skyrmions [1] and understand the conditions to stabilize anti-skyrmions [2]. Experimentally I grew epitaxial thin films and studied the crystal symmetry, the magnetic properties and the magnetic configurations [3].



Schematic spin configuration of a skyrmion (a) and an anti-skyrmion (b)

OUTCOMES

[1] The skyrmion-bubble transition in a ferromagnetic thin film, SciPost Phys. 4, 027 (2018).

[2] Micromagnetics of antiskyrmions in ultrathin films, Phys. Rev. B 97, 134404 (2018)

[3] Anisotropic Dzyaloshinskii-Moriya interaction in ultrathin epitaxial Au/Co/W(110), Phys. Rev. B 95, 214422 (2017)

Oral presentations: JEMS, Glasgow, UK, 2016; INTERMAG, Dublin, Ireland 2017; SKYMAG 2, Paris, France, 2017 ; MAGNET, Assisi, Italy, 2017 ; DPG , Berlin, Germany, 2018.

Collaborations: Stanislas Rohart (LPS, Orsay), Laurent Ranno, Nicolas Rougemaille, Alexis Wartelle, Anne Bernand-Mantel, Maurizio De Santis (NEEL), Mohamed Belmeguenai, Yves Roussigné, Andreï Stachkevitch (LSPM-CNRS-Paris Sorbonne)

Leverage: ANR-14-CE26-0012 ULTRASKY, ANR TOPSKY
PhD GreQuE: José Pena Garcia

Ultra MFM - an ultimate resolution and sensitivity with a table-top AFM

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LABORATORIES: NEEL, INAC

PRINCIPAL INVESTIGATORS : Simon Le Denmat (NEEL, Engineering advisor), **Olivier Fruchart** (Spintec, Scientific advisor)

The investigation of magnetization textures is a cornerstone in modern nanomagnetism and spintronics, associated with novel fundamental questions, as well as applications in data storage and computing. Nanosized systems of increasing complexity and decreasing size are considered, requiring continuous progress in the sensitivity and spatial resolution of magnetic microscopy. It is in this context that we identified the need for an advanced although table-top instrument for magnetic imaging.

Following a broad technical investigation, the choice went for a prototype being developed by the Nanoscan company, combining the sensitivity and resolution of the high-performance instruments with the versatility required from a platform instrument. This can be achieved with an instrument operating under secondary vacuum, decreasing losses associated with air viscosity, thereby increasing the sensitivity. In turn this allows us to use sharper and low-moment tips, thus improving the spatial resolution.

The unprecedented combination of technical features like a 5 µm-resolution optical view (to locate nanofabricated devices), sample size up to 100x100x15 mm (suitable from wafers to bulk materials) and its unique 200x200x15 mm (X, Y, Z) stage travel range with a 20 nm resolution reached an almost limitless repositioning capability.

After few years of joined development with the company, this prototype, the first of its kind, was able not only to give access to high sensitivity and high resolution in MFM, but also to open new possibilities like surface potential measurements and static magnetic force measurements on functional materials and devices with a remarkable easiness of use. These features opened the doorway to collaborations and gave access to measurements that were never reached before on the AFM platform of the NEEL Institute.

Fig. 1: Nanoscan VLS-80 microscope installed at the NEEL open AFM facility.

In the future, the development of a variable-temperature sample stage (100K – 600K) will be finalized in a collaboration between the Nanoscan company and NEEL combining their complementary expertise on high temperature and cryogenics, respectively.

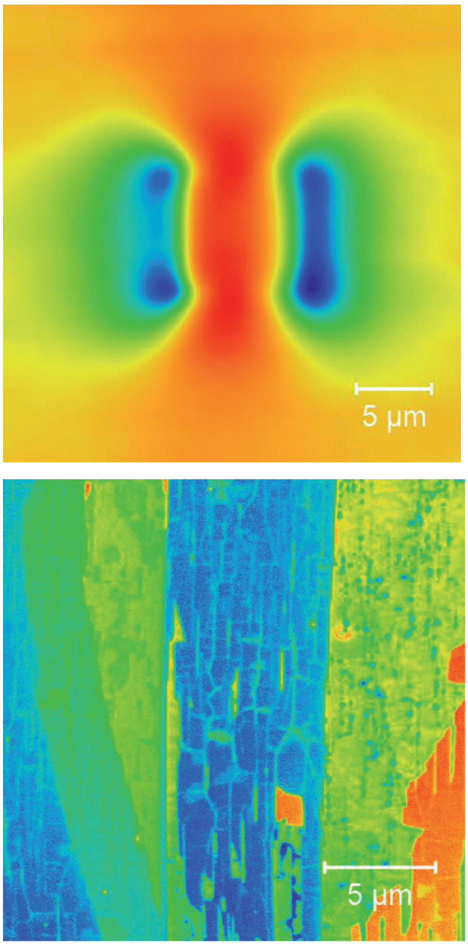

Fig. 2: Top: magnetic force measurement above an iron micro pillar. Bottom: Graphene on SiC CPD

OUTCOMES

Collaboration: Claire Berger, GeorgiaTech, USA.

Publication: Mechanotransductive cascade of Myo-II dependent mesoderm and endoderm invaginations in embryo gastrulation, Nat. Commun. 8, 13883 (2017)see also those of the PhD students.

PhD : Ioan-Augustin Chioar (2012-2015), Michal Stano (2014-2017), Lorenzo Camosi (2015-2018), **Post doc fellow:** Vladimir Prudkovskiy (NEEL/GeorgiaTech)

Leverages: DARPAproject N° HR001117S0038. 2018-2021, coordinated by O. Boule (INAC). Partners CNRS-Thales, FZ Jülich

ANR TOPSKY: TOpological Properties of magnetic SKYrmions and opportunities for novel spintronic devices. 2018-2021, coordinated by S. Pizzini (NEEL).

ANR SHAMAN: Soft in HArd MAgnetic Nanocomposites, 2018-2021, coordinated by N. Dempsey, (NEEL).

PHD GRANT

Exploring frustration in artificial magnetic architectures

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LABORATORY : NEEL

Frustration is a ubiquitous concept and can be defined as a competition between interactions which cannot all be satisfied simultaneously. Using modern nano-fabrication and characterization techniques, artificial magnetic systems exhibiting such behavior can be designed, visualized and controlled, enabling the exploration of magnetic frustration effects in a "statistical physics laboratory". Such nano-architectures facilitate the exploration of celebrated classical frustrated spin models characterized by non-conventional and exotic magnetic textures. Our work has focused on two artificial realizations of the kagome geometry, with Ising-like magnetic islands having moments within the lattice plane (kagome spin ice) or perpendicular to it (kagome Ising). Using different experimental and numerical protocols, we highlighted how dipolar couplings, spanning beyond nearest-neighbors, drive the overall behavior of both these networks, each of them having its own story to tell (Fig. 1).

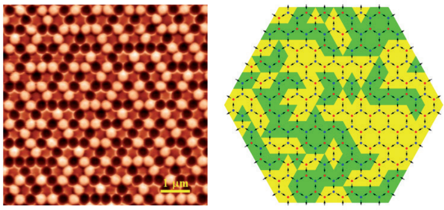


Fig. 1: A magnetic force microscopy image of an artificial kagome Ising network (left)[1] and the formation of magnetic charge crystallites in an artificial kagome spin ice (right) [2].

OUTCOMES

[1] Nonuniversality of artificial frustrated spin systems, Phys. Rev. B 90, 064411 (2014).

[2] Size distribution of magnetic charge domains in thermally activated but out-of-equilibrium artificial spin ice, Sci. Rep. 4, 5702 (2014).

[3] Ground-state candidate for the classical dipolar kagome Ising antiferromagnet, Phys. Rev. B 93, 214410 (2016);

[4] Fragmentation of magnetism in artificial kagome dipolar spin ice, Nat. Commun. 7, 11446 (2016);

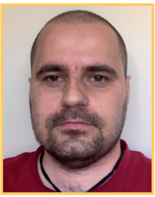
[5] Kinetic pathways to the magnetic charge crystal in artificial dipolar spin ice, Phys. Rev. B 90, 220407 (2014);

Oral presentations: MSNOWS, Nancy, France, 2014; EMRS, Lille, France, 2015; ICM, Barcelona, Spain, 2015; MML, Uppsala, Sweden, 2016.

Collaborations: M. Hehn, D. Lacour, F. Montaigne, Institut Jean Lamour, Nancy, France; A. Locatelli, T. O. Menteş, B. Santos Burgos, ELETTRA Synchrotron, Trieste, Italy.

Leverage : ANR Biolce coordinated by Inst. Jean Lamour. New collaorations: P. Tierno (IN2UB, Barcelona) T. Šikola (CEITEC, Brno, Czech)

PHD GRANT



Very low temperature and high magnetic field Faraday force magnetometer for frustrated magnets

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LABORATORY : NEEL

The objective of this work was to develop a Faraday magnetometer to measure absolute values of magnetization at very low temperatures (40 mK) and high magnetic fields (16 T) with a high sensitivity (10^{-5} emu). The challenge was to push the boundaries of the existing magnetometers to complete the Grenoble instruments in very low temperature magnetometry, needed in numerous studies in condensed matter physics. My thesis has implied experimental developments in several technological fields: i) cryogenics, with the building and optimization of a ^{3}He-^{4}He dilution refrigerator to reach very low temperatures, ii) electronics, with the development of a cold amplifier needed to reach a high sensitivity, iii) microfabrication, iv) the optimized design required to make the magnetometer operational (Fig.1).

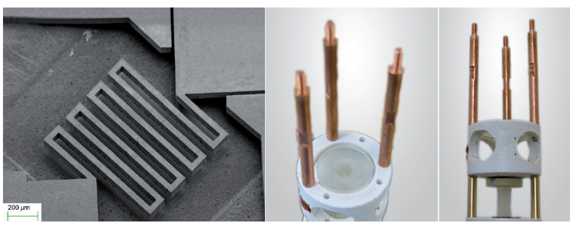

Fig. 1: Capacitive sensors: left: zoom of a silicon spring of the MEMS sensor. right: «macroscopic» sample holder, fabricated with a 3D printer.

In parallel, I focused on the experimental study of classical and quantum frustrated magnets [1,2]. We completed the H-T phase diagram of the puzzling spin-liquid compound $Gd_3Ga_5O_{12}$ [3]. Through the first very low temperature study on the isomorphous compound $Gd_3Al_5O_{12}$ [4], and contrary to theoretical predictions, we proved that this phase diagram is robust. We put into evidence the convergence of all observed phases to a unique point in both samples.

OUTCOMES

[1] Antiferroquadrupolar correlations in the quantum spin ice candidate $Pr_2Zr_2O_7$, Phys. Rev. B 94, 165153 (2016).

[2] Fluctuations and All-In–All-Out Ordering in Dipole-Octupole $Nd_2Zr_2O_7$, Phys. Rev. Lett. 115, 197202 (2015).

[3] Updating the phase diagram of the achetypal frustrated magnet GdGaO, Phy. Rev. B 91, 014419 (2015).

[4] Absence of magnetic ordering and field-induced phase diagram in the Gadollinium aluminum garnet, Phy. Rev. B 96, 220413 (2017)

Oral Presentations: ICM 2015, Barcelona, Spain. SFP 2013, Marseille, France , 2013.

Main collaboration: P.P. Deen, ESS, Lund, Sweden


A nano -trampoline to probe quantum behavior

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PRINCIPAL INVESTIGATORS : Aviad Frydman (Chair of excellence), Olivier Bourgeois (Grenoble contact), **Tuyen Nguyen Duc** (post-doctorate), Benjamin Piot, Sharaf Poran.

In recent years the scientific community has shown growing interest in quantum phase transitions in which a system transits between two thermodynamic states at absolute zero temperature, as a result of manipulating a physical parameter such as magnetic field, pressure or chemical composition instead of temperature. In these transitions, the change is driven not by the thermal energy provided to the system by heating, but rather by quantum fluctuations.

The theoretical prediction of quantum criticality was provided a few decades ago, but how to measure this experimentally has remained a mystery. Through this Chairs of excellence project, we have for the first time provided the answer [1].

In normal phase transitions there is a unique measurable quantity which is used to detect a critical point: this is the specific heat which measures the amount of heat energy that should be supplied to a system in order to raise its temperature by one degree. The specific heat rises near the critical point and its measurement provides information on the fluctuations.

Measuring specific heat of a system close to a quantum critical point poses a much greater challenge. Firstly, the measurements must be carried out at low temperatures. Secondly, the systems under study are nano-thin layers which require extremely sensitive measurements. The team overcame these obstacles by developing a unique experimental design based on a thin membrane suspended in air by very narrow bridges, thereby forming a «nano-trampoline» (Fig. 1). This setup enabled specific heat measurements of the thin films through a quantum phase transition from a superconducting state to an electrically insulating state, close to absolute zero temperature.

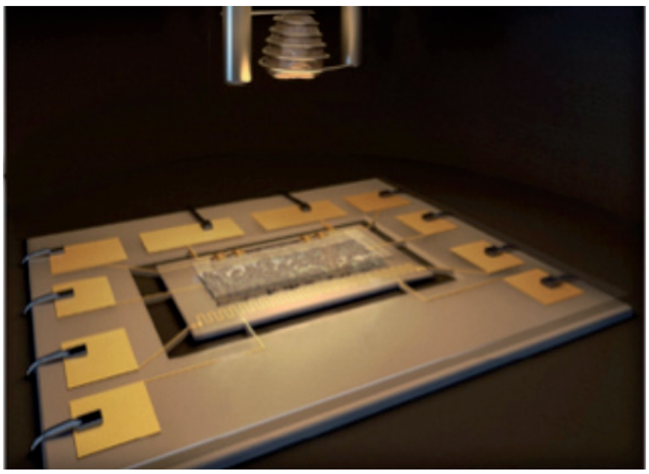

Fig. 1: view of the experimental setup.

This is the first of its kind. The results demonstrate that just as in the case of a thermal phase transition, the specific heat increases in the vicinity of a quantum critical [1] point, and can be used as a probe for quantum criticality. This work is expected to be a milestone in the understanding of physical processes that govern the behavior of ultrathin systems at ultralow temperatures.

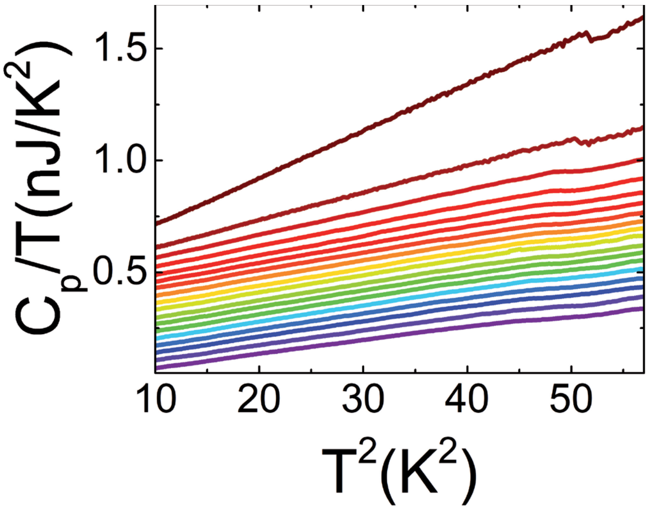

Fig. 2: Specific heat versus T obtained on thin layers of Pb with different thickness values from 8.9 to 29 nm.

OUTCOMES

[1] Quantum criticality at the superconductor-insulator transition revealed by specific heat measurements, Nature Commun. 8, 14464 (2017).

[2] Specific heat measurement set-up for quench condensed thin superconducting films, Rev. Sci. Instrum. 85, 053903 (2014).

Conferences: Oral presentation, Conference on Applied and Nano Superconductivity, Germany, july 2016.

PhD: S. Poran (2013-2017); Y. Stein (2017-2020).

Leverage: Bourse Chateaubriand, one year PhD visit


2D Topological Semimetals grown by Molecular Beam Epitaxy

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Topological Dirac and Weyl semimetals, often called the « new 3D graphene», are a new state of matter that shows linear dispersions (Dirac cones) in all three dimensions in the reciprocal space. Weyl fermions predicted by quantum field theory have never been observed in free space, so their low energy « incarnations » in semimetals offers a unique opportunity to merge high energy elementary particle physics with condensed matter. Discovering and engineering topological semimetals from the family of 2D Transition Metal Dichalcogenide materials could open the way to the exploitation of their unique topological properties by fabricating thin epitaxial films and devices on suitable crystalline substrates.

At the Epitaxy and Surface Science Laboraotory (ESSL) of INN / NCSR DEMOKRITOS in Greece, we grow 2D $HfTe_2$, $ZrTe_2$, $TiTe_2$ and $MoTe_2$ thin films by MBE on technologically important AlN/Si and InAs/Si substrates. ESRF synchrotron GIXD and STEM at INAC show that the materials are rotationally aligned with the InAs substrates having low in-plane mosaicity (lowest observed so far) and a clear quasi van der Waals (vdW) gap with the substrate indicating high quality vdW epitaxy (Fig. 1). Imaging of electronic band structure by in-situ ARPES at NCSRD provides for the first time compelling evidence that 1T-$HfTe_2$ and 1T-$ZrTe_2$ are Dirac semimetals (Fig. 2). The 2D Dirac cones persist down to the ultimate 2D limit of a single layer indicating that $ZrTe_2$ could be regarded as an electronic analogue to graphene.

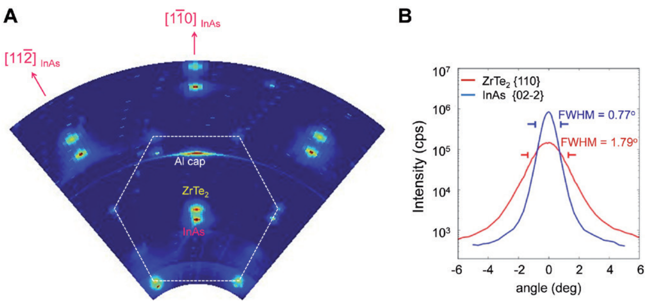

Fig. 1: XRD reciprocal space map (A) and rocking curves (B) showing excellent epitaxial alignment of $ZrTe_2$ epilayer substrate

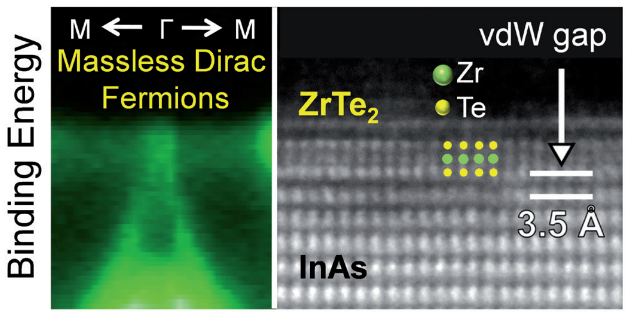

Fig. 2: ARPES imaging (left) showing Dirac cone of 1 ML $ZrTe_2$, STEM (right) showing quasi vdW gap at the interface.

Moreover, using STEM, we made the first direct observation at room temperature of the orthorhombic (Td), type-II Weyl semimetal phase in epitaxial $MoTe_2$ (Fig. 2). Its stability at room temperature is a result of tensile strain from the substrate which stabilizes an elongated interlayer antibonding state characteristic of Td-$MoTe_2$.

In a single monolayer 1T-$TiTe_2$, using in-situ STM we obtained evidence for a charge density wave instability at room temperature which is not expected on the basis of electronic band structure imaged by in-situ ARPES.

OUTCOMES

[1] Massless Dirac Fermions in $ZrTe_2$ semimetal grown on InAs (111) by vdW epitaxy, ACS Nano 12, 1696 (2018)

[2] MBE of thin $HfTe_2$ semimetal films, 2D Mater. 4, 015001 (2017)

[3] Direct observation at room temperature of the orthorhombic Weyl semimetal phase in thin epitaxial $MoTe_2$, Adv. Funct. Mat. (2018) doi.org/10.1002/adfm.201802084

Invited presentations (A. Dimoulas)

-EUROMBE19, St. Petersbourg, Russia, 2017

-EW-MOVPE17, Grenoble, 2017

-EUROMAT 2017, Thessaloniki, Greece, 2017

-FLATLANDS beyond Graphene, Lausanne, Switzerland (2017)

-NANO-KISS Summer School, Seoul, Korea 2017

-ECS 223rd meeting, Seattle, 2018

Leverage:

-ERC-AdG-SMARTGATE-291260

-Equipex ANR-11-EQPX-010

A two-dimensional crystalline form of silicon oxide

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PHD GRANT

LABORATORIES : NEEL, INAC

Graphene was the first member of the family of two-dimensional (2D) materials. The quest for novel 2D materials is boosted by the prospect for complementing the toolkit of properties of this family. A much sought-for property for optoelectronics applications is a wide band-gap in the electronic band-structure. To this respect, silicon-based 2D materials, noteworthy silicon oxide and silicon carbide, are exciting candidates.

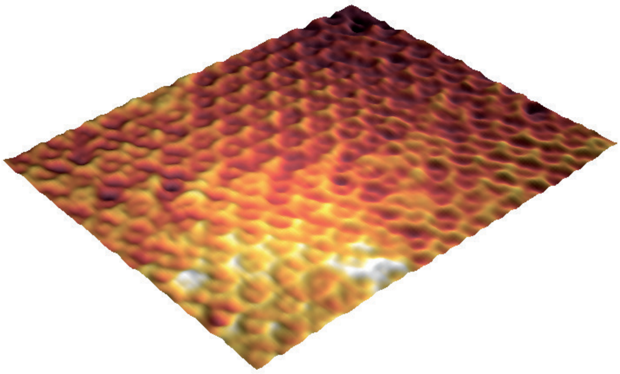

Fig.1: Scanning tunneling micrograph of the honeycomb lattice of silicon oxide, with defects. The distance between the centers of hexagons is 0.54 nm.

Our aim was to prepare these materials and to understand their structure, including the nature of defects which are expected to have strong influence on the microscopic and macroscopic properties. A single-layer of crystalline silicon oxide, prepared on a metallic surface, was specifically addressed (Fig. 1). We revealed that epitaxy in this system systematically involves one-dimensional defects. We also identified a local modulation of the chemistry of silicon atoms in the system.

This study is currently pursued, and focuses on the structural phases transitions in this system, which is especially rich.

OUTCOMES

[1] Degenerate epitaxy-driven defects in monolayer silicon oxide, Phys. Rev. B 92, 161410(R) (2015).

[2] Strain relaxation in CVD graphene: wrinkling with shear lag, Nano Lett. 15, 5098 (2015).

Oral presentations: ECOSS31, Barcelona, Spain, 2015.
EWEG/2D, Bergish Gladbach, Germany, 2016.

Leverage: ANR project 2DTransformers, 2015.

Helical Superconductivity and the Anomalous Josephson Effect

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PHD GRANT

LABORATORY : INAC

The interplay of spin-orbit coupling (SOC) and the Zeeman effect due to a magnetic field plays an important role in spintronics and in the realization of so-called topological superconductivity. The aim of our project is to theoretically study this interplay in novel materials such as transition metal dichalcogenide monolayers (TMDC) – two-dimensional systems similar to graphene but with two different atoms in the unit cell. They host a strong intrinsic SOC, often called Ising SOC, which acts as an effective Zeeman field perpendicular to the plane of the material and having opposite orientations at the two corners of the Brillouin zone, K and K'=-K (Fig.1).

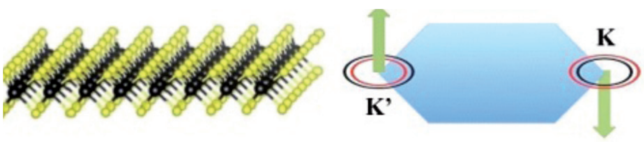

Fig. 1: Left: Crystal lattice of TMDC monolayers. Right: Schematic representation of the Ising spin-orbit coupling.

The Ising SOC plays a very important role in TMDC superconductors, where it causes unconventional pairing of Cooper pairs and, as a consequence, a great enhancement of the upper critical field [1]. We are interested in the properties of these "Ising superconductors" and their Josephson junctions, the effect of disorder on those properties, as well as possible topological superconducting phases that might appear and the ways to probe them.

OUTCOMES

[1] Enhancement of the upper critical field in disordered transition metal dichalcogenide monolayers, Phys. Rev. Lett 119, 117001 (2017).

[2] Weak localization in transition metal dichalcogenide monolayers and their heterostructures with graphene (in preparation).

Oral presentations:
Workshop "Superconductivity, spintronics and beyond", Grenoble, 14.11.2017
GDR meeting "Physique Quantique Mesoscopique", Aussois, 05.12.2017
Spring school "Transport in Nanostructures", Capri, 19.04.2018

PHD GRANT

Shiba states in superconducting graphene

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LABORATORIES : INAC, NEEL

Yu-Shiba-Rusinov states emerge from the competition between superconductivity and magnetism. Our goal is to study these states in graphene. Though bare graphene does not exhibit intrinsic superconductivity, one can make it superconducting using the proximity effect. The nature of this peculiar state in graphene has been little explored up to now. Studying its response to magnetic impurities should provide insights into its robustness, in particular through the study of the spatial variations of the electronic density of states associated with Yu-Shiba-Rusinov states.

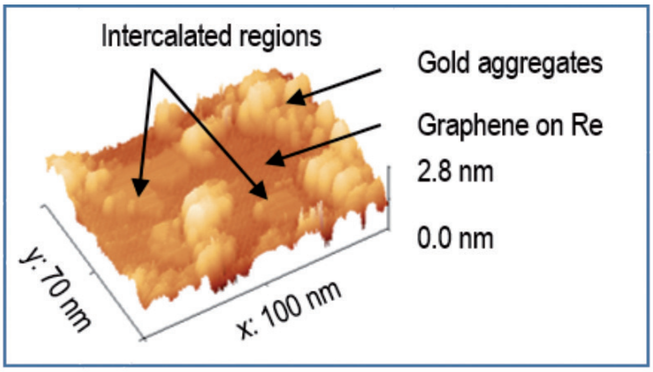

Fig.1: Scanning tunnelling microscopy image (T = 50mK)

We grow graphene directly on a superconductor, namely rhenium. Unfortunately, the coupling between graphene and its substrate, which guarantees a good proximity effect, also leads to the formation of covalent bonds which kill most of the interesting properties of graphene. In order to recover two-dimensional free-standing graphene – a great asset for the observation of Yu-Shiba-Rusinov states with a low temperature scanning tunneling microscope - gold is locally intercalated between graphene and rhenium (Fig.1). Our next step is to deposit magnetic molecules on this platform.

OUTCOMES

Poster presentations: IOT workshop, Grenoble, France, 2017; RJP, Grenoble, France, 2017; 2D@Grenoble, Grenoble, France, 2017; GDR Graphene & co, Aussois, France, 2017; Journée ARC6, Grenoble, France, 2017.

Collaborations: C. Bucher, Ecole Normale Supérieure de Lyon, Lyon, France ; B. Gilles, SIMAP, Saint-Martin d'Hères, France.

Co-funding between LANEF and Région Auvergne-Rhône-Alpes

PHD GRANT

Electronic and magnetic properties of iron based superconductors

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Hadrien Grasland (PhD student), Hervé Cercellier (thesis supervisor), Thierry Klein (thesis director)

LABORATORIES : NEEL, INAC

Reaching a good understanding of the superconductivity of materials requires an accurate knowledge of their electronic and magnetic properties. During my PhD work I have implemented point contact spectroscopy and scanning Hall-probe microscopy to study the superconducting properties of iron based materials. The differential conductance of superconductor-metal junctions turned out to exhibit unexpected oscillating features related to the superconducting gap of the so-called 122-phases. I derived a model of this signal by undertaking a study of superconductor-metal-metal junctions.

In this model, the second metallic region emerges from a local transition from the superconducting to the normal state due to a local increase of the current density above the "depairing current". Alternatively, electron injection could also locally alter the electron energy distribution to the point of destabilizing the superconducting state. I also performed a study of the vortex creep in FeSe single crystals down to 0.3K [1] showing that the creep rate remains finite at zero temperature and hence that quantum creep plays a dominant role in the relaxation process at low temperature.

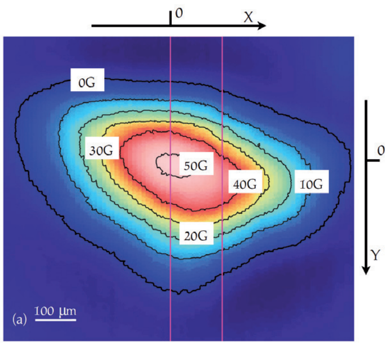

Fig. 1: Contour plot of the remanent magnetic induction in a FeSe superconductor.

OUTCOMES

[1] Vortex creep down to 0.3K in superconducting Fe(Te,Se) single crystals, Phys. Rev. B 89, 014514 (2014).

[2] Dynamically current-driven de Gennes-St James states in Metal-Superconductor junctions, arXiv1604.0839

Poster Conferences: Congrès SFP 2013 (Marseille), SCES 2014 (Grenoble) and M2S 2015 (Geneva).

Collaborations: Z.S.Wang & H.H.Wen, Chinese Academy of Sciences, Beijing and S.Ono CRIEPI, Tokyo-Japan.

Leverage: The development of this original point contact spectroscopy setup is widely used now to probe superconducting effects.

Synthesis and physical properties under high pressure of Cr^{4+}-based compounds

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PHD GRANT

LABORATORY : NEEL

Potential candidates as parent High-Tc compounds are the members of the chromate family, as a result of their layered structure (Fig. 1). Their physics is unknown, due to the harsh high pressure - high temperature synthesis conditions. Several members of the family Æn+1CrnO3n (Æ=Ca, Sr or Ba) were synthesized and studied. New compounds, new crystallographic structures, and new physics were discovered [1]. At n=1, Sr2CrO4 (TN = 112K) showed an unusual anti-Jahn-Teller effect, with an apparently lower symmetry state at low temperatures, explained by the importance of covalency in Cr-O bonds. At n=2, Sr3Cr2O7 (TN = 210K) presented a magnetic and orbital ordering transition, demonstrated by theoretical calculations to be the first evidence of orbital singlets (Fig. 1) [2]. In the previously unknown Ca system, Ca2CrO4 is a central step towards superconductivity, due to its almost metallicity that encourages further pressure and doping studies. At n=3, Ca4Cr3O10, presents another important type of ordering [3], now under theoretical analysis. We are currently working to optimally dope these materials in order to destabilize the antiferromagnetic state and hopefully obtain a metallic and superconducting state.

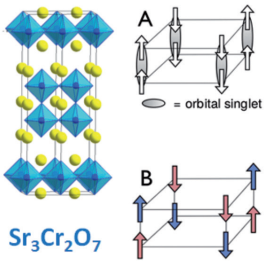

Fig. 1: Left: crystal structure of Sr3Cr2O7 with bilayer of CrO2 planes. Right: Two different orderings of 3d electron spins (arrows) and orbitals (colors) in the bilayer obtained by numerical Lanczos calculations (A) and analytical calculations (B).

OUTCOMES

[1] Ba19Cr12O45 : A high pressure chromate with an original strucutre solved by electron diffraction tomography and powder X-ray diffraction, Inorg. Chem. 56, 6404 (2017).

[2] Singlet orbital ordering in bilayer Sr3Cr2O7, Phy. Rev. Lett. 118, 207207 (2017).

[3] Structural and physical properties of the high pressure perovskite layered Sr4Cr3O10 chromate, J. Solid State Chem. 251, 164 (2017).

Oral presentation: CMD 25 – JMC 14, Paris, France, 2014; 54th EHPRG Meeting, Bayreuth, Germany, 2016.

Collaboration: C. Lacroix and A. Ralko, NEEL; E. Salas Colera, G.R. Castro, ESRF; C. Colin, V. Nassif and E. Suard, ILL; A. Aligia and R. Weht , CNEA, Argentine

Interplay between charge-density waves and high-Tc superconductivity in cuprates

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PHD GRANT

LABORATORY : LNCMI

The origin of superconductivity in cuprates is among the toughest problems in condensed matter physics. One of the most spectacular advances in the field is the recent discovery that superconductivity actually competes with a charge-density wave (CDW). The exact nature of their relationship, however, remains debated.
In his PhD, I. Vinograd has used four complementary parameters (temperature, magnetic field, carrier concentration and hydrostatic pressure) to tune the competition between CDW and superconductivity in $YBa_2Cu_3O_y$. [1-3]

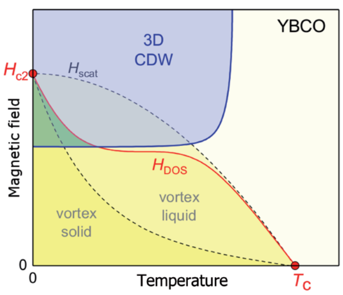

Fig. 1: Sketch of H-T phase diagram highlighting the field HDOS above which superconductivity ceases to affect the electronic density of states.

One of the most remarkable outcomes is a set of NMR data (obtained on the 20 T magnet funded by LANEF) suggesting that, beyond their fierce competition, CDW and superconductivity eventually establish a form of cooperation in order to coexist at low temperature. [2] Cooperation has been predicted to arise from a novel state called pair-density wave in which Cooper pairs carry a finite momentum k (k=0 in BCS theory) and the superconducting gap amplitude varies in space as does the charge density. The work of I. Vinograd thus opens exciting perspectives as a further scrutiny of this phase is likely to shed new light on the high-Tc problem.

OUTCOMES

[1] NMR study of the pressure-tuned competition between charge-density waves and superconductivity in YBa_2Cu_3Oy, in preparation (2018).

[2] Unusual interplay between superconductivity and charge order in underdoped YBa_2Cu_3Oy, arxiv 1805.06853 (2018).

[3] Spin susceptibility across the upper critical field in charge ordered YBa2Cu3Oy, PNAS 114, 13148 (2017).

Poster presentation, School on Unconventional Superconductivity, Cargèse, France, 2017.

Collaborations: C. Marcenat, INAC, T. Klein, NEEL, D. Leboeuf, LNCMI-G, D. Bonn, UBC Vancouver, Canada.

EQUIPMENTS

SUPERMAG: a superconducting 20 T magnet platform for applied and basic science

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LABORATORIES: INAC, LNCMI, NEEL

PRINCIPAL INVESTIGATORS : C. Marcenat (INAC), A. Demuer, M. H. Julien, D. Le Bœuf, H. Mayaffre (LNCMI), T. Klein (NEEL)

Supramag offers a platform for applied and fundamental science. The superconducting magnet is designed to achieve 19 T at 4.2 K and 20 T at 2 K. In general, magnetic fields offer one of the most powerful tools to control, modify and probe the properties of matter. Novel and exotic electronic states, such as the integer and fractional quantum Hall effects, are induced by application of a magnetic field. The Supramag magnet extends significantly the maximum magnetic field achievable with superconducting magnets in Grenoble, so that new phenomena are within reach. In addition to its enhanced experimental window, it also offers a low noise environment that allows us to perform challenging experiments such as quantum oscillation, nuclear magnetic resonance (Fig. 1) or thermodynamic measurements (these techniques dramatically suffer from the environmental noise found in resistive magnets). Therefore, the 20 T magnet constitutes an additional input in the high magnetic field facility.

The Supramag platform is a central stage for the research of many scientists (5 PhD students, 2 postdoc fellows, 18 researchers) from NEEL, INAC and LNCMI who regularly gather at its location (Fig. 2). It is hence particularly well-suited for fostering new collaborations and projects. For example, researchers from NEEL and LNCMI have united force in order to determine the upper critical field of a high-T_c superconductor, a property which has remained elusive for decades and has generated much debate. Moreover, researchers from INAC and LNCMI have combined their expertise to make the first ultrasound measurements in superconducting ferromagnets. Originally focused on research on superconductors, the scope of use of Supramag is now widening to the whole community of physicists working in quantum and topological materials. A collaboration between researchers from NEEL and LNCMI on the development of thermodynamic tools to explore the quantum limit of semi-metals has just started.

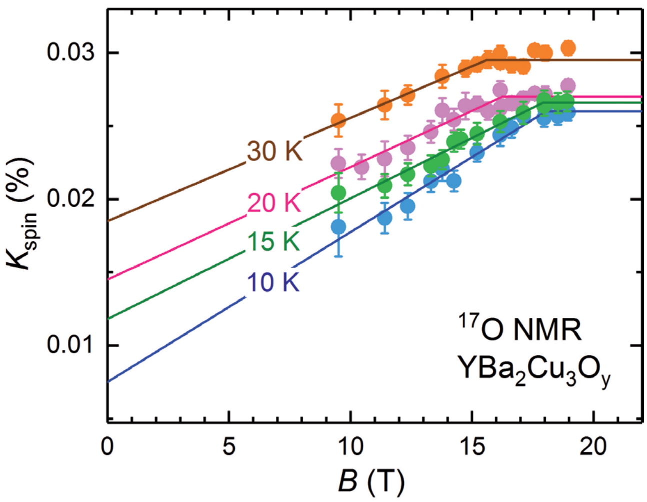

Fig.1: Nuclear Magnetic Resonance measurements in a high-Tc superconductor as a function of magnetic field up to 20 T. at different temperatures. The 20 T magnet allows us to track the upper critical field down to the lowest temperatures.

Fig. 2: Heat capacity measurements on superconductors using the 20 T magnet.

OUTCOMES

[1] Thermodynamic signature of quantum criticality in cuprates, arXiv:1804.08502

[2] Unusual interplay between superconductivity and charge order un YBCO, arXiv:1805.06853

[3] High field charge order across the phase diagram of YBCO, NPJ Quant. Mat. 3, 11 (2018).

[4] Thermodynamic signatures of the field-induced states of graphite, Nat. Comm. 8, 1337 (2017).

[5] Observation of electronic bound states in charge-ordered YBCO, Phys. Rev. Lett. 118, 017001 (2017).

[6] Spin susceptibility of charge ordered YBCO across the upper critical field, PNAS 114, 13148 (2017).

[7] Calorimetric determination of the magnetic phase diagram in underdoped YBCO Nat. Commun. 6, 7927 (2015).

PhD: M. Frachet (2016-2019), C. Girod (2017-2020), B. Michon(2014-2017), M. Raba(2015-2018), I. Vinograd (2015-2018).

Users: D. Braithwaite, J.-P. Brison, G. Knebel, A. Pourret (INAC), X. Chaud, G. Seyfarth, I Sheikin, (LNCMI), K. Hasselbach, E. Lhotel, M. A. Méasson, P. Monceau, P. Rodière (NEEL)

Leverage: ANR project SCATE submitted at AAP2018, IRS project from UGA (2107/2018).

HTS Windings - a winding machine dedicated to High Temperature Superconducting tapes

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LABORATORIES: LNCMI, G2ELAB, NEEL

PRINCIPAL INVESTIGATORS : Xavier Chaud (Project Leader), Arnaud Badel, Jung-Bin Song , Dominique de Barros (Consultant, Stigma SA)

High critical temperature superconducting (HTS) coated conductor tapes are very promising for several applications involving coil fabrication, especially high field insert because of their high critical field well above the one of classical, low temperature superconductors. But the specific architecture of these tapes (mainly, a 1-2 µm functional superconducting layer made of a well textured brittle ceramic deposited on a 50-100 µm high mechanical strength Hastelloy substrate) requires a dedicated winding machine with special features : adapted and controlled smooth tension and guides, several winding payoffs together enabling co-winding technique, enough torque and space to accommodate several coil sizes, safety and dust protective cover with a preserved and easy access for mounting operation, easy change of the settings for prototyping, and last but not least, reproducibility and reliability.

After a long search for a suitable on-the-shelves winding machine, we finally fabricated our own machine (Fig.1) with the help of an external consultant. This winding machine is at the heart of our work for developing high-field magnets in the frame of the ANR project NOUGAT, aiming at fabricating a 10 T HTS insert to be operated in a 20 T background magnetic field at LNCMI. A careful development was conducted to fix critical issues such as tension control throughout the whole winding process, careful alignment of the guideways, several procedural points using Hastelloy dummies, and then tests with the superconducting tapes to control the effect of tension on the joints and the winding quality. We recently wound two double pancakes meant to be mounted together as a first prototype of our high field insert (Fig. 2). We used a technology called "metal as insulation" (MI) consisting in co-winding bare HTS and stainless steel tapes for mechanical reinforcement as well as for electrical protection purpose.

Fig 1: The HTS winding machine during operation

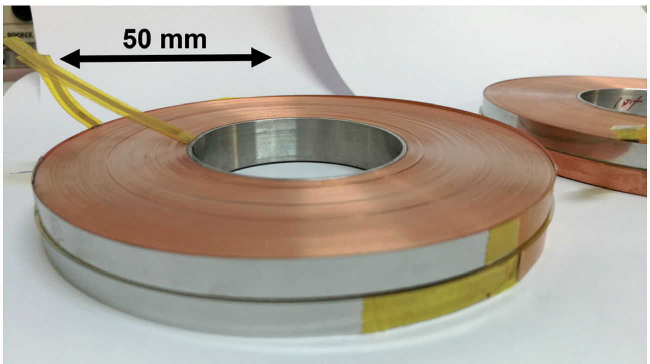
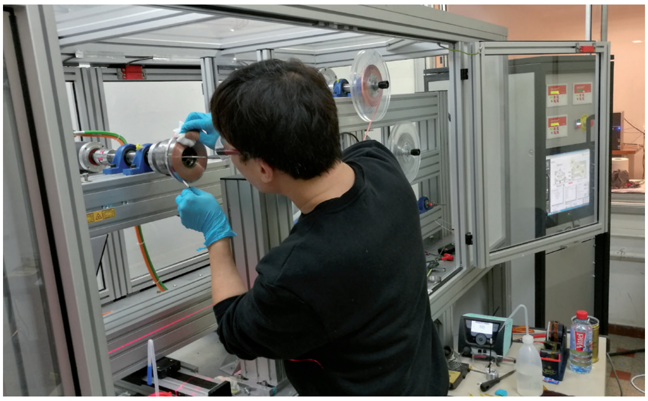


Fig. 2: Ø50 / Ø110 "metal as insulation" double pancake insert leading to a total of 27 T magnetic field.

This HTS insert prototype was then tested at 4 K at several fields up to 20 T. At 20 T the insert generated successfully 7 T leading to a total of 27 T magnetic field, with a current of 416 A (engineering current density of 658 A/mm^2), twice the foreseen operating current of the final insert. This is a very important step towards an all-superconducting 30 T+ magnet, and to our knowledge the first operation of an insert coil using the MI technology in such extreme conditions.

Acknowledgments: NEEL: André-Julien Vialle; LNCMI: Julien Marpaud, Eyub Yildiz, Claude Mollard, Jürgen Spitznagel, David Ponton.



OUTCOMES

Publications:

[1] "Metal-as-insulation variant of no-insulation HTS winding technique: pancake tests under high background magnetic field and high current at 4.2K", Supercond. Sci. Technol. 31 055008(2018).

[2] "Metal-as-Insulation sub-scale prototype tests under High Background Magnetic Field", Supercond. Sci. Technol. doi.org/10.1088/1361-6668/aad225.

Leverage: ANR project NOUGAT "NOuvelle Génération d'Aimant supraconducteur pour la production de Teslas avec une consommation électrique réduite" 2014-2018, project leader: Xavier Chaud (LNCMI), partners: LNCMI, CEA DACM, NEEL, G2ELab.

FET-Open project FuSuMaTech "Future Superconducting Magnet Technology" 2017-2019, project leader: Antoine Daël (CEA), partners: CEA, CERN, CNRS, KIT, PSI, STFC, ASG, Bilfinger, Elytt, Oxford, Sigmaphi, Tesla.

Collaboration: Thibault Lécrevisse and Philippe Fazilleau (CEA Saclay, DACM)

PhD: Tara Benkel (2014-2018) « Contribution to the design and realization of a HTS insert to obtain high magnetic field »

PHD GRANT

Production of micron-sized films and pellets of solid hydrogen and its isotopes

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Stéphane Garcia (PhD student), Bernard Rousset and Mathieu Gibert (PhD supervisors), Denis Chatain (supervisor)

LABORATORIES : INAC, NEEL

Physicist studying laser-matter interaction are really interested in having very thin (10 µm) ribbons of solid hydrogen that could be used as a target. Indeed, during the interaction between a laser and such a target, a proton beam can be created. Hadrontherapy is one of the main potential uses. Huge particle accelerator could be then replaced by a laser and a cryostat, much smaller and cheaper. This PhD thesis was about developing a way to get such ribbons. A new extrusion process based on the use the thermodynamic properties of hydrogen (no moving part) has been studied. A cryostat working at 10K and 400 bar was built and first solid hydrogen ribbons 1 mm wide and 100 microns thick have been obtained in March 2014.

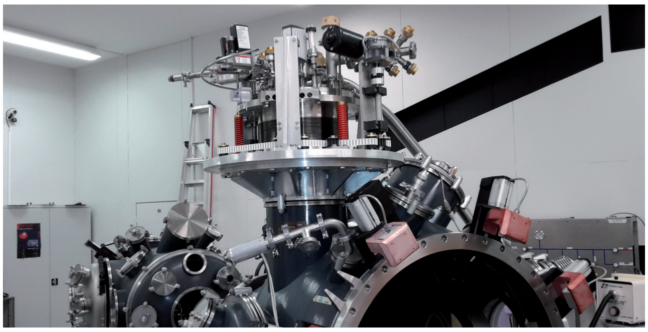

Fig. 1: A view of the cryostat installed on the laser PALS.

Several laser teams have shown a great interest for this kind of target and a collaboration contract has been signed with the laser PALS team (Prague) to install the cryostat in their vacuum chamber (Fig. 1) where first proton beams were obtained. Some experiments were also performed at LULI at Palaiseau in France on the laser ELFIE in 2015 and more recently, 50 MeV proton beams have been obtained with the PW laser VULCAN at the Rutherford Appleton Laboratory in England.

OUTCOMES

[1] Continuous production of a thin ribbon of solid hydrogen. Laser and particle beams, 32, 569 (2014).

[2] Proton Acceleration Driven by a Nanosecond Laser from a Cryogenic Thin Solid-Hydrogen Ribbon, Phys. Rev. X 6, 041030 (2016).

Oral presentations: TFW5, Saint Andrews, Scotland
INTDS2014, Tokyo, Japan
21st TFM 2015, Las Vegas, USA

Leverage: This development has motivated several new collaborations and contracts with IOP (Prague, Czech) and HZDR (Dresden). New experiments were performed at LULI (Palaiseau) and at the Rutherford Appleton Laboratory (England).

PHD GRANT

Next step toward the miniaturisation of space cryocoolers

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Arkadii Sochinskii (PhD student), Nicolas Luchier (thesis supervisor), Frederic Ayela (thesis co-supervisor), Damien Colombet, Manuel Medrano-Munoz

LABORATORIES : LEGI, INAC, NEEL

An experimental and numerical study of Darcy – Weisbach friction factor and Nusselt number at moderate Reynolds numbers ($1<Re<100$) in a well-controlled microstructure for regenerators of pulse tube cryocoolers has been performed. The microstructure consists in convoluted channels of width 10, 20 or 40 µm and depth 150-300 µm, generated by rhombic-or sinusoidal-shaped staggered pillars (bottom of Fig. 1). The channels are etched in silicon wafers using the deep reactive ion etching of MEMS technology. The wall temperature is locally measured by thermometers lithographed on the Pyrex cap of the regenerator (top of Fig. 1).

The influence of the porosity, from 40 to 70%, and that of the geometry parameters have been studied. The possible integration of such passive modules in pulse-tube cryocoolers is also considered.

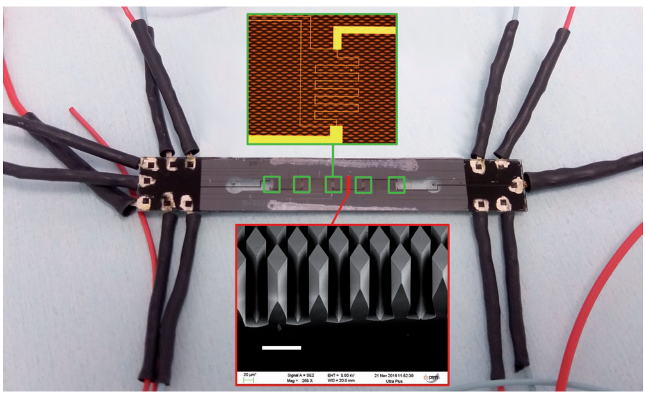

Fig. 1: Sample of micro-machined regenerator. Zoom on: thermometer (up) and bunch of micro-pillars (down), the scale bar is 100 µm.

OUTCOMES

[1] Hydrodynamic Experimental and Numerical Study of Micro-Fabricated Regenerator, Proceedings of the 5th European Conference on Microfluidics, 85 (2018).

[2] A numerical and experimental study of pressure losses inside silicon microregenerators, in preparation.

Oral presentation: joined conference MicroFlu'18 NEGF'18, Strasbourg, France , 2018

Collaboration: Nanofab-Néel.

Leverage: reflexion about the technology readiness level of these products.


Multipoint statistics and large scale structures of turbulence

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LABORATORIES: NEEL, INAC, LEGI, CARL VON OSSIETZY UNIVERSITÄT OLDENBURG

PRINCIPAL INVESTIGATORS : Prof.Dr. Joachim Peinke (Chair of excellence), Alain Girard (Grenoble contact), **Emeric Durozoy** (PhD student), Mathieu Gibert (PhD supervisor), S. Kharche (PhD CEA and Oldenburg), André Fuchs (Oldenburg).

The main focus of the work is to apply comprehensive stochastic analysis methods, yielding to multipoint characterizations of turbulence. This stochastic approach is set in the context on non-equilibrium thermodynamics, to achieve a new understanding of turbulent fluctuations, intermittency and extreme events. Moreover, thanks to the collaboration built around this project, our vision is to extend this comprehensive approach for ideal isotropic turbulence to non-classical fluids in low temperature helium flows, where quantum effects emerge in the Eulerian and Lagrangian framework as well as non-ideal turbulence like for instationary conditions which is important for example for real life wind conditions.

The Eulerian framework : To apply this highly demanding analysis in the Eulerian framework, we used the SHREK (Superfluid à Haut Reynolds en Ecoulement de von Karman) experiment at INAC. This extreme experiment (3000 L of liquid He) is able to generate unprecedented high Reynolds numbers in stable laboratory conditions in various conditions. By changing the rotation speeds a continuous transition to a pulsing (instationary) turbulent state can be achieved. We used micron-sized hot wires (Fig. 1) in order to acquire turbulent fluctuations for hours and converge the high order statistics in the signal (rare events). The preliminary results obtained [A. Fuchs, 2017] indicate that the Integral Fluctuation Theorem is a new fundamental law for turbulence and holds even for highest Reynolds numbers achievable in laboratory conditions.

The Lagrangian framework : In this framework we used the Cryogenic Lagrangian Exploration Module (CryoLEM) at the Néel Institute. This cryostat is equipped with multiple angle optical access in order to perform 3D Lagrangian Particle Tracking (3D-LPT) on micron-sized particles evolving in turbulent helium-4 fluid or superfluid flow. Moreover, this experiment is entirely setup on a spinning table (up to 2 revolutions per second) to study the influence of rotation on the different turbulent flows generated and control their anisotropy. We have obtained in early 2018 the first Lagrangian particle trajectories in a rotating cryogenic turbulent flow (Fig. 2). Our aim is now to adapt our stochastic analysis to this moving frame of reference.

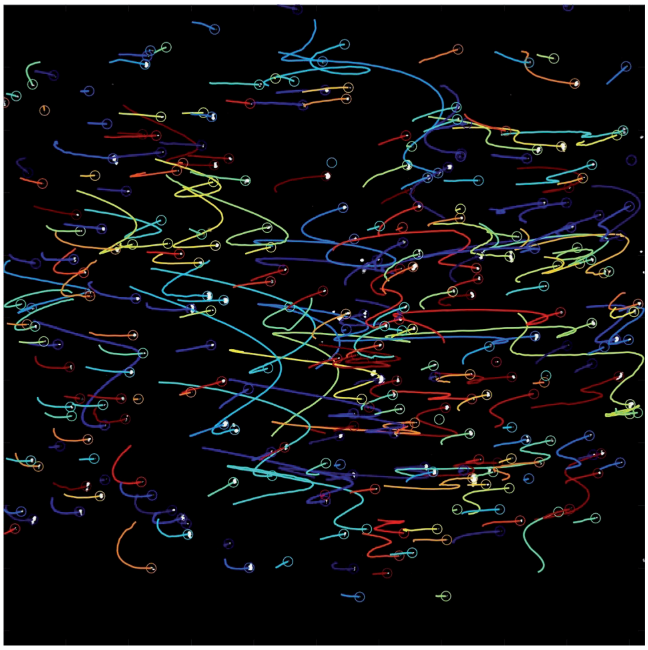

Fig. 2: Lagrangian trajectories obtained in the CryoLEM

Within a cooperation with Martin Obligado (LEGI) a new characterization of the turbulent structure of wind turbines could be worked out.

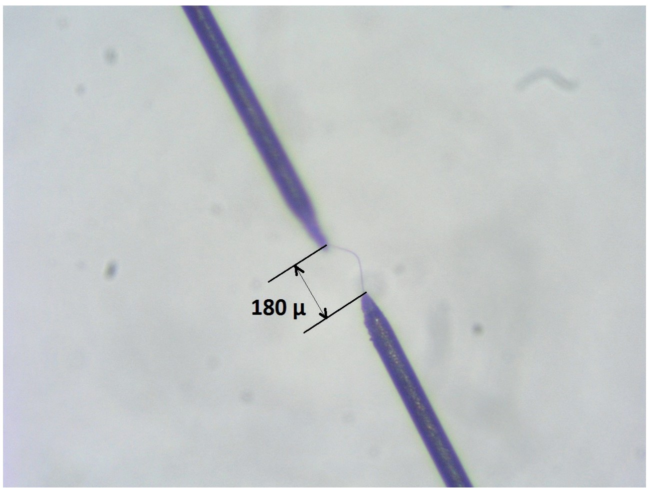

Fig. 1: Micron size (180 µm long) Wollaston hot wire

OUTCOMES

Oral presentations:

-A. Fuchs, ETC Conference, Stockholm, 2017

-Quantum Turbulence Workshop April 10 - 12, 2017 Tallahassee, Florida.

-Chasing tornadoes: vorticity above, below, and in the lab 9-11 April 2018, Newcastle.

Collaboration:

The European EUHIT program supported part of the Work

LANEF Workshops:

-Measurement Methods in Turbulence, 5-7 July 2017 (NEEL)

-Workshop on Fluctuations, Large Deviations in Turbulence, 28-30 August, Autrans (2017)

Leverage: Extension of collaboration to LEGI, Grenoble.

CHAIRS OF EXCELLENCE

EQUIPMENTS

Easycool – An Adiabatic-Demagnetization-Refrigerator-based solution for high sensitivity scientific instrumentation

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LABORATORIES: NEEL, INAC

PRINCIPAL INVESTIGATORS : Philippe Camus, Jean-Marc Duval

Easycool is a continuous magnetic refrigerator cooling at a temperature below 100 mK. It is focused at providing a cryogen-free solution for designing advanced instrumentation for physics and astrophysics.

The challenge in the realization of Easycool is the design of an adiabatic demagnetization refrigerator (ADR) which provides two levels of continuous cooling (1K and 0.1K). Designed for scientific research and high sensitivity cryogenic detectors, this system is compatible with the more demanding applications. For validating the cooler, we have integrated the new technology of KID detectors (Kinetic Inductance Detectors) developped within the instrumentation group at Institut Néel. Those detectors have several applications in millimeter astrophysics or Teraherz radiation imaging in biology.

Easycool is based on a series of 5 adiabatic demagnetization stages. Each stage operates in a defined temperature range with a limited temperature gradient to optimize the efficiency and low mass of the cryocooler (Fig.1).

The key technologies needed for the cooler are the heat switches (gas-gap or superconductive), the magnetic materials manufacturing and the superconductive coils. Those components benefit from the high maturity and reliability of the developments made at INAC for space applications under several CNES and ESA contracts.

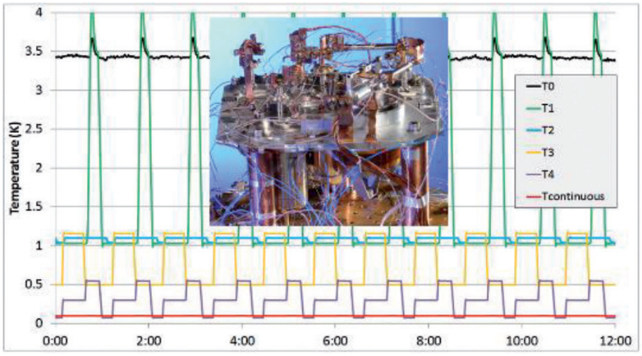

Fig.1: Temperature evolution of the 5 cooler stages (time in hours)

Easycool has been integrated in a modern cryogen-free cryostat based on a 4K Pulse-Tube cryocooler at INAC. It fully demonstrated the magnetic shielding efficiency.

We are currently developping an original solution based on a Gifford-MacMahon cryocooler and a 4K Joule-Thomson cooler in order to provide a competitive cryogen-free system with a low level of induced microvibrations, which is a limiting factor in high sensitivity intruments. This development is made in collaboration with Absolut System (Grenoble, France). Easycool will be fully operational in 2019 at NEEL for future applications (Fig.2).

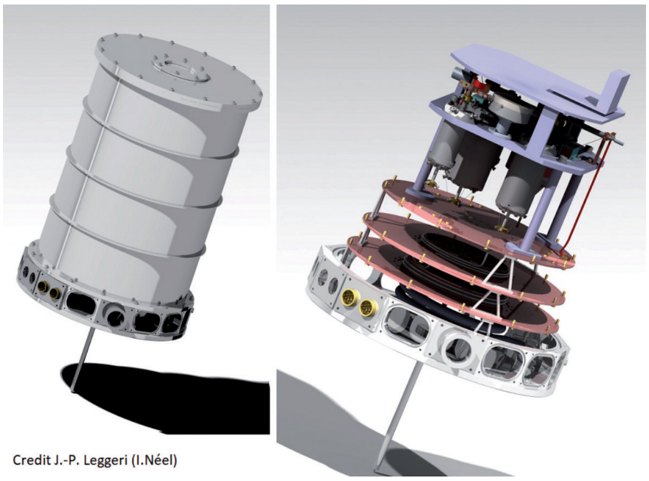

Fig.2: Integration of Easycool in an optical instrument for millimeter astrophysics.

OUTCOMES

[1] Development of an ADR Refrigerator with Two Continuous Stages, J. Low Temp. Phys. 184, 604 (2016).

PhD: Diego Paixo Brasiliano, Etude et réalisation d'une désaimantation adiabatique spatiale 4-50mK, Université Grenoble Alpes (2017)

Leverage:

Collaboration with private sector:

Entropy (Germany): licencing of the gas-heat switches for ADR products (2017)

Absolut System (France): development of a GM/JT 4K for a cryogen-free system

This plateform will support several projects based on KID detectors.

MacroBB - Macro-visualisation Bas Bruit

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LABORATORIES: NEEL, INAC

PRINCIPAL INVESTIGATORS : Mathieu Gibert (Equipment supervisor), Panayotis Spathis, Etienne Wolf, Bernard Rousset, Pantxo Diribarne

Visualization techniques at cryogenic temperature are important for many activities carried out within the alliance «New Frontiers of Cryogenics», from the study of cryogenic hydrodynamics to that of phase transitions of cryogenic fluids in porous media, through the use of cryogenic fluids to study bubble collapse, or the production of solid hydrogen ribbon as a source of proton beams. To increase the spatial resolution and the detection sensitivity in these experiments, LANEF funded a shared visualization equipment, portable, complete and versatile. This equipment consists of two complementary long-focal microscopes, and a Scientific-CMOS camera. Over the past four years, this equipment has been used in INAC and NEEL on different setups and has contributed to reinforce the existing links between these two laboratories.

In F. Sy's PhD work, we combined the long focal microscopes and fast cameras to compare the isothermal turbulence in Helium I (classical fluid) and in Helium II (which has one inviscid component) through a Lagrangian analysis. Using an oscillating grid turbulence generation, we showed using that turbulence in Helium I behaves in agreement with previous results obtained in similar flows using classical fluids. Interestingly, the same turbulence properties stand also in superfluid conditions.

The CMOS camera has been used during V. Doebele's PhD work to characterize, through speckle correlation, the evolution of the microscopic spatial distribution of liquid helium confined in a silica aerogel during condensation-evaporation cycles at 5 K (Fig. 2). The high sensitivity of the CCD translates to a 1% stability of the correlation function between two images acquired in identical conditions. This allowed us to show the so-called microscopic return point memory effect along minor hysteresis loops. While this effect was theoretically expected at the microscopic scale for systems in the Random Field Ising Model class, this is its first experimental demonstration.

MacroBB equipment has also been used to study the dynamics of quantum vortices in superfluid He4 (ongoing PhD of E. Durozoy), to develop solid hydrogen ribbon as a source of proton beams (PhD of S. Garcia), perform tests on the thermal stability of high Tc supraconductive wires (A. Badel), and made it possible to obtain new contracts and collaborations between NEEL and INAC-SBT (ANR ECOUTURB).

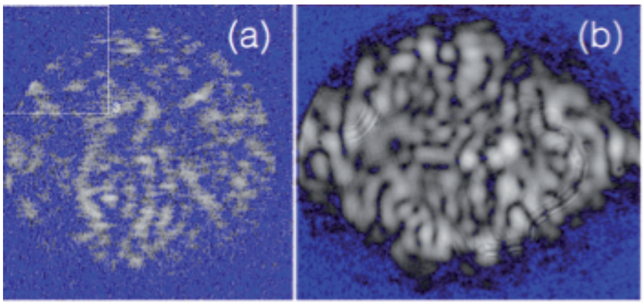

Fig. 2: Speckle images with standard CCD and CMOS cameras.

OUTCOMES

[1] Oscillating grid high Reynolds experiments in superfluid. Proc. 15th European Turbulence Conference Paper no. 318. Delft University of Technology.

PhD "Turbulence de Grille Oscillante à Basse Température" F. Sy, co-supervised by B. Rousset and M. Gibert, defended October 2016.

PhD of V. Doebele, co-supervised by P. Spathis and P. E. Wolf, defense Fall 2018, and paper in preparation

Leverage: ANR ECOUTURB (2016), ANR CAVCONF (2017)

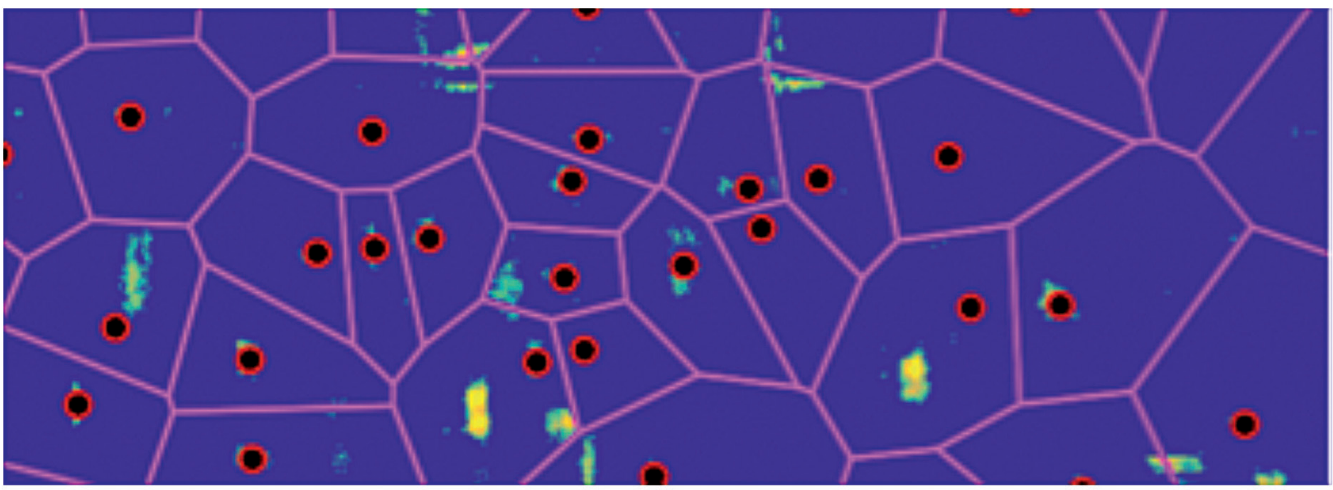

Fig. 1: Particle tracking in the Glass Cryostat at INAC

EQUIPMENTS

BIOPHAB, optical tweezers for single molecule manipulations

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LABORATORIES: NEEL, INAC

PRINCIPAL INVESTIGATORS : Hervé Guillou, Jochen Fick, Yannick Sonnefraud

Nanoscale systems are of great interest because of their peculiar physical properties generated by their low size. However, this size makes their manipulation and study challenging. Two strategies have been developed: either these systems are studied statistically and their properties are ensemble averaged, or they are studied individually. Optical trapping is in that case very convenient because it allows simultaneous manipulation and observation. It is the method of choice if spectroscopic properties need to be measured.

We started the development of an instrument able to trap micro or nanoparticles. The instrument is based on the RAMM system from ASI that offers a modular platform for microscopy. We use a laser diode @790 nm to generate the trapping beam. It is expended by using Newton telescopes to fill the back aperture of the objective lens (Olympus 60X Water NA1.2). The high numerical aperture insures a strong focusing of the laser beam and thus high trapping forces. We trapped micron sized polystyrene beads. The trapping force was calibrated by recording the backscattered laser beam with a high speed sCMOS camera (Andor). The fluctuations of the positions were analyzed by a homemade software in order to calibrate the trap stiffness (Fig. 1). To achieve the development of the instrument, the software, the trap symmetry and the bandwidth need to be improved. For that purpose we will interact with groups who are expert in nanomechanical systems and develop similar detection setup.

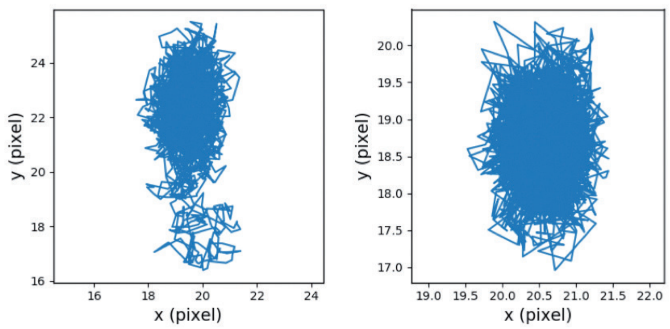

Figure 1 Brownian motion of a trapped particle for low and high trap stiffness.

About 30 students in Master 2 Nano and Complex Matter and Living Matter were invited for a hand-on experience on optical trapping (Fig. 2).

The instrument is now ready to be applied to specific studies. We expect to use it to investigate the force-extension curves of DNA origami with Didier Gasparutto: the information obtained in such experiment is intimately related to the free energy landscape of the system. The experimental setup will also be used to study the fluctuation theorem for self-assembled nanostructures in an open system. In collaboration with Cecile Delacour we will use the highly focused laser beam to cut and reverse engineer neuron networks using photo-ablation: we want to identify the minimal amount of links needed to achieve robust information transmission and processing.

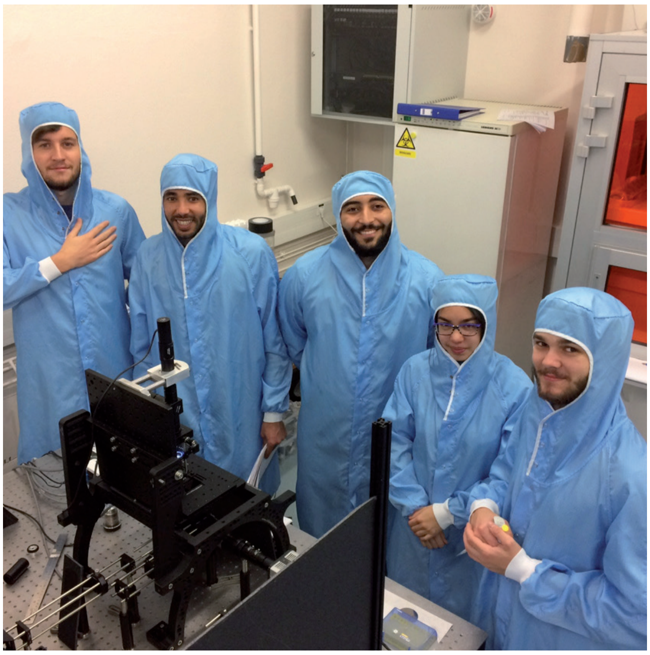

Figure 2 : Students from the master Complex Matter, Living Matter studying optical trapping.

OUTCOMES

Dissemination: give access to state of the art experimental setup to M2 students.

PHD GRANT

Development of electronic tongues for study of complex mixtures and bacteria

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Laurie-Amandine Garçon (PhD student), Yanxia Hou-Broutin, Martial Billon and Franck Omnès (thesis supervisors).

LABORATORIES : INAC, NEEL

Today, novel analytical tools providing rapid and reliable analysis are increasingly demanded in diverse domains such as food and beverage industries. Recently, electronic tongues have emerged as a promising alternative to traditional analytical methods. At INAC, an original electronic tongue was developed based on combinatorial cross-reactive receptors and surface plasmon resonance imaging. It is able to generate vivid 3D images as fingerprints for analytes.

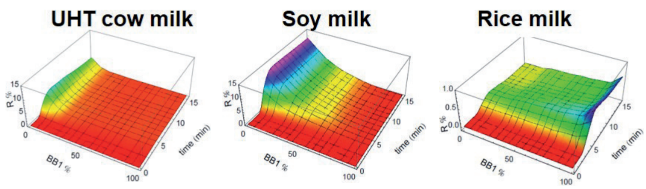

Fig. 1: 3D images of complex mixtures as fingerprints generated by the electronic tongue.

In this PhD thesis, we have explored the potential applications of such a device for the analysis of complex mixtures (milk samples) and bacteria. We have demonstrated that the electronic tongue is able not only to discriminate and classify different milk samples (Fig. 1), but also to monitor the deterioration of milk, thus offering a great potential for quality control. Furthermore, the electronic tongue is efficient for the differentiation of different bacteria according to their genus, species and strains based on 3D images, thus promising for food safety applications.

OUTCOMES

[1] A versatile electronic tongue based on surface plasmon resonance imaging and cross-reactive sensor arrays- a mini-review, Sensors 17, 1046 (2017).

[2] Complex mixtures analysis by landscape imaging based electronic tongue, Talanta 130, 49 (2014).

[3] Electronic tongue generating continuous recognition patterns for protein analysis, JoVE, e51901 (2014).

[4] Landscapes of taste by a novel electronic tongue for the analysis of complex mixtures, Sensor Letters 12, 1059 (2014).

Oral presentation: 2nd International Symposium on Profiling, Portugal, 2015 (invited talk); 16th ISOEN, Dijon, 2015; 2nd ERC Biomim, Grenoble, 2015; 15th ISOEN, South Korea, 2013.

Patent: SPrAM Patent "Capteurs de nez ou de langue électronique" (FR 12 51579), licensed to Aryballe Tech. in 2014.

Start-up: Aryballe Technologies created in 2014 based on our licensed patent.

Collaboration: Prof. David Bonnaffé, Université Paris-Sud, David Eon (NEEL), Roberto Calemczuk, Arnaud Buhot and Thierry Livache (INAC)

START-UP

ARYBALLE Technologies

ARYBALLE TECHNOLOGIES

Record odors by a novel optoelectronic nose based on surface plasmon resonance imaging

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Aryballe Technologies was created in 2014 in Grenoble, based on an exclusively licensed patent by the INAC laboratory SyMMES (CEA-CNRS-UGA). Aryballe aims to develop innovative technologies, databases, software and devices applied to the identification, measurement and representation of smells. Most of the developments are based on technologies initially developed at INAC: the optoelectronic nose uses biomimetic approaches for designing new sensing materials and surface plasmon resonance imaging as detection system (Fig.). Aryballe has successfully miniaturized such an optoelectronic nose, and launched the first portable and universal odor detection device (NeOse Pro™) in 2018 (Fig.). Today, these handheld devices are routinely used in the Aryballe laboratory and by clients for odor analysis related to various market segments including anosmia, flavor & fragrances, olfactory pollution/environment, home automation, etc.

To learn more, please visit http://neosepro.com/ and http://aryballe-technologies.com/

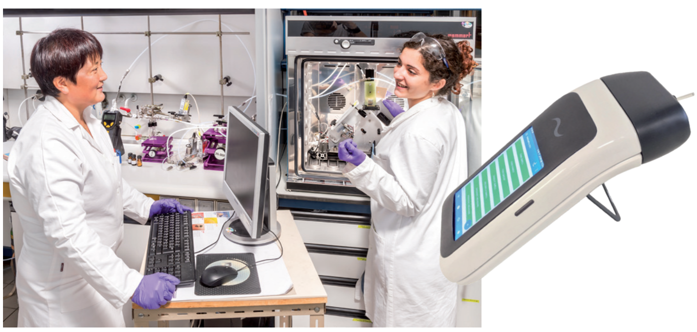

Fig. : Left: Optoelectronic nose: laboratory set-up (copyright: © Denis Morel / CEA); Right: Miniaturized handheld optoelectronic nose, NeOse Pro™ developed by Aryballe Tech. (copyright: Aryballe Tech.)

OUTCOMES

Patents: [1] SPrAM (now SyMMES) Patent "Capteurs de nez ou de langue électronique" (FR 12 51579), licensed to Aryballe Tech. in 2014 ; [2] patent SyMMES/Aryballe FR1758547 (2017) ; [3] patent SyMMES/Aryballe FR1751751 (2017)

Leverage: Project WISE (FUI) 2016; Industrial Chair of Excellence for Thierry Livache, Nanosciences Foundation, 2018

PHD GRANT

Graphene bioelectronics for long-term neuronal interfacing in-vivo

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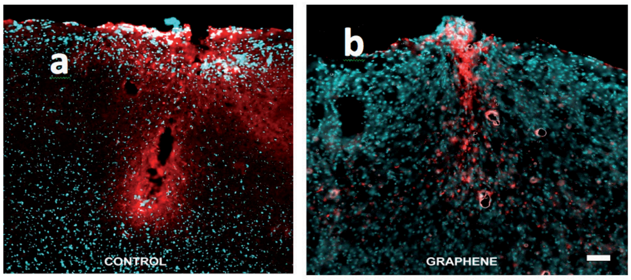
Antoine Bourrier (PhD student), Cécile Delacour and Vincent Bouchiat (Supervisors), Grégoire Courtine (EPFL)

LABORATORIES : NEEL, EPFL

This PhD thesis aimed at testing new materials and coatings to improve in-vivo implants for brain bioelectronics interfaces. The high invasiveness of current implants is responsible for the formation of inflammatory reactions resulting from the concentration of reactive glial cells around the implant site, creating a physical barrier between the motor cortex neurons and the electrodes. This causes moto-neurons signals to disappear from recordings which become flooded by background noise. For that purpose, we have investigated how graphene coatings could be useful, as it allows combining a good bio-acceptance and a high-sensitivity electronics for the first time.



Cross sections of rat brain taken 3 months after implant surgery showing the inflamatory response (red : astrocytes) around the implant position. This response is reduced for graphene-covered implant (b) compared to state-of-the-art commercial implant (a).

Graphene offers an ideal platform for providing a stable bioelectronics interface. It is cytocompatible, chemically inert and flexible. We have tested graphene-coated surfaces and compared them to state-of-the art commercial implants, with tests both in vitro, by cultivating primary hippocampal neurons on the graphene monolayers, and in-vivo, by graphene implants (Fig 1). The graphene coated implants have been the best signal providers in term of spikes quality as well as regarding implant durability, a fact that is supported by the reduced inflammatory response at the implantation site. Accurate real-time samplings of motor cortex neurons signals at the single cell level are promising to re-establish proper locomotion control after spinal cord injuries.

OUTCOMES

[1] Sensing ion channels in neuronal networks with graphene transistors, arXiv :1705.00295 (2017), accepted for publication in 2D materials

[2] Biomimetic coating for minimizing the invasiveness of brain interfaces, compatible with graphene bioelectronics, submitted to Biomaterials.

Oral presentation: Graphene week Conference , Warsaw (Pl) 2016

Collaboration: EPFL

START-UP

GRAPHEAL

Smart Bandages for improved wound healing

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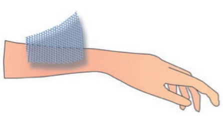
Grapheal is a Startup project which aims at building an innovative bandage technology addressing chronic wounds (i.e. wounds that does not heal after 6 weeks, affecting diabetics and the elderly). The innovation consists in integrating a new material made of a stabilized medical-grade graphene layer onto a biocompatible polymer film. Graphene consists of an ultimately thin layer (a single atom thickness, 0.3nm) of pure carbon, flexible and transparent, which combines healing and antibacterial action, optical transparency and electrical conductivity. It is obtained by integrating a large uniform graphene monolayer into a bandage in order to provide a bio-stimulating and electrically-active platform directly applied in contact with the wound. It allows the development of a range of intelligent dressings that combine a therapeutic and diagnostic actions.



-Therapeutic because graphene functions as a growth matrix, promoting healing but at the same time acting as an electrode in close contact with the wound. This allows the application of electrical pulses whose actions promote faster healing and reduce pain.
-Diagnostic because it plays at the same time the role of an embedded detection platform for on the bed, parameters used to monitor evolution and detect at an early stage the onset of infection.

Double-blind in vivo tests conducted at Grenoble and Montpellier University Hospitals have shown improved wound healing times. The primary target market is the chronic wounds, and more precisely diabetic wounds, that is nowadays a major public health problem, resulting in nearly 500,000 amputations each year worldwide. The market of the connected dressing with the remote diagnosis will be addressed in a second phase.
The startup to be created mid-2018 benefits from a transfer of technology based on 10 years of academic research and 3 patents. The startup project is a spinoff of Néel Institute, currently under incubation phase and supported since 2015 by CNRS and Linksium SATT-Grenoble technology transfer offices.
Grapheal was selected as the most innovative medtech startup and received the Audience Prize at the 2017 edition of Medfit, the leading European business convention dedicated to innovation partnerships and the main marketplace for early-stage investment in medical technologies and diagnostics

Rapid immunoassays exploiting magnetic nanoparticles and micro-magnets

Sarah Delshadi (PhD student), Orphée Cugat and Patrice Marche (Thesis supervisors), Guillaume Blaire, Paul Kauffmann, Nora Dempsey, Franz Bruckert, Marianne Weidenhaupt

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LABORATORIES : G2ELAB, IAB (GRENOBLE), NEEL, LMGP (GRENOBLE)

Magnetic attraction is widely used in *in vitro* diagnostics, as it provides non-contact forces able to capture the objects of interest. Down-scaling the particle size allows diffusion-based transport for much faster reactions; however, due to their high Brownian motion, sub-micrometric superparamagnetic nanoparticles (SPN) are not efficiently trapped by conventional macro-magnets. We exploit high local gradients from micro-magnets to manipulate and locally capture SPNs. We first developed a colorimetric magnetic immunoassay (MagIA), performed in multi-well plates. We then developed a radically innovative, magnetically localized fluorescent detection immunoassay (MLFIA) which allows rapid molecule quantification, without any fluid handling (see Fig.). We optimized MagIA and MLFIA with ovalbumin model, then transferred MLFIA to the detection of clinical parameters (Toxoplasma gondii IgG and IgM) and C reactive protein in human samples. MLFIA presents several key advantages: it is compatible with biological media, uses a small volume and requires little energy. It is also versatile. We are currently developing a portable reader for point-of-care diagnostics. The results will open the way to a new generation of sensitive immunological lab-on-chip.

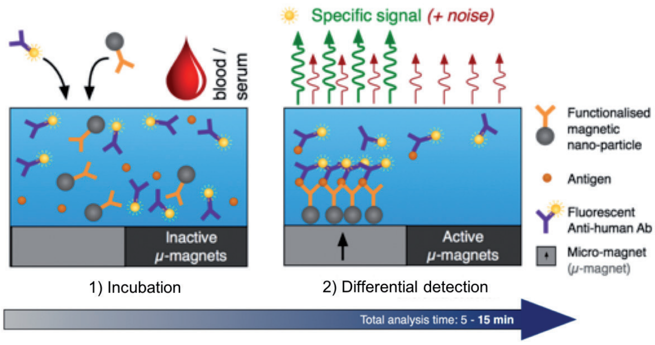

Fig.: Principle of the magnetically localized fluorescent immunoassay.

OUTCOMES

[1] Rapid immunoassay exploiting nanoparticles and micro-magnets, Bioanalysis 9, 517 (2017).

Conference: Poster, Innovative no-wash immunoassay, Intermag, Dublin, Ireland, 2017.

Start-up: Co-founder of MagIA Diagnostics

MAGIA-DIAGNOSTICS

Innovative multiplex Hepatitis B point of care

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MagIA-Diagnostics was founded in Grenoble in July 2017 after a period of incubation at Linksium. Founders Paul Kauffmann (Phelma engineer / physicist), Guillaume Blaire (UGA physicist), Sarah Delshadi (UGA biologist), Cedric Bruix (ESSEC, finances), and Mario Fratzl (Phelma/Darmstadt, mechatronics engineer) collaborate with senior scientific advisors Franz Bruckert (LMGP/Phelma, biochemistry), Orphée Cugat (G2Elab/CNRS, magnetic MEMS), Patrice Marche (IAB/INSERM, immunologist) and Nora Dempsey (Néel/CNRS, magnetic materials).

This start-up develops a lab-on-chip and associated optical reader and aims at revolutionizing immunodiagnostics: the simple and robust portable device exploits proprietary, patented micro-magnetic technology to detect antibodies signaling the presence of a viral infection, in less than 15 minutes and with a single drop of blood from a finger-prick. «We managed to simplify dramatically the many steps of biological tests into a one-step process, while preserving established biochemical reagents and protocols». MagIA expects CE marking by 2020, and is currently focusing on Hepatitis B screening.

https://www.challenges.fr/start-up/magia-diagnostic-un-nouveau-dispositif-d-analyses-biologiques_575658

Diamond Power Devices Research and development on normally-off type diamond power switching devices

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LABORATORIES: NEEL, G2ELAB, AIST (JAPAN)

PRINCIPAL INVESTIGATORS : Hitoshi Umezawa (Chair of excellence), Etienne Gheeraert (Grenoble contact), **Khaled Driche** (PhD student), Nicolas Rouger, Julien Pernot, David Eon, Pierre-Olivier Jeannin

Diamond is one of the promising materials for next generation semiconductor devices because of its superior material characteristics such as high breakdown field, high carrier mobility/saturation velocity, highest thermal conductivity and low dielectric constant. Thanks to these unique properties, extremely high output power with low loss devices operated at high temperature environment are expected on diamond. In this decade, diamond semiconductor devices such as high voltage or high current diodes and switching devices have been reported and showing superior device characteristics. However, the output power of the reported devices are still limited less than 1kW.

In this project, two research topics have been carried out to realize commercially available high power diamond devices. The first topic is to clarify the reasons of poor electrical field strength of the experimentally fabricated diamond device. Using electron beam induced current (EBIC), we have clarified that the hot spots, present in the laterally expanded depletion layer where the high electric field crowds, initiate inevitable breakdown (Fig. 1).

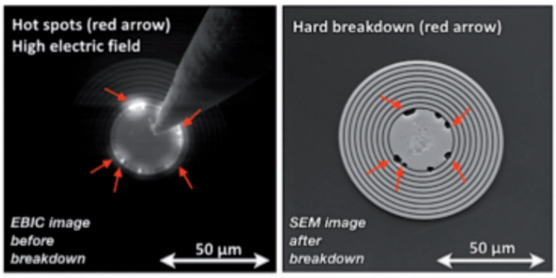

Fig. 1: High electric field regions (bright spots) viewed by EBIC before device breakdown and corresponding damaged regions after device breakdown.

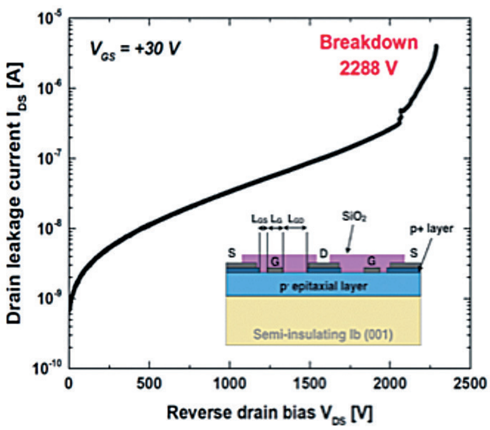

Fig. 2: Breakdown behaviour of diamond MESFET. Breakdown voltage > 2.2 kV has been realized.

The second topic is to fabricate high voltage diamond devices. By extending the gate-drain distance in diamond metal-semiconductor field-effect transistor (MESFET) to 50 µm, a breakdown voltage over 2.2kV has been realized (Fig. 2). This value is the best one in diamond switching devices to date. Reverse blocking MESFETs which are required for next generation matrix converter systems have been also realized for the first time. Schottky drain instead of Ohmic contact was used to resist high reverse voltage up to 3kV

OUTCOMES

[1] Characterization of breakdown behavior of diamond Schottky barrier diodes using impact ionization coefficients, Jpn. J. Appl. Phys. 56, 04CR12 (2017).

[2] Defect and field-enhancement characterization through electron-beam-induced current analysis, Appl. Phys. Lett. 110, 182103 (2017).

[3] Electric field distribution using floating metal guard rings edge-termination for Schottky diodes, Diam. Relat. Mater. 82, 160 (2018).

[4] Recent advances in diamond power semiconductor devices, Mater. Sci. Semicond. Process. 78, 147 (2018).

[5] Electric field characterization of diamond metal semiconductor field effect transistors using electron beam induced current, Mat. Sci. Forum 2018 (Accepted).

Book

"Power Electronics Device Applications of Diamond Semiconductors", Ed. by S. Koizumi, H. Umezawa, J. Pernot, M. Suzuki, Elsevier 2018.

Oral presentations: H. Umezawa, SBDD XX, Hasselt, Belgium 2015 (invited). H. Umezawa, ICDCM Xi'an, China 2016 (invited). H. Umezawa, 2016 MRS Spring, Arizona, USA 2016 (invited). H. Umezawa, ICDCM Gothenburg, Sweden 2017 (invited). K. Driche, H. Umezawa, F. Donatini, J. Pernot, D. Eon, E. Gheeraert, SBDD XXII Hasselt, Belgium 2017. K. Driche, S. Rugen, N. Kaminski, H. Umezawa, E. Gheeraert, ICDCM Gothenburg, Sweden 2017.

Collaboration

N. Kaminski, Universität Bremen, Germany.

D. Araùjo, Cadiz Universidad, Spain.

Leverage

The chair is co-funded by AIST.

An agreement is in discussion to continue the collaboration.

Diamond MOS capacitor for future diamond transistors

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Aurélien Maréchal (PhD student), Etienne Gheeraert (thesis supervisor), Nicolas Rouger (thesis co-supervisor)

PHD GRANT

LABORATORIES : NEEL, G2ELAB

Diamond has attracted a lot of interest in the last 20 years: it shows the ultimate physical properties which can improve the performances of future power devices in terms of conduction and switching losses. Thus, my thesis dealt with two main objectives : i) the fabrication and electrical characterisation of diamond metal-oxide-semiconductor capacitors (MOSCAP) (Fig. 1), one of the building blocks of the future field effect transistors (FETs), and ii) the development of a simulation plateform to perform TCAD

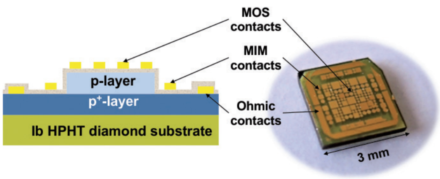

Figure 1 : Schematic cross section (left) of the fabricated diamond MOS capacitor and the corresponding actual device (right).

simulations (Technology Computer Aided Design) in order to anticipate the architecture of the future diamond FETs. In order to gain insight into the properties of the diamond MOSCAP, we performed x-ray photoelectron spectroscopy measurements in collaboration with C. Vallée (LTM-Grenoble). The measurements enabled to establish for the first time the interfacial band diagram alignement of the Al_2O_3/Oxygen-terminated diamond heterostructure.

With N. Rouger (G2Elab, now at LAPLACE, Toulouse) we developed a TCAD simulation platform specific to diamond. It allows us to take into account the unique physical properties of diamond for the design of future diamond power devices.

OUTCOMES

[1] Energy-band diagram configuration of Al2O3/Oxygen-terminated p-diamond metal-oxide-semiconductor, Appl. Phys. Lett. 107, 141601 (2015).

[2] Model implementation towards the prediction of J(V) characteristics in diamond bipolar device simulations, Diamond Relat. Mater., 43, 34, (2014).

[3] Diamond bipolar device simulation, 1st IEEE Workshop on Wide Bandgap Power Devices and Applications (WIPDA) 151 (2013).

Oral presentations: ICDCM, Bad Homburg, Germany, 2015. 3rd French-Japanese Workshop on Diamond Power Devices, Nîmes, France, 2015. 2nd French-Japanese Workshop on Diamond Power Devices, Kyushu, Japan, 2014. ICDCM, Madrid, Spain, 2014.

Patent: "Procédé de fabrication d'un empilement MOS sur un substrat en diamant" (FR11 62052)

Award: PhD Award for A. Marechal, ICDCM Conference, Madrid, 2014.

Collaborations: LTM (Grenoble, France) AIST (Tsukuba, Japan), NIMS (Tsukuba, Japan).

DIAMFAB

Diamond epitaxial layer for power device application

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Gauthier Chicot (Projet Leader), David Eon (Project Initiator), Julien Pernot (Scientific Expert) and Etienne Gheeraert (Scientific Expert).

START-UP

DiamFab is a future company currently in incubation step before foundation in 2019. This original idea came from a small group of persons at Institut Néel who is participating to DiamFab. The research work performed for 20 years allows the company to acquire many skills and know-how on homoepitaxial growth of diamond and doping. During the pre-incubation, Linksium is an incubator company helping inventors to build their projects and prepare company assembly. DiamFab business model is focused on diamond epitaxial growth and development of diamond power devices components.

Diamond is the next generation semiconductor material for high power electronic applications with its unique electrical and thermal properties. Based on its expertise in diamond epitaxy, DiamFab produces bare die device ready diamond. On a well selected substrate, the desired layers of p-type diamond are grown by Plasma enhanced CVD with a wide range of doping level and thickness. The epitaxial layer fabricated by DiamFab is the key part of the electronic component and its properties (crystalline quality, thickness and doping level) directly determine the performances of devices fabricated with it. DiamFab material is electronic grade and is ready for electronic devices fabrication but can also be used for other applications such as optical ones.

http://diamfab.eu/

EQUIPMENTS

CARAPACE: Advanced Characterization of Power Semiconductor Devices

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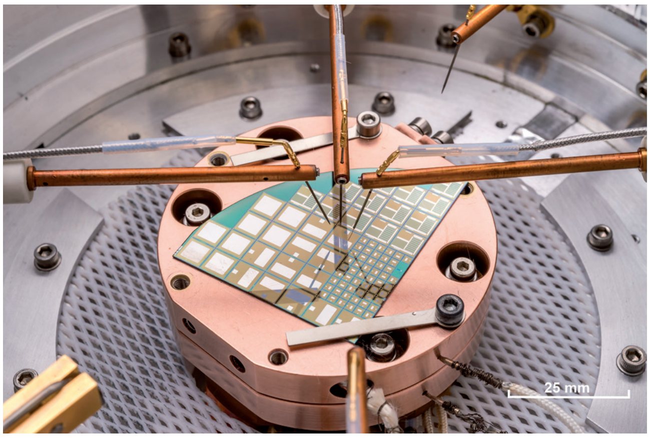
LABORATORIES: G2ELAB, NEEL

PRINCIPAL INVESTIGATORS : Pierre Lefranc, Pierre-Olivier Jeannin, **Alexis Derbey** (equipment supervisor), David Eon, Etienne Gheeraert, Julien Pernot

CARAPACE characterization platform was designed accordingly to multidisciplinary requirements between high voltage, high temperature range, optical and electrical constraints. Its purpose is to accurately measure the static performances of novel power semiconductor devices and their integrated functions (Fig. 1). New materials for power electronics such as diamond (C) or Gallium Nitride (GaN) are pushing the limits of the current state of the art in terms of current density, on-state losses and dielectric breakdown voltage, operating temperatures and high frequency power applications. This new situation imposes new requirements around the characterization at high voltage, high temperature and high frequency that were not available in the Grenoble area. In addition, the necessary insulation levels and associated robustness rely on new solutions for gate signal transfer such as optical control.

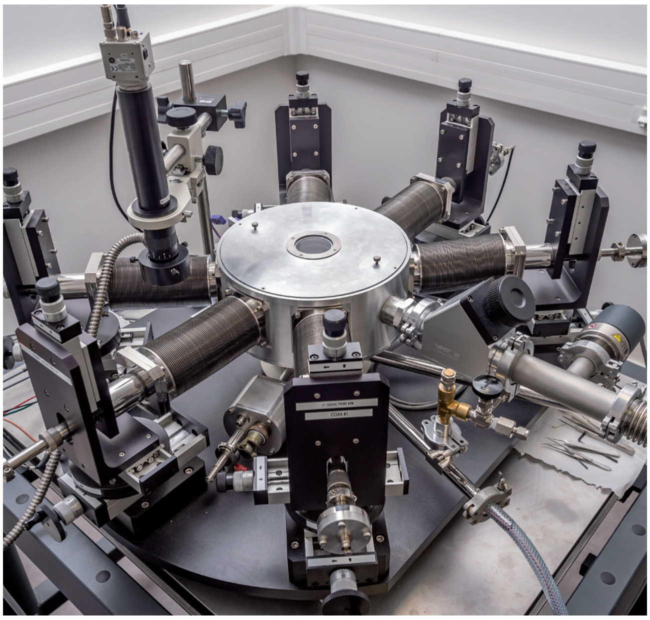
In addition to a hardware consolidation, this platform aims to bring together teams working on these new components, gathering common needs around a high-performance equipment. This platform supervised by G2ELab involves one team at NEEL and two teams at G2ELab, working closely with CEA-Leti.

CARAPACE is based on a Janis station feed by an Agilent B1505 curve tracer with additionnal modules (Fig. 2). The main ratings of the equipment are:
- 6 probe needles (2 coax / 2 triax / 1 HV / 1 optical)
- Vacuum (5×10-4 mbar),
- Temperature: -200°C to > 300°C,
- Electrical: 3000V max (pulse and DC), and 2.5 A max (pulse).



Denis MOREL/G2ELab/CNRS Photothèque

Fig. 1: Characterization of power semiconductor devices.



Denis MOREL/G2ELab/CNRS Photothèque

Fig. 2: Global view of the Janis station.

OUTCOMES

[1] Above 2000V breakdown voltage at 600 K GaN-on-silicon high electron mobility transistor, Phys. Status Solidi 213, 873 (2016).

[2] Deep-depletion mode boron doped monocrystalline diamond metal oxide semiconductor field effect transistor, IEEE Electron Device Lett. 38, 1571 (2017).

[3] Integrated temperature sensor with diamond Schottky diodes using a thermosensitive parameter, Diam. Relat. Mater. 78, 83 (2017).

[4] Realization and Characterization of Instrumented Power Diode with Aluminum RTD Sensor – Application to Thermal Impedance Evaluation, EPE Journal 27, 106 (2017).

Oral presentations:
MRS Spring meeting, Phoenix, USA, 2016.
ICDCM, Montpellier, France, 2016.
NDNC, Cairns, Australia, 2017.
MRS Fall meeting, Boston, USA, 2017
SGE, Nancy, France, 2018.

Collaborations: CEA-Grenoble, Grenoble, France - IEMN, Lille, France - AIST, Tsukuba and Osaka, Japan – NTNU, Trondheim, Norway.

Awards: PhD Award for A. Marechal, ICDCM Conference, Madrid, 2014.

PhD students: J. Letellier (2016-), C. Masante (2016-), K. Driche (2015-), L. Oluwasayo (2015-), G. Perez (2015-), D. Colin (2014-2017), T. Thanh Pham (2014-2017), I. Ka (2014-2017), B. Letowski (2013-2016), G. Regnat (2013-2016), S. Madassamy (2013-2016).

Leverage: GreenDiamond H2020 EU fundings, 2015-2019 - MEMPHIS ANR, 2013-2017 - Diamond_HVDC ANR, 2017 to 2019 – Several projects funded by Grenoble Universities.

Highly conductive PEDOT materials for all-polymeric flexible transparent heaters and thermoelectricity

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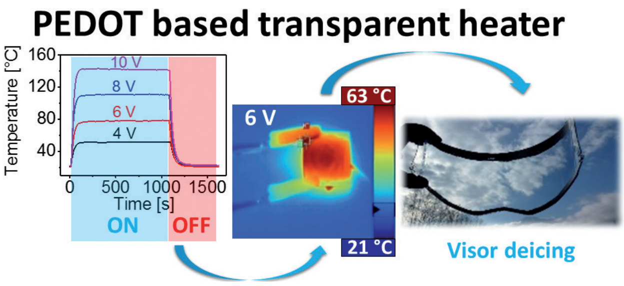
PHD GRANT

Magatte Gueye (PhD student), Alexandre Carella (thesis supervisor), Renaud Demadrille (thesis supervisor) and Jean-Pierre Simonato (thesis director)

LABORATORIES : INAC, LITEN

During this thesis we developed one of the most conductive PEDOT-based material for future optoelectronic and thermoelectric applications. First our materials were fully characterized and the interesting properties for the targeted applications were investigated using techniques available in different laboratories in Grenoble (ESRF, INAC, Liten, PTA nanocharacterisation facilities of CEA). In particular, not alone are our materials very conductive, but they also are highly transparent. Finally they were investigated as thermoelectric materials, transparent electrodes in solar cells and we also demonstrated a novel application of PEDOT as transparent heater. Noteworthy, our PEDOT materials can heat above 120 °C under a bias of 12 V, a result that opens the route for future applications of de-icing or defogging windshields or other surfaces during winter.

These experimental results are comforted by a theoretical physical model; and a prototype of a visor de-icer has also been demonstrated to highlight this new application .



Left: temperature response time under different bias, middle: Thermal image showing the uniform heating, right: visor de-icer prototype.

OUTCOMES

[1] Structure and dopant engineering in PEDOT thin films: practical tools for a dramatic conductivity enhancement, Chem. Mater. 28, 3462 (2016).

[2] All polymeric flexible transparent heaters, ACS Appl. Mater. Interfaces 9, 27250 (2017).

Patent: Liten patent "Utilisation à titre d'élément chauffant d'un films polymérique conducteur et transparent à base de polymères poly(thio-séléno-)phéniques" (n° WO2018069286A1)

Oral presentations: EMRS-Fall, Warsaw, Poland, 2016; Orzel, Scztzyrk, Poland, 2017; Synohe, Annecy, France, 2017.

Semiconducting Nanowires for Thermoelectrics

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PHD GRANT

Dhruv Singhal (PhD student), Denis Buttard & Olivier Bourgeois (thesis supervisors), Dimitri Tainoff (thesis co-supervisor), Pascal Gentile, Jessy Paterson, Daniel Bourgault, Jacques Richard, Hanako Okuno

LABORATORIES : INAC, NEEL

For high thermoelectric efficiency, materials with high electrical conductivity and low thermal conductivity are needed. The thermal conductivity of semiconductors is dominated by phonon transport, implying that the electrical and thermal conductivities can be decoupled. For instance, the mean free path of phonons in a silicon nanowire is strongly reduced by surface scattering if the diameter of the nanowire is reduced.

We grow forests of doped silicon nanowires using Chemical Vapor Deposition with gold droplets to induce the Vapor-Liquid-Solid mechanism. The nanowires undergo guided growth in alumina templates with pores formed by anodizing aluminum. The nanowire profile follows the internal geometry of the pores, which is tuned by changing the parameters of the anodization (Fig. 1). We measure the thermal conductivity of the forest of nanowires embedded in the template (using the 3ω method and Raman thermometry) and the electrical conductivity of single nanowire; we use SEM and TEM for structural characterization. The thermal conductivity of silicon nanowires of diameter equal to 65 nm was measured to be 10 $Wm^{-1}K^{-1}$ at 300K, an order of magnitude below that of bulk silicon. Optimizing the thermal conductivity through the nanowire morphology and the electrical conductivity through doping should allow us to obtain large values of the power factor and realize a cost-effective thermoelectric device.

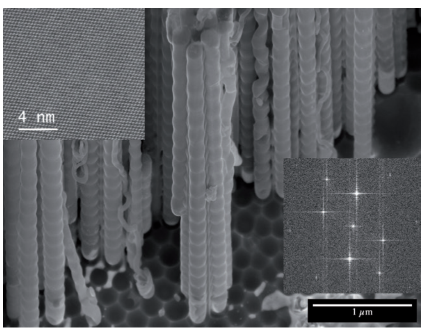

Fig. 1 : SEM image of the diameter-modulated silicon nanowires. (Insets) High-resolution TEM image and its FFT showing the crystal structure of the nanowires.

OUTCOMES

[1] Anisotropic thermal conductivity of a dense forest of nanowires with 3 ω method, accepted Rev. Sci. Instrum.

Communications: EMRS, Strasbourg, 2017; GDRe Thermal NanoScience, Lille, 2017

Collaboration: Institut Català de Nanociència i Nanotecnologia, Barcelona

Others: Selected for the InnoEnergy PhD School.

PHD GRANT

Non-equilibrium quantum modeling of nano-structure based solar cells

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Kevin-Davis Richler (PhD student), Didier Mayou (thesis supervisor)

LABORATORIES : NEEL, INAC

The development of solar photovoltaic systems has been essentially related to inorganic semiconductors. However, solar cells based on organic materials have emerged, showing many advantages compared to their inorganic counterparts. One important difference is that light absorption does not lead instantaneously to free charge carriers but instead to an exciton

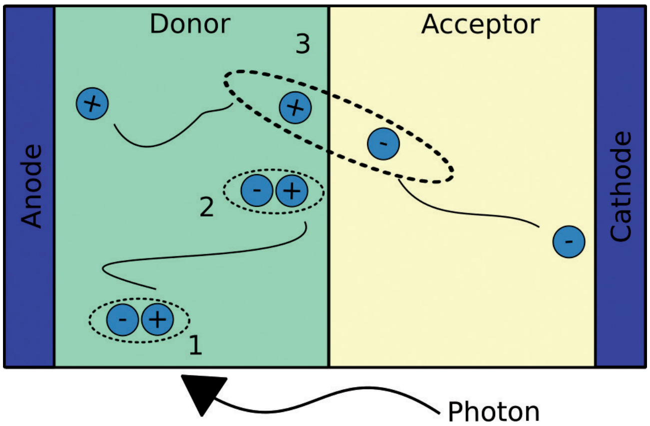

Fig. 1: Generation of a photocurrent in a bulk-heterojunction organic solar cell.

(see Fig. 1) The efficiency of organic cells therefore relies on a good charge separation of the exciton at the donor-acceptor interface. Understanding the influence of the electron phonon interaction in this process is crucial because in organic systems it may lead to the formation of a polaron. In this project we study the influence of polaron formation on the electron transfer process as well as its effect on photocurrent efficiency. So far we have developed and benchmarked a new numerical method to take into account the role of polarons [1]. We apply now this new formalism to study charge injection at the donor-acceptor interface.

OUTCOMES

[1] Inhomogeneous Dynamical Mean Field Theory of the Small Polaron Problem. arXiv:1806.04543 (2018).

Collaborations:

S. Ciuchi, University of L'Aquila, Italy

S Fratini, NEEL

M. Ernzerhof, University of Montreal, Canada.

D. Aldakov (INAC)

PHD GRANT

Pathway towards improved efficiency of kesterite based solar cell

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Md Abdul Aziz SUZON (Ph.D. student), Louis GRENET (thesis supervisor), Henri MARIETTE (thesis director)

LABORATORIES : CEA-LITEN, INAC

CdTe and Cu(In,Ga)Se_2 (CIGS) materials are used in commercial thin-film solar cell technologies. However, both of them contain critical raw material (toxic and/or scarce elements). Kesterite $Cu_2ZnSn(S,Se)_4$ (CZTSSe) absorbers are very attractive since they are made of abundant and non-toxic constituents. However, despite very similar optoelectronic properties, CZTSSe-based solar cells exhibit half of the CIGS-based devices efficiency.

In order to improve carrier collection and to increase efficiencies in kesterite solar cells, we aimed at introducing a band gap gradient in the device absorber. It was successfully implemented by varying the [S]/([S]+[Se]) ratio in the depth of the absorber as demonstrated by material characterization. In parallel, improving efficiencies of CZTSe and CZTS devices was necessary to fabricate efficient devices with bandgap gradient. In CZTS devices, it was done through the incorporation of Na (Sodium) and Sb (Antimony) into the kesterite absorber : this was found to be beneficial in terms of defect passivation (Na) and morphology quality (Na+Sb). Particularly, best efficiency with optimized Na content is doubled (> 4.5%) compared to the sample without Na. Maximum efficiencies of 6.5% and 9.4% have been obtained for CZTS and CZTSe solar cells respectively (see Fig.).

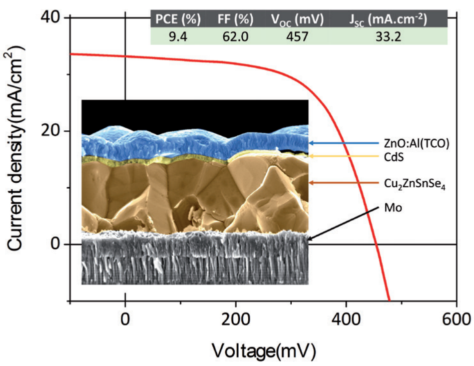


Fig. : I-V curve under AM 1.5G illumination and SEM cross section of our best experimental kesterite based device

OUTCOMES

[1] Analysis of failure modes in Kesterite solar cells, ACS Appl. Energy Mater. (2018), DOI: 10.1021/acsaem.8b00194

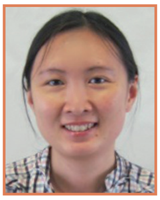
[2] Comparing strategies for improving efficiencies in vacuum processed $Cu_2ZnSnSe_4$ solar cells, J. Renew. Sust. Ener. (2018), DOI: 10.1063/1.5034526

[3] Na and Sb doping in $CuZnSnS_4$ solar cells, in preparation

[4] S/Se gradient in kesterite absorbers through sequential annealing, in preparation

Oral presentation:

- 8th EU Kesterite Workshop, Barcelona, Spain 2017
- JNPV, Dourdan, France, 2017

Nanowire Innovative Solar Cells

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LABORATORIES: INAC, NEEL, UNIVERSITY OF CRETE

PRINCIPAL INVESTIGATORS : Nikos Pelekanos (Chair of excellence), Henri Mariette (Grenoble contact), **Siew Li Tan** (Post-doctoral fellow)

In the quest for next generation photovoltaic technology, nanowire solar cells attract wide interest for two reasons. First, the enhanced light absorption of nanowire arrays, based on their anti-reflecting properties, light trapping and resonant waveguiding effects, allows for an order of magnitude reduction in the amount of materials, needed for an efficient solar cell. Second, due to their large surface/volume ratio, nanowires exhibit relaxed lattice-mismatch requirements allowing for high quality nanowire growth on less costly substrates (e.g. GaAs nanowires on Si). Recently, a conversion efficiency of 15.3% has been demonstrated using GaAs nanowires, underlining their potential to compete with other solar cell technologies.

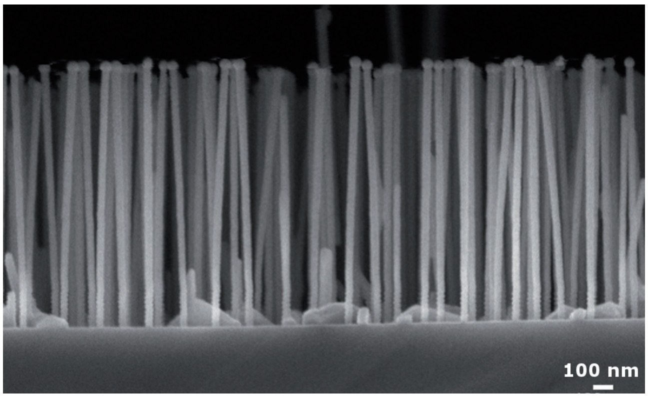

Fig. 1: SEM image of highly uniform GaAs nanowires grown on Si(111) substrates covered with chemical oxide.

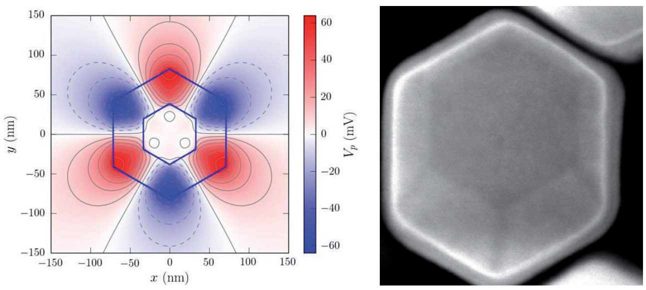

Fig. 2: (Left) Piezoelectric potential profile across a GaAs/In0.05Ga0.95As core-shell nanowire. (Right) Cross-section TEM picture of a GaAs/InGaAs core-shell nanowire.

A critical parameter in fabricating a nanowire solar cell is the uniformity of the nanowire array. This issue is typically addressed by pre-patterning the substrate in order to trigger simultaneous nucleation of the nanowires. This pre-patterning step, however, adds to the complexity and cost of fabrication of the nanowire arrays. In this project, we have devised a new method producing highly uniform GaAs nanowire arrays on unpatterned Si substrates. The method consists of a controlled chemical oxidation process to replace the native oxide on Si(111) substrate with a reproducible chemical oxide. As a result, a high yield (over 90%) of vertical GaAs nanowires is achieved with excellent uniformity on chemical oxide-covered substrate, as shown in Fig. 1. In addition, the structural quality of the nanowires is significantly improved and pure zinc blende crystal structure is achieved with minimal defects.

The above method was successfully extended to the case of GaAs/InGaAs core-shell nanowire arrays, with In content between 10-50%. In these nanowires, the piezoelectric potential profile shown in Fig. 2 is expected to reduce carrier recombination losses and improve the conversion efficiency. First solar cell devices have been fabricated in the context of this project, but have shown significant shunt resistance paths which need to be addressed.

OUTCOMES

Publications:

[1] Highly Uniform Zinc Blende GaAs Nanowires on Si(111) Using a Controlled Chemical Oxide Template, Nanotechnology 28, 255602 (2017).

[2] Strained GaAs/InGaAs core-shell nanowires for photovoltaic applications, Nanoscale Res. Lett. 11, 176 (2016).

[3] Ultra-low threshold polariton lasing at room temperature in a GaN membrane microcavity with a zero-dimensional trap, Sci. Rep. 7, 5542 (2017).

Oral presentations:

E-MRS, Warsaw, 2016

ISCS, Toyama, 2016.

Poster presentations:

J2N, Grenoble, 2017

MBE, Montpellier, 2016

NGW, Barcelona, 2015.

Collaboration:

Th. Kehagias, Aristotelean University of Thessaloniki, Greece.

EQUIPMENTS

COESIHON - Caractérisation Optique / Électrique de Cellules Solaires Inorganiques / Hybrides / Organiques Nanostructurées

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@cea.fr

LABORATORIES: INAC, LITEN, NEEL

PRINCIPAL INVESTIGATORS : J. Faure-Vincent (Equipment supervisor), J.-P. Travers (project initiator).

To facilitate the validation of proofs of concept in the field of photovoltaics, COESIHON offers powerful tools for device fabrication and characterization to the Grenoble's community. These tools are gathered in a facility named "Hybrid-En" which is dedicated to the study of new concepts, materials and structures in the field of energy. This facility is opened to researchers, students and post-docs, and to industrial partners.

In the photovoltaic field, the LANEF researchers have a known expertise in the fabrication and characterization of new nano-materials (organic, inorganic or hybrid semiconductors). Organic materials are mainly used in bulk heterojunction and researchers focus on new polymers with a better bandgap tuning for their use in tandem solar cells. Researchers also work on hybrid organic/inorganic structures (perovskite, Grätzel, or extremely thin quantum-dot-sensitized-absorber solar cells). The third main field concerns the development of type-II heterojunction nanostructures (core-shell nanowires) and new materials based on $Cu_2ZnSn(S_xSe_{1-x})_4$ or $In_{1-x}Ga_xN$ alloys.

COESIHON is focused on the fabrication and characterization of devices. It comprises a set of three interconnected gloveboxes under Argon atmosphere (spin coater, balance, hot plate), a deposition setup (metal and organic organic sources), and a certified AAA-class sun simulator (I-V characteristics, efficiency, semiconductor analyzer). In addition, the Hybrid-En facility offers an Incident-Photon-to-electron Conversion Efficiency setup to investigate the quantum efficiency of the solar cells, and an ageing test chamber for the study of the thermal and photochemical stability of the materials and devices.

Clément Thomassé

Fig. 1: Glovebox line at the Hybrid-En facility.

OUTCOMES

Users:

P. Reiss, L. Grenet, H. Mariette, F. Alam, D. Joly, M. Mendez, D. Aldakov, R. Demadrille, R. André.

Publications:

[1] Efficient eco-friendly inverted quantum dot sensitized solar cells, J. Mat. Chem. A 4, 827 (2016);

[2] Structure and dopant engineering in PEDOT thin films: practical tools for a dramatic conductivity enhancement, Chem. Mater. 28, 3462 (2016);

[3] Synthesis, optoelectronic properties and photovoltaic performances of wide band-gap copolymers based on dibenzosilole and quinoxaline units, rivals to P3HT, Polym. Chem. 7, 4160 (2016);

[4] Insulated Molecular Wires: sheathing semi-conducting polymers with organic nanotubes through heterogeneous nucleation, Adv. Elec. Mater. 6, 1600370 (2017);

[5] Carbazole-based twin molecules as hole-transporting materials in dye sensitized solar cells, Dyes and Pigments 151, 238 (2018);

[6] Increasing the efficiency of organic dye-sensitized solar cells over 10.3% using locally ordered inverse opal nanostructures in the photoelectrode, Adv. Func. Mater. 1706291 (2018);

[7] CuSCN nanowires as electrodes for p-type quantum dot sensitized solar cells: charge transfer dynamics and alumina passivation, J. Phys. Chem. C 122, 5161 (2018)

Patents:

«Colorants organiques et leur utilisation dans les cellules PV» (FR1654125, 2016);

«Organic photochromic dye and uses thereof for dye sensitized solar cells» (EP17305597, 2017)

Collaborations:

P. Fedorko, Univ. of Bratislava, Slovakia;

M. Schiavon, Univ. of Sao Joao del Rei, Brazil;

L. Xu, Jilin Univ., China.

PhD:

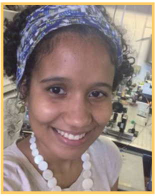
C. Aumaître, M. Bouchard, F. Caffy, M. Godfroy, M. Gueye (LANEF), R. Fillon, M. Suzon (LANEF).

Post-doc :

G. Raj.

Leverage:

ANR projects (MATISSE, SUPERSANSPLOMB, ODYCE, HARVESTERS, PERSIL); European project (ORZEL).



Model nanosystems to progress in the understanding of hard magnetic materials

CONTACT
isabelle.de-moraes
@neel.cnrs.fr

Isabelle De-Moraes (PhD student), Nora Dempsey (thesis supervisor), Thibaut Devillers, Dominique Givord

LABORATORY : NEEL

There is significant growth in demand for high performance magnets for use in green energy technologies (e.g. in (hybrid) electrical vehicles and wind turbines) and robotics, while the demand for mid-range magnets is also growing. The coercivities achieved in today's magnets are typically only 10-20% of their theoretical values, and improved performance is required for long term sustainable development with respect to the materials used. All studies related to coercivity analysis point to the importance of understanding the subtle link between a material's nanostructure and the magnetization reversal processes at play.

The aim of this thesis (started Oct 2017) is to study original nanostructured model samples to improve our understanding of coercivity. We plan to exploit exchange, Zeeman and shape anisotropy in combination with magnetocrystalline anisotropy. Work to date has focused on the preparation of model hard-soft nano-composites, through nano-lithography of soft magnetic (Co, FeCo) elements and the development of very thin hard magnetic matrix layers based on the $Nd_2Fe_{14}B$ phase (see figure).

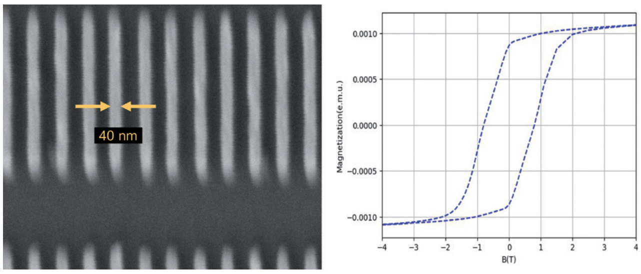


Fig.: SEM image of an array of Co nano-rods produced by e-beam lithography and hysteresis loop of a 50 nm thick NdFeB layer.

OUTCOMES

Presentations at ANR-SHAMAN meetings
Poster presentation at JEMS 2018

Three more PhD students have been hired recently (end of 2017 and 2018)

Congying YOU

"Atomic layer etching of wide band gap materials"

• collaboration NEEL, INAC, LTM, University of Tsukuba and Air Liquide Laboratories-Tsukuba,

• general supervision by E.Gheeraert, cofunding Air Liquide

Jose Antonio PEÑA GARCIA

"Spintronics with skyrmions: understanding and controlling magnetic skyrmion stability and movement from micron to nanoscale",

• collaboration NEEL and INAC,

• supervision S.Pizzini,

• cofunding GreQuE

Michael Schöbitz,

"Dynamics and robust clocking of magnetic domain wa along engineered cylindrical nanowires, driven by magne field and spin-polarized current",

• collaboration INAC, NEEL and chemistry department of t Friedrich-Alexander University Erlangen-Nürnberg,

• supervision Olivier Fruchart and Julien Bachmann

• cofounding Friedrich-Alexander University Erlangen-Nürnbe

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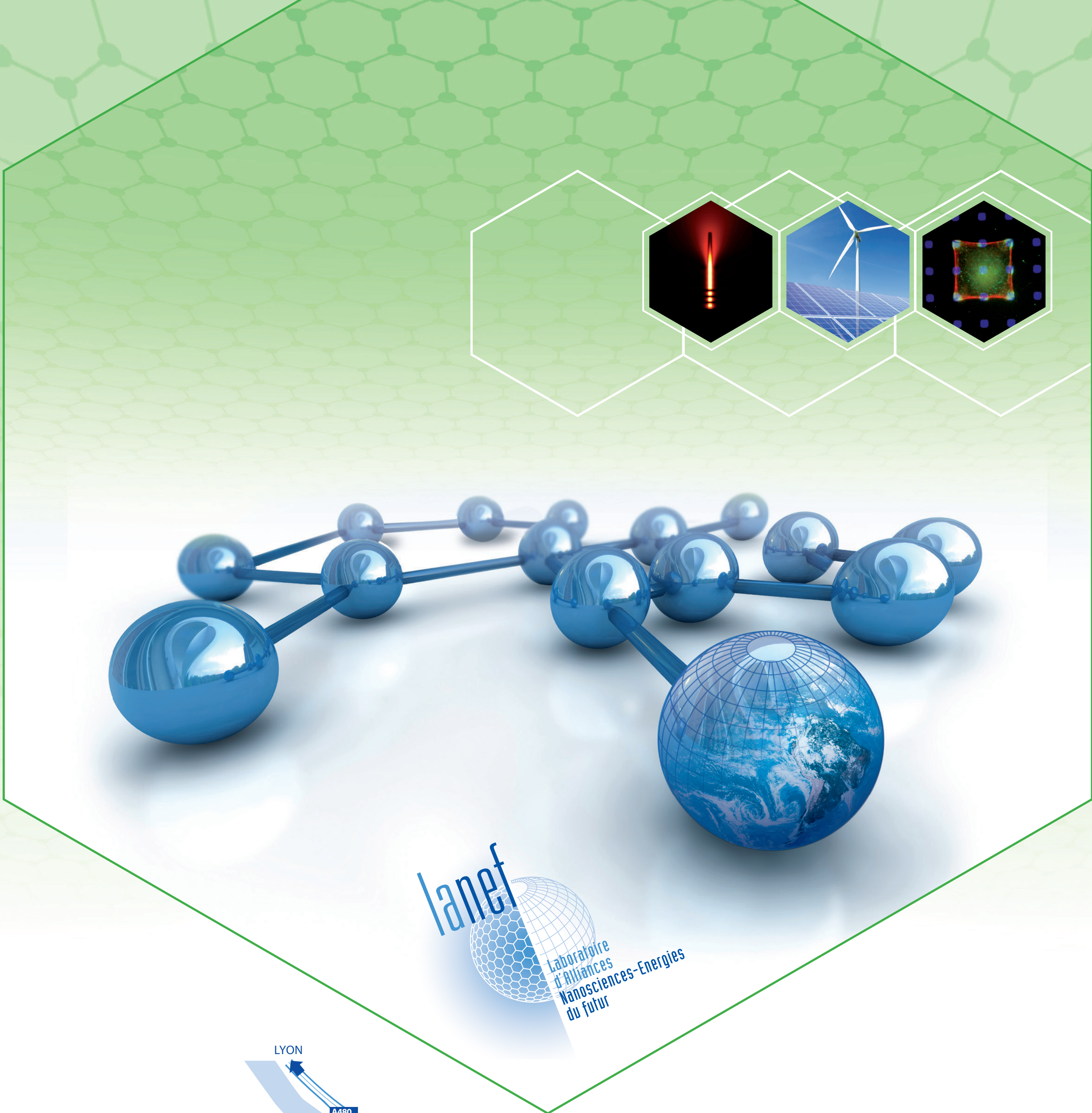
PhD student	Call	Supervisors	start	defense	page
Daria BEZNASYUK	Fall 2014	Moïra HOCEVAR & Julien CLAUDON	1-mars-15		20
Antoine BOURRIER	Fall 2013	Vincent BOUCHIAT & Cécile DELACOUR	1-janv.-14	23/03/2017	42
Lorenzo CAMOSI	Fall 2014	Jan VOGEL	1-mars-15		26
Nicolas CHAUVET	Spring 2015	Guillaume BACHELIER & Gilles NOGUES	1-oct.-15		21
Ion CHIOAR	Spring 2012	Benjamin CANALS et Nicolas ROUGEMAILLE	1-oct.-12	16/10/2015	28
Isabelle DE MORAES	Spring 2017	Nora DEMPSEY	1-oct.-17		51
Sarah DELSHADI	Spring 2014	Orphée CUGAT & Patrice MARCHE	1-oct.-14	17/10/2017	43
Ovidiu FLOREA	Spring 2012	Elsa LHOTEL & Rafik BALLOU	1-oct.-12	21/12/2015	28
Francesco FOGLIANO	Fall 2015	Olivier ARCIZET	7-janv.-16		19
Alvaro GARCIA CORRAL	Spring 2016	Clemens WINKELMANN	1-oct.-16		13
Stéphane GARCIA	Spring 2012	Bernard ROUSSET, Mathieu GIBERT & Denis CHATAIN	1-oct.-12	06/11/2015	36
Laurie-Amandine GARCON	Spring 2012	Yanxia HOU-BROUTIN & Franck OMNES	1-oct.-12	05/11/2015	41
Gaétan GIRARD	Spring 2017	Vincent FAVRE-NICOLIN & Joël EYMERY	1-oct.-17		19
Hadrien GRASLAND	Spring 2012	Thierry KLEIN & Hervé CERCELLIER	1-oct.-12	26/11/2015	32
Magatte GUEYE	Spring 2014	Alexandre CARELLA, Renaud DEMADRILLE & Jean-Pierre SIMONATO	5-janv.-15	18/12/2017	47
Stefan ILIC	Spring 2016	Julia MEYER & Manuel HOUZET	1-oct.-16		31
Justin JEANNEAU	Spring 2013	Manuel NUNEZ-REGUEIRO & Pierre TOULEMONDE	1-oct.-13	15/12/2016	33
Mathieu JEANNIN	Spring 2013	Gilles NOGUES & Kuntheak KHENG	1-oct.-13	28/10/2016	21
Kévin LE CALVEZ	Spring 2013	Benjamin SACEPE	1-oct.-13	12/04/2017	14
Minh Ahn LUONG	Spring 2016	Eric ROBIN & Martien den HERTOG	1-nov.-16		14
Aurélien MARECHAL	Spring 2012	Etienne GHEERAEERT & Nicolas ROUGER	1-oct.-12	27/11/2015	45
Shashank MATHUR	Spring 2012	Pascal POCHET & Johann CORAUX	6-juin-13	16/09/2016	31
Estelle MAZALEYRAT	Spring 2016	Claude CHAPELIER & Johann CORAUX	1-oct.-16		32
Paul NOEL	Spring 2016	Jean-Philippe ATTANE & Laurent VILA	1-oct.-16		25
Marta ORRU	Fall 2013	Joël CIBERT & Edith BELLET-AMALRIC	15-juin-14	26/09/2017	20
Van Tuong PHAM	Fall 2013	Jean-Philippe ATTANE & Laurent VILA	17-mars-14	12/05/2017	25
Javier PUERTAS MARTINEZ	Fall 2014	Nicolas ROCH	1-avr.-15	29/06/2018	13
Kevin-Davis RICHLER	Spring 2016	Didier MAYOU	1-sept.-16		48
Katarina ROJAN	Spring 014	Anna MINGUZZI, Maxime RICHARD & Giovanna MORIGI	16-déc.-15	14/06/2017	22
Tobias SATTLER	Spring 2014	Jean-Michel GERARD	1-sept.-14	28/11/2017	22
Dhruv SINGHAL	Spring 2015	Denis BUTTARD, Olivier BOURGEOIS & Dimitri TAINOFF	1-nov.-15		47
Arkadii SOCHINSKII	Spring 2015	Nicolas LUCHIER & Frédéric AYELA	1-oct.-15		36
Michal STANO	Spring 2014	Olivier FRUCHART	1-oct.-14	03/10/2017	26
Md Abdul Aziz SUZON	Fall 2014	Henri MARIETTE & Louis GRENET	20-juil.-15		48
Igor VINOGRAD	Spring 2015	Marc-Henri JULIEN	1-oct.-15		33

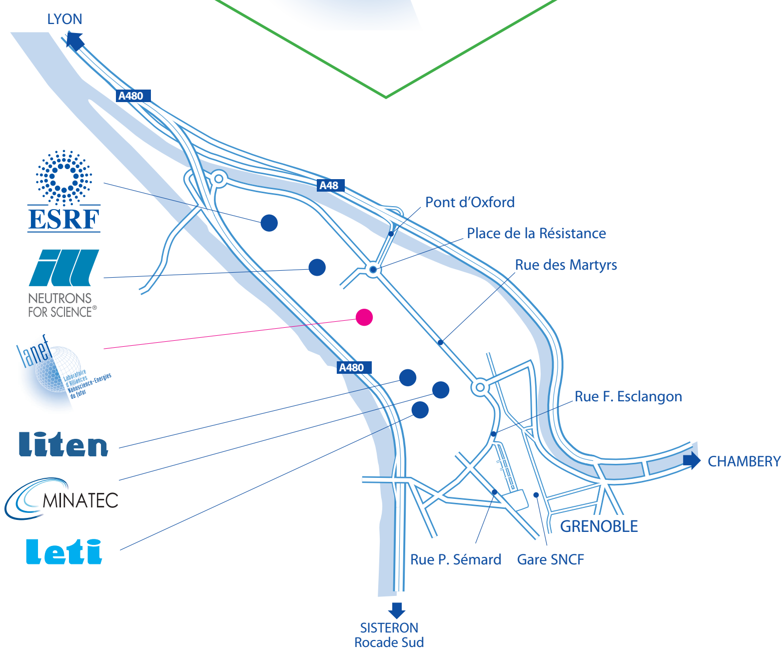
ANR-10-LABX-51-01

LANEF – Laboratoire d'Alliances Nanosciences - Energies du Futur – est un des laboratoires d'excellence dont le financement a été annoncé le 24 mars 2011 par Monsieur François Fillon, premier ministre, et Madame Valérie Pécresse, ministre de l'Enseignement supérieur et de la Recherche, suite à l'évaluation menée par un jury international dans le cadre des investissements d'avenir.

Le projet a été porté par le PRES Université de Grenoble, avec le soutien de l'Université Joseph Fourier, de Grenoble - Institut National Polytechnique, du Centre National de la Recherche Scientifique, et du Commissariat à l'Energie Atomique et aux Energies Renouvelables.

Il est maintenant porté par l'IDEX Université Grenoble-Alpes.





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