National Network of Large Technological Facilities and Basic Technological Research program

2020 Report

Forward

In 2003, the French Ministry of Research expressed the need for a national initiative in nanosciences and nanotechnologies in order to increase the competitiveness of the national research community in this field. Indeed, it is generally accepted that the ability to model, image, manipulate matter at micro and nanoscale is leading to new technologies that impact many sectors of the economy including information and communications, healthcare, transportations, energy and security. The Ministry launched with the "Centre National de la Recherche Scientifique (CNRS)" and the "Commissariat à l'énergie atomique et aux energies alternatives (CEA2)", a dedicated program entitled "A national network of large technological facilities and **Basic Technological Research** in micro and nanotechnologies" to be named as the BTR program throughout this document.

The BTR program covered three main fields:

The **development of competitive clean-room infrastructures**, able to provide the support and technologies needed for the national research activities of the national community in the field of micro and nanotechnologies;

The **training of PhDs and post-docs** in technological facilities;

The **production of IP activity** in nanotechnology for future exploitation through industry.

It involves a network of 5 academic (CNRS and universities) facilities distributed over France belonging to the "Renatech" network (www.renatech.org) and associated to a large facility, CEA-Leti (www.leti.fr), located in Grenoble and dedicated to technological developments targeting transfer to industry.

Mainly supported by an investment plan, the results of the BTR program are reviewed each year by an international panel based on the leverage for the scientific and industrial community and the progress of the networking activity.

The present report presents

- The history and evolution of the BTR Program
- The activity indicators of the Renatech network for the year 2019
- The scientific results & outreach activities
- The Prospects and evolutions
- Funding request for 2019 and investment policy for 2019-2020

The 2018 & 2019 highlights are given in the annex.

I. BTR network overview

The detailed structure of the original and the current perimeter of the BTR network and its **organization** are described in this section, highlighting the effective **link provided between the proof of concept and the integration for transfer to industry** over a comprehensive **range of technological fields.**

I.1 History and evolution of the BTR Program

I.1.1 RTB program

The key objective of this program was to set up in France a competitive clean room infrastructure providing the support and technologies needed for the national research activities in the field of micro and nanotechnologies, in order **to reinforce its impact on EU industry and economy**. Six facilities were selected by the Ministry of Research (MESR) to tackle these objectives and to participate in this network:

CEA-Leti, an integration center that develops research in the field of micro and nanotechnologies, which means assessment of technologies and associated process tools including characterization, from early demonstrators up to prototypes in the view of transfer towards industry (www.leti.fr);

The Five largest academic nanofabrication facilities (C2N, FEMTO, IEMN, LAAS and LTM) managed by CNRS and universities, are associated within a network of academic facilities called Renatech (www.renatech.org). This academic research infrastructure network **has invested in processing and characterization tools** oriented towards long-term and high-risk investigations.

The BTR program was launched, with a budget of 100 M€ (split along 54 % CNRS and 46% CEA). The program was initially planned for a period of 4 years. In fact, this first phase ended in 2008. Since then, the program is renewed each year according to the recommendation of the international panel.

However, the French government support has been decreasing every year since 2007. In particular, the amont was cut of 50% between 2010 and 2012 and since 2012, it is remaining stable at the level of 3.8 M € (2.052 M€ for CNRS part) despite the positive opinion of the international panel.

The following map shows the geographical distribution of the Renatech network and the CEA-Leti together with the main technological competencies of each member.

Mapping of Renatech network members with their main technological competencies

The main reason for this facilities network is to take advantage of the complementarities of the research infrastructures, and to capitalize on the highest fields of expertise of each member. Limiting the number of selected facilities was necessary to concentrate investments, and to obtain a critical mass in these facilities, in exchange for a commitment of the selected facilities to be able to provide micro & nanofabrication service to any academic or industrial user.
Since 2008, the BTR network undertakes a **strategic review of the technical fields** that could benefit of micro- and nanotechnologies. Presently, 4 main technological fields and one transverse field are considered to describe all BTR actions.

	Technological fields
Main fields	Micro & Nano electronics / Spintronic
	MEMS/NEMS/MOEMS & Acoustics
	Photonics
	Micro & Nano for biology
Transversal field	Characterization / Instrumentation

Renatech simplifies and streamlines the technology offering by providing a single point of entry for all academia and industry in nanofabrication. The Renatech network supports multidisciplinary research activities in its historical fields, including ICT (40%) and life sciences (14%), while contributing to various high-visibility projects in other fields.

I.1.2 Renatech+

Three years ago, Renatech network was extended to federate the vast majority of smaller nanofabrication facilities in French academia. The **RENATECH+** network now includes the "large academic nanofabrication centers "Renatech" with the 27 "regional clean-room" that complement the large facilities with specific skill.

The added facilities are smaller, distributed over France, with marked specialties on which they are the best in France. The main objective is to enhance cooperation between cleanrooms and to increase their global level of service, for the benefit of the whole French nanotechnology user-community, which will be better qualified to participate in major international projects such as the Quantum Technology Flagship, the SpinFactory network or the Nanoengineering project, for example.

[Left] Map of the Micro-Nano Technology landscape in France. In white: the 5 large academic cleanrooms of RENATECH. In grey: CEA-LETI industry-oriented cleanrooms. Red dots: regional cleanrooms. [Right] The 27 RENATECH+ regional facilities: NE (North-East), SE (South-East), SW (South-West), IdF (Paris region), NW (North-West), with their 33 associated laboratories

Region	Facility name	Laboratory	Ville
NE	ARCENT-CARNOT	ICB	Dijon
NE	Nano'Mat	L2n	Troyes
NE		LRN	Reims
NE	Photion'tech	Icube	Strasbourg
NE	Minalor	IJL	Nancy
NE	STNano	IPCMS	Strasbourg
SE	PLANETE	CINAM	Marseille
SE	CRHEATEC	CRHEA	Valbonne
SE	Espace Photonique	FRESNEL	Marseille
SE	NanoTechMat	IM2NP	Toulon
SE	Optique sur verre	IMEP-LAHC	Grenoble
SE	NanoLyon	INL	Lyon
SE	ASUR/LaMP	LP3	Marseille
SE	NanoFab	Néel	Grenoble
SE	SPINTEC	SPINTEC	Grenoble
SE	NanoSaintEtienne	LHC	St Etienne
SW	CTM	IES	Montpellier
SW	IMS	IMS	Bordeaux
SW	PLATINOM	XLIM	Limoges
IdF/NW	ESIEE	ESYCOM	Noisy le Grand
IdF/NW	NanoRennes	IETR	Rennes
IdF/NW		FOTON	Rennes
IdF/NW	IDA	Institut d'Alembert	Saclay
IdF/NW	SB Paris Centre	INSP	Paris
IdF/NW		IPGG	Paris
IdF/NW		LPENS	Paris
IdF/NW		MPQ	Paris
IdF/NW		OBSPM	Paris
IdF/NW	C(PN)2	LPL	Villetaneuse
IdF/NW	SPEC	SPEC	Saclay
IdF/NW	GREMAN	GREMAN	Tours
IdF/NW	GREMI	GREMI	Orléans
IdF/NW	Nano-LPS	LPS	Orsay

Support of CNRS.

Note that BTR program is only dedicated to the investments of the 5 Major clean rooms. Since the creation of RENATECH, the CNRS has been contributing significantly to its operating expenses. In 2019, these expenses amount to 11.3 M€ and are covered for 5.9 M€ by the CNRS, for 0.7 M€ by partner universities and for 4.7 M€ by invoicing to users. These figures show the strong involvement of CNRS in RENATECH, which is a key resource for French NanoLabs.

I.1.3 NanoFutur project

NanoFutur project is an investment proposal for **key equipment**, written in the context of EQUIPEX+/ESR PIA3 in June 2020, put forward by the French nanotechnology community (Renatech+). 20M€ (for 6 years duration) have been asked to the Research French Ministry to support NANOFUTUR project. The result of this EQUIPEX+/ESR PIA3 call is expected by the end of 2020.
The NANOFUTUR project associates for the first time the CEA and the whole RENATECH+ consortium (the 5 RENATECH national facilities and the 27 recently associated regional facilities) to a common and organized investment. This project will therefore also be a powerful structuring instrument to federate the community. Through NANOFUTUR, sub-groups of RENATECH+ (organized by challenges) will be created, which will stimulate medium or long-term partnerships.
The main objective is to enhance cooperation between cleanrooms and to increase their global level of service, for the benefit of the whole French nanotechnology user-community, which will be better qualified to participate in major international projects such as the Quantum Technology Flagship, the SpinFactory network or the Nanoengineering project. By addressing the major current challenges in nanoscience and nanotechnology, NANOFUTUR will thus help to strengthen France's position in these fields and to better contribute to the "EuroNanoLab" ESFRI project.
The NANOFUTUR proposal identifies equipment in which the community needs to invest to tackle the challenges in nanofabrication and nanotechnology for the coming decade. Indeed, despite investments that helped modernize the RENATECH network up until 2012, the lack of key equipment was a bottleneck in the successful completion of several highly promising research projects.
More specifically, the research areas in which French academia excels in 6 areas:

- **photonics**, which is evolving towards the on-chip integration of an ever-growing number functions, functions that now include transmission and storing of quantum information or artificial intelligence,
- **spintronics**, the applications of which promise to vastly reduce power consumption of electronics,
- **TeraHertz** technologies, which hold the future of ultra-high speed wireless communications beyond 5G,
- **bio-nanodevices**, both to better understand the workings of living organism and to deliver miniaturized medical implants,
- **sensors**, that will become ubiquitous in the Internet of Things.
- an underlying fundamental challenge common to all of the above, namely "**nano-manipulation and nano-assembly**" that will allow the development of previously inaccessible functions through the assembly of ultra-pure nanometric layers.

For each area key equipment have been identified and will be installed where the most appropriate expertise is available. That will be developed in the next chapter.
Laboratories involved in each challenge will pursue international recognition as experts on the technologies they will develop, and will aim to attract users beyond the national framework. This expertise will also be an asset for the EuroNanoLab ESFRI project, which should eventually showcase specialties recognized at the European level. In addition, the members of RENATECH+ have individually established partnerships with about 40 companies of various sizes which will obviously be able to benefit from the NANOFUTUR project.

In order to obtain this recognition as well as an increase in the number of users of the equipment, it is planned to communicate internationally on the work carried out thanks to NANOFUTUR by organizing annual information meetings for potential partners (users outside the Nano field, international academic partners). In addition, the creation of a club of industrial users will enable more confidential communication with industrial partners.

I.1.4 EuroNanoLab

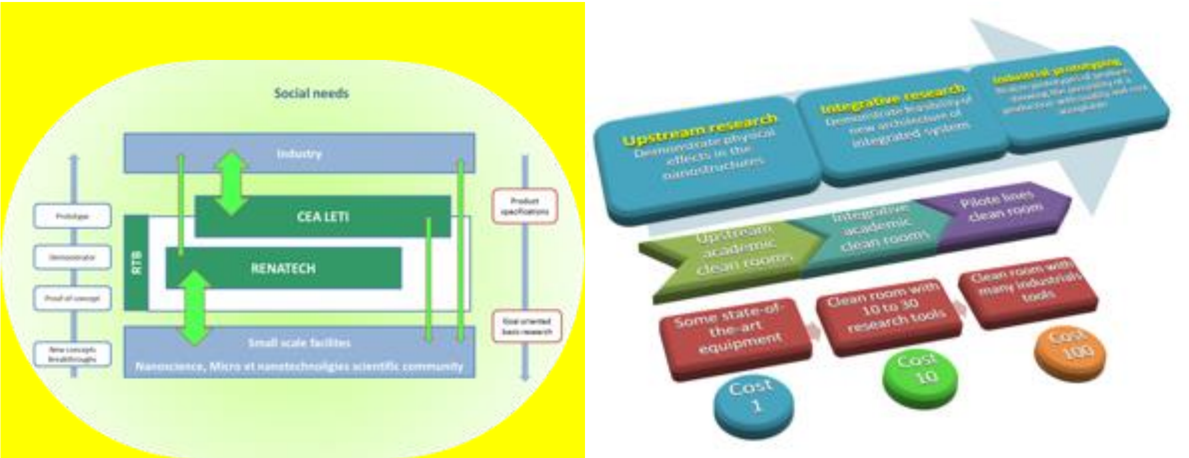
EuroNanoLab consortium, comprising 14 countries and 44 nanofabrication centers.

Moreover, RENATECH is leading the EuroNanoLab consortium, which aims at creating a distributed research infrastructure of over 40 European academic nanofabrication centers through an ESFRI project.

I.2 Operation of the BTR

I.2.1 From the proof of concept to the integration for transfer to industry

The following scheme shows the way that the BTR network wants to interact with all the actors of the nanosciences and nanotechnologies in order to coordinate its investment policy. On one hand, the social and industrial needs will be more efficiently transferred to the academic community in the frame of "goal-oriented basic research" projects. On the other hand, the continuum from early concept demonstration to integration in products will be reinforced.



The BTR network is supporting research activities up to TRL 7, and then taking care of the transfer of the research results to industry.

Based on the recommendations of the international panel, the members of the BTR network gathered their efforts for the past years, towards a common strategy:

-To focus on technological challenges preparing breakthrough in innovation highways;

-To reinforce the continuum from early concept demonstration to integration in products;

-To enlarge the scientific and technological scope for an optimized coverage of the key domains of nanotechnology and nanoscience.

I.2.2 Governance

Since 2004, the INSIS Institute (Institute of Engineering Science) at CNRS headquarters in Paris has been responsible for the operational management (coordination and structuring) of RENATECH, through the allocation of two senior scientists and a full-time administrative staff, in charge of implementing common procedures and joint actions for all its cleanrooms.

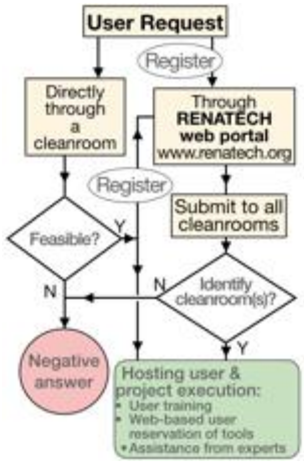
The management of RENATECH+ will involve two CNRS institutes (INSIS and INP) that will manage together the network on behalf of the consortium of legal entities involved in RENATECH+ (including universities, schools and CEA).

Renatech is a "Scientific Interest Group (GIS)" allowing a clear and continuous coordination. A GIS is a light structure intended to assist the technical work without creating any bureaucratic difficulties: this is essential to the smooth and effective advancement of the technological projects. This management structure is organized in three committees. Their main mission is to promote the coordination efficiency and effectiveness of the scientific and technical network activities.

The board of directors gathers the directors of the Renatech facilities. It is responsible of the overall management of the network.
The **steering committee** gathers representatives of CNRS, University and Engineer schools that are parent organizations of the Renatech facilities. The steering committee is the coordinating and supervisory body for the network in compliance with the decisions of the board of directors and the contractual obligations. Its primary function is to take responsibility for achievement of BTR outcomes (and NANOFUTUR investment in case of success) in providing the necessary resources (especially the human resources,) as well as controlling that the targets are met.
A **second administrative officer**, thanks to a CNRS position specially created, will complete the Renatech administrative staff, in order to specifically coordinate the administrative, financial and communication activities of the Nanofutur project.

I.2.3 Sharing of the equipment

Access to Renatech equipment is always granted through a research collaboration with the laboratory that possesses equipment in question. In addition, over the past ten years, RENATECH gradually put in place an open access procedure that grants users access to equipment for a fee without being involved in a research project with the host laboratory. This access mode is available for most cleanroom equipment of the network and is guaranteed for any external user, including private users and users that do not belong to Renatech+ laboratories. Renatech's equipment access are describe in the hosting charter displayed in the Renatech web site. All equipments are easily accessible by external users, either through direct contact with a cleanroom or through registration on the website - www.RENATECH.org - where they can submit their nanofabrication project (see fig. below). All equipment is thus accessible to the whole user community needing nanofabrication tools. In the future, all members of Renatech+ will commit to comply to this procedure.



RENATECH open-access process flow for nano-fabrication external users.

I.2.4 Size of user communities

RENATECH has already about 1000 users, of which 430 internal users (facility members). The number of external users has increased fourfold in the last 6 years.
In the case of the success of NANOFUTUR investment program, the network will rise by at leat 370 internal users which currently share and use equipment in regional facilities of RENATECH+. Thanks to a better visibility coming from NANOFUTUR project, we expect that new external users will gradually access RENATECH+ and that the ratio of total to internal users will reach the same value as for RENATECH. <u>An estimation leads to a community of ~1800 users for RENATECH+ in 6 years.</u>

I.2.5 Pricing.

Following the recommendations from the European Commission, the RENATECH network has promoted the « unit cost » method for the pricing of the nanofabrication service and the principles of a fair pricing are already well-established. With this method, all user (either internal or external) pay running costs according to their share of access-time to the cleanroom machines. Since the machines are paid by public money, a share of the depreciation of the machine is not charged for an academic user, but will be charged for a user from the private sector. When human resources of the cleanroom are heavily involved in the project (except for the user training, which is included in the service), their cost will be charged to the user. If the machine is used through a research collaboration with a local researcher, the involved local researcher has to pay a share of the running costs as any other user and these expenses will be their contribution to the project.

I.3 NanoFutur project

I.3.1 Ambition and scope of the project.

The ambition of the proposed project is to make decisive contributions to the new challenges in nanotechnology. Although research in French academia encompasses all fields of nanoscience, the scope of NANOFUTUR has been limited to exclude Quantum Technologies. Given the importance of this field, it is be the subject of a separate and specific proposal for funding.

The 6 main challenges addressed in the NANOFUTUR project gather 13 laboratories, sorted in the list of challenges below to indicate their main contributions in the fields concerned by this proposal;

ADVANCED PHOTONICS & SOLAR ENERGIES, with **FOTON** (Rennes) on III-P growth for photonics (~10 papers/yr), **INL** (Lyon) on III-V & oxide grown by MBE (~17 papers/yr), **C2N** (Palaiseau) on oxides growth & hybrid photonics (~35 papers/yr) and **FEMTO-ST** (Besançon) on nanophotonics (~20 papers/yr).

SPINTRONICS, with **SPINTEC/LTM** (Grenoble) on Spintronics, MRAMs, Skyrmions, Spin-orbitronics or neuromorphic computing (~40 papers/yr) and **C2N** (Palaiseau) on topological materials (~5 papers/yr).

TERAHERTZ TECHNOLOGIES, with **IEMN** (Lille) on THz technologies (~20 papers/yr) and **XLIM** (Limoges) on antennas and RF communication (~5 papers/yr)

NANO-BIOTECHNOLOGIES, with **LAAS** (Toulouse) on biological & biomedical engineering (~20 papers/yr) and **FEMTO-ST** (Besançon) on laser material processing, piezoelectric materials, biomedical & micro-robotics (~20 papers/yr)

SENSORS, IOT AND MICRO-ENERGY, with **IEMN** (Lille) on sensors & micro-energy (~20 papers/yr), **ESYCOM** (Marne-la-Vallée) on sensors (~5 papers/yr) and **IMS** (Bordeaux) on sensors & organic MEMS (~5 papers/yr)

NANO-MANIPULATION & NANO-ASSEMBLY, with **CRHEA** (Nice) on 2D materials growth (~45 papers/yr), **C2N** (Palaiseau) on material transfer printing (~15 papers/yr) and **MPQ-Paris Centre** on low-dimensional materials (~40 papers/yr)

I.3.2 Structuring of the RENATECH+ community.

Beyond the laboratories listed above that are formally partners of this proposal, many others actively work on these challenges, including the following members of the RENATECH+ network:

Challenge#1. **XLIM** (Limoges), **IEMN** (Lille), **FRESNEL & LP3** (Marseille), **LPL** (Paris-Nord), **IMEP-LAHC** (Grenoble), **L2n** (Troyes), **ICB** (Dijon), **LHC** (St. Etienne) and **IES** (Montpellier)

Challenge#2. **UMPhy CNRS-THALES** (Palaiseau), **Inst. Jean Lamour** (Nancy), **IPCMS** (Strasbourg), **SPEC** (Saclay), **LPS** (Orsay)

Challenge#3. **IETR** (Rennes), **OBSPM** (Paris), **C2N** (Palaiseau), **IES** (Montpellier)

Challenge#4. **IES** (Montpellier), **FEMTO-ST** (Besançon), **LAAS** (Toulouse), **SPINTEC** (Grenoble)

Challenge#5. **IEMN** (Lille), **IPGG** (Paris), **Inst. d'Alembert** (Paris), **C2N** (Palaiseau)

Challenge#6. **IPCMS** (Strasbourg), **INSP** & **LPENS** (Paris), **Inst. NEEL** (Grenoble), **CINAM** (Marseille), **L2n** (Troyes)

These laboratories are collaborating actively with the partners of the present project and will have full access to the requested equipment. Beyond these partners, it is the RENATECH+ mission statement to facilitate access to any equipment within the network to external users. Any equipment within the NANOFUTUR proposal will, therefore, be largely available to external users. Furthermore, members of the present project will actively solicit RENATECH+ members, that are not partners of NANOFUTUR, to create joint projects. As a result, the new equipment will benefit all laboratories from RENATECH+ and give them the opportunity to investigate topics at the forefront of the research at the nanoscale.

The expectations of NANOFUTUR are therefore to provide high-performance equipment to the whole RENATECH+ community and to stimulate collaborations that will strengthen and structure the national community at a regional/national level, or even beyond the national framework.

NANOFUTUR will have a definite impact on the quality of the scientific production, it will increase the international visibility of the French nanofabrication centers and will stimulate innovation in highly competitive research areas.

I.3.3 Scientific program

The NANOFUTUR scientific program is built around 6 challenges that are described below:

CHALLENGE#1. ADVANCED PHOTONICS & SOLAR ENERGIES.

In the next 10 years, integrated circuits will combine an increasing number of functions, including built-in sensing, photonic circuits to route information and energy harvesting. Developing circuits that jointly manipulate light, heat and electricity at the device level is a key milestone. Thanks to its long-standing leadership in Si photonics and in hybrid oxide/semiconductor integration, France is a major player at the international level and is best suited to tackle this challenge. The hybrid integration of III-V semiconductors with functional oxides on silicon, combined with 2D/3D multiscale systems structured at the nanoscale, offers the prospect of beyond state-of-the-art devices.

Research goals Through the national RENATECH+ network, we will build a unique scientific and technological chain for large-scale co-integration of III-V semiconductors, oxides and 2D/3D nanophotonics structures on silicon platforms. Such a multisite coordination will address three main challenges in the fields of optoelectronic and energy harvesting: (1) highly reconfigurable optical neuromorphic computing chips: building on recent demonstrations of optical spiking neurons and waveguide (WG)-based reservoir computing, we will develop a fully functional, compact, reconfigurable photonic neuromorphic computing platform on chip (Si WG, oxide- & III-V-based 3D-nanostructured components to ensure neurons excitability and network plasticity), (2) on-chip combined thermal/optical energy harvesting with greatest solar energy conversion, by coupling III-V photovoltaics with thermo-/pyroelectric features of oxides and (3) ultimate gas sensors based on the engineering of III-V/oxides light-matter interactions: to reach "beyond-the-standard" gas sensing, we target the coupling of III-V sources with nonlinear oxides for wide-band light generation and 3D plasmonic nanostructures that will drastically enhance light/molecules interactions at local scales.

Nanofabrication technology requirements. The envisioned multiscale architectures based on hybrid compact devices require the development of technological capabilities involving photonics, material sciences and state-of-the-art nanofabrication. To this end, specific equipment, which will be unique at the national level and among a handful in the world, are required: a gas-source MBE for III-V nanostructured materials and devices on Si, a hybrid MBE for oxide thin layers and superlattices on Si and III-V and a metalorganic (MO)-MBE for thick doped oxides on large sized substrates. The ultimate 2D/3D nano-structuration will be enabled using a multisource ion-beam station.

CHALLENGE#2. SPINTRONICS

France has played a major role in the development of spintronics, yielding a Nobel prize and an internationally recognized ecosystem (SPINTEC and Néel Institute in Grenoble; UMPhy CNRS-Thales, C2N and SPEC in Paris-Saclay and the Jean Lamour Institute and IPCMS in the Grand-Est region).

Spintronics offers clear prospects for the development of low-energy consumption and reconfigurable electronic circuits, which are key elements for greener digital applications, in various fields that range from the Internet of Things to ultimate computing. Taking these demonstrations to the next TRL requires the demonstration of new stacks of materials.

Research goals. In order to capitalize on basic concepts discovered by the French spintronic community and to accelerate technology transfers for innovative devices, we propose to set up a national academic pilot line for spintronic materials, with 3 main scientific objectives:

(1) « beyond CMOS electronics » that uses original concepts such as magnetic textures, spin to charge conversion and topological properties of new electronic surfaces,

(2) neuromorphic architectures for artificial intelligence, based on the fact that spintronics can provide both hardware synapses and neurons, and promises a simple route to greatly reducing the power consumption in AI circuits,

(3) reconfigurable metamaterials for signal processing, combining magnonics with photonics, plasmonics and phononics for innovative applications in digital information processing of compact and energy-efficient analog signals.

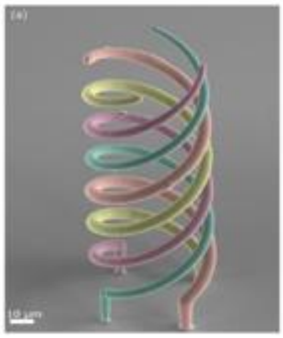
Nanofabrication technology requirements. The core of the proposed pilot line is represented by 2 new specific sputtering deposition and reactive ion etching clusters in addition to a MBE cluster that will allow the exploration of topological materials for next-generation spintronics.

CHALLENGE#3. THz TECHNOLOGIES

Over the last decade, numerous revolutionary applications have stemmed from the emergence of mm-wave and Terahertz (THz) devices, such as imaging, spectroscopy, telecommunications and bio applications. To fulfill their potentials, cutting-edge power and sensitivities at very high frequencies (0.3 to 1THz) are required. Reaching these objectives implies:

(i) the use of components still dominated by III-V technologies, for which state-of-the-art performances have already been demonstrated in the RENATECH+ network, and

(ii) a breakthrough in interconnecting and interfacing technologies.



Radiating element for a THz antenna made by additive manufacturing

Research goals. In this frame, we specifically aim to provide:

- new concepts for sources and detectors, that fulfill the requirements for future 6G systems and THz imagers/spectrometers systems for field use. We aim at a 10-fold increase in both emitted power and detection sensitivity, thus yielding a 100-fold gain in the efficiency of the complete chain.
- new cost-effective technologies suitable for making high-performance sub-systems for the next generation of complex integrated THz devices (antenna phased arrays for THz beam forming, ultrafast integrated THz modulators, THz radar for remote THz imaging, etc.) for which tight specifications should also be met for passive elements (antennas, interfacing and integration elements).

Such performances would allow Tbps transfer rates using THz waves, i.e. a more than tenfold improvement in bandwidth over the state-of-the-art in wireless telecom applications.

Nanofabrication technology requirements. In order to reach these goals, we will set up a new fabrication line for the targeted components/subsystems by completing existing equipment with 3 new dedicated machines to go beyond state-of-the-art integrated THz components. To avoid frequency filtering effects, the lateral dimensions of III-V THz sources and detectors have to drop below one micron. Devices of this characteristic lengths (e.g cylindrical mesa structures) will present high area/volume ratios. Therefore, the quality of bottom and top contact resistances become critical to avoid a large series resistance as well as to the quality of side-walls passivation to avoid large side-wall currents. Dedicated equipment is required in both instances. For the fabrication of subsystems, new hybridization, interfacing (waveguides, antennas) and packaging concepts will need to be co-designed with the new sources/detectors. Fabricating research demonstrators by conventional mechanical machining is not precise enough for THz devices and cleanroom technologies take too much time to test new concepts. Therefore, metallic additive technologies optimized for the aforementioned THz components and devices is presently the most effective option.

CHALLENGE#4. NANO-BIOTECHNOLOGIES

The engineering of integrated biomedical microrobots (e.g. for in vivo surgery/drug delivery), in vivo & early diagnosis devices (Lab-on-Chips) and models of microenvironment for cell culture and tissue engineering (organs-on-chips) are strategic goals in the field of preventive, curative, and regenerative medicine. A non-exhaustive list of major breakthroughs foreseen in the next ten years includes minimally-invasive medical procedures, the improvement of their therapeutic efficiency, and an increase of in vivo diagnosis capabilities (for example by targeting detection of rare cells, circulating DNA, exosomes, …). Moreover, the development of tissue models will solve the “3R” challenge (Reduce, Replace, or Refine) for animal experimentation. Addressing these major challenges will require the development of microdevices that integrate multilevel 3D architectures, incorporate biocompatible materials, and go beyond the scope of silicon technologies.

Research goals. In this context, our goals will focus on:

- Microrobotics for minimally invasive therapy & diagnosis where highly-compact micro-robots with multiple degrees of freedom and high precision motion in confined in vivo environments will be used for localized analysis and microsurgery.
- High sensitivity Lab-on-Chips for early and non-invasive medical diagnosis of disease where devices based on microfluidics, sensor/actuators and active materials will be integrated to analyze and measure of emerging biomarkers (e.g. rare cells, circulating DNA, exosomes) and study the impact of the environment on health.
- Microphysiological systems (organ-on-chip, 3D models for cell culture and tissue engineering): models of tissues will be used for in-vitro diagnosis and analysis of cancer or stem cells, in a physiologic or pathophysiologic context that will also help decreasing exploitation of animals in medicine.

Nanofabrication technology requirements. A full-3D fabrication line for in-vivo microrobots and integration/characterization equipment for Lab-on-Chips, with a particular focus on biocompatibility issues are essential and needed.

- 3D nano-fabrication/metrology and integration/assembly: for mm-scale microrobots, actuators can only be directly integrated on flexible structures localized actuators. This requires 3D structuring, that integrates both structural (polymers, metals, glass) and active materials (e.g. piezoelectrics). In addition, the hybridization of micro-sensors for observations in confined structures is necessary to provide a fully functional system.
- Processing of biocompatible materials: the integration of novel biocompatible (lead-free piezoelectrics, functional polymers) or bio-sourced materials (cellulose based polymers, natural hydrogel materials) will allow building artificial environments (scaffolds for cell culture, organ-on-chip, microfluidic devices for tissue regeneration) and implantable devices (neuroelectrodes or devices for rare cell capture), with a dramatic improvement of their capacity to be accepted for long term by living organisms (e.g. cell growth, implant, etc).

CHALLENGE#5. SENSORS, IoT AND MICRO-ENERGY

Over the past decade IoT concepts have been implemented based on physical data given by on-the-shelf sensors, electronics and data processing. However, several domains (including science experiments, exploration and industry) are excluded from IoT because they lack high-end, compact sensors that are able to work in complex environments. This includes harsh conditions - temperatures, accelerations, corrosive environments - but also situations where small dimensions or fabrication constraints make sensor insertion and dense sensor networks unfeasible. Moreover, current performances (sensitivity, bandwidth, range) of sensors are not high enough for both reliable metrology and fast dynamical monitoring, nor can they be assembled in network allowing rapid field mapping.

Research goals Our objective is to provide small sensors for instrumentation beyond the current limitations. These micro/nano system sensors target 'outside the lab' operation with miniature packages (1mm), compact signal chains and autonomy. One key is the use of specifically developed wide bandgap materials for MEMS: poly-diamond, poly-SiC, GaN. Another important target is to use collective fabrication and scalable design strategies that take advantage of silicon/SOI wafers hosting these materials. This will enable miniature devices with high performance transducers and compact packaging. Our goals include:

- high range, high sensitivity inertial sensors (R>+/-1000g, S<100ng), temperatures from 250° to 800°C.
- force sensors able to sense 10fN with 10MHz bandwidth, and NEMS magneto-opto-mechanical sensors able to replace SQUIDs for magnetic field imaging without cryogenic environment
- microelectrode-based sensors/chemical sensors taking advantage of diamond large electrochemical window (3 times better than Pt technologies), high Young's modulus and stable up to 850°C.
- To address novel environments with ultra-tight spaces, we also plan to develop the concept of 'process embedded sensor'. This approach includes:
- sensors based on flexible or ink-based technologies, directly printed above IC or inserted during macroscopic additive manufacturing schemes.
- ultimate micro-energy devices for powered or self-powered sensors (objective: $E = 50$ $mWh.cm^{-2}$, $P = 100$ $mW.m^{-2}$). Combined with printed technologies, this will unlock lifetime sensor data production from many industrial components, parts, and structures.

Nanofabrication technology requirements. These new generations of sensors will require the mastering of not only materials but also process integration. Our approach is to purchase key equipment, which will complete existing capabilities, to set up 2 fabrication lines able to handle up to 10 mask levels. These pilot lines will be highly pooled: addressing both labs at TRL 2-4 and industrial partners at TRL>4, they will enable testing original micro-sensor designs with 3 novel materials and allow faster industrial transfer.

CHALLENGE#6. NANO-MANIPULATION AND NANO-ASSEMBLY

The emergence of 2D materials and more recently van der Waals heterostructures has opened a new realm where the physical properties can be tailored at will by assembling monolayer materials. To go even beyond, this assembly engineering could be further extended to colloidal or organic heterostructures (quantum nanoplatelets, perovskite nanocrystals, quantum dots…), ultimately offering an extended portfolio of low dimensional materials designed at the nanoscale.

Research goals Our objective is to unleash the full potential of low dimensional materials that will be at the basis of the next generation of devices addressing some of the challenges presented in the next items. These ultimate stackings at the atomic scale offer unprecedented perspectives to study fundamental transport issues in nanoelectronics, building the next generation of transistors, neuromorphic-compatible chips, or to develop photonic integrated circuits with locally enhanced capabilities (quantum, collective, nonlocal…).

NANOFABRICATION TECHNOLOGY REQUIREMENTS. The next frontier is to address and leverage the multiscale dimension offered by these structures. We propose to tackle this issue with a three-pronged approach involving nano-manipulation and nano-assembly, combining wafer-scale epitaxy, sub-micro and micro-scale transfer printing and bottom-up nano-scale additive manufacturing. More specifically, we will set up a nanomanipulation and assembly process line mixing van der Waals heterostructures, organic and colloidal materials, and 3D heterostructures. These will be combined using epitaxy, bottom-up approaches and assembly through transfer.

I.3.4 Structure and building of the equipment

The equipment requested in NANOFUTUR will be distributed over **13 sites** in France (Fig. 4), mainly in the 5 large RENATECH facilities (C2N, LAAS, FEMTO-ST, LTM and IEMN) but also in 8 regional and specific facilities (XLIM, MPQ, CRHEA, IMS, ESYCOM, FOTON, SPINTEC and INL). These key pieces of equipment will complement existing cleanroom equipment to tackle the six challenges highlighted above. Each partner laboratory will contribute engineers and researchers to the most relevant challenge. For each of the challenges, the following table lists the laboratories, their locations, the label of the requested equipment, its cost and relation to existing equipment.

NANOFUTUR members: in white the 5 RENATECH facilities. Yellow dots: 8 regional facilities

KEY EQUIPMENT FOR RENATECH+ ADVANCED PROGRAMMES						
	SCIENTIFIC PROGRAMME		**Laboratory** location	Equipment names	Relation to existing equipment*	Budget (M€)
1	ADVANCED PHOTONICS & SOLAR ENERGIES	**1.1**	**C2N,** Palaiseau	Oxide Metalorganic (MO)-MBE	NE	1.3
		1.2	**INL,** Lyon	Advanced Oxide MBE	RE	1.25
		1.3	**FOTON,** Rennes	Gas source MBE III-V on Si	RE&EE	1.15
		1.4	**FEMTO-ST,** Besançon	Multisource ion (FIB) system on nanolithography platform	NE	1.25
2	SPINTRONICS	**2.1**	**LTM/ SPINTEC,** Grenoble	Sputter deposition cluster RIE etching cluster	NE	1.9+0.869
		2.2	**C2N,** Palaiseau	MBE topological	NE	0.6
3	THz TECHNOLOGIES	**3.1**	**IEMN,** Lille	PVD deposition reactor ALD and Etching cluster	EE	1.5
		3.2	**XLIM,** Limoges	3D metal nano-printer	NE	0.7
4	NANOBIO TECHNOLOGIES	**4.1**	**LAAS,** Toulouse	3D laser lithography, structuration, printer High Aspect-ratio electroplating Wafer bonding / Flip-chip Interferometer	NE	2.3
		4.2	**FEMTO-ST,** Besançon	Laser ablation & assisted CVD	NE&EE	1.35
5	SENSORS, IoT & MICRO-ENERGY	**5.1**	**IMS,** Bordeaux	3D printer for printed sensors	NE	0.3
		5.2	**ESYCOM,** Marne-la-vallée	Reactor for Diamond with Boron doping	NE	0.4
		5.3	**IEMN,** Lille	Reactor PECVD of SiC/Si/SiN	NE	1.2
6	NANO-MANIPULATION AND NANO-ASSEMBLY	**6.1**	**C2N,** Palaiseau	Micro-transfer-printing station	NE	0.3
		6.2	**MPQ,** Paris	Bottom-up & maskless nanofabrication	NE	0.9
		6.3	**CRHEA,** Valbonne	MBE-CVD cluster for 2D & VdW materials	NE	1.25
* NE: new equipment, EE: extension of existing equipment, RE: replacement of existing equipment.						**18.5**

Table. 1 - List of necessary equipment for RENATECH+ advanced scientific programs

For each challenge, details on the requested equipment are given below:

ADVANCED PHOTONICS & SOLAR ENERGY

1.1 Oxide Metalorganic (MO)-MBE. This equipment allows the growth of stoichiometric oxides at rates significantly higher than those of competing techniques, while preserving sharp (MBE-grade) interfaces between different layers. Selective-area growth is possible in a dedicated UHV-CVD mode, taking advantage of the nanostructuration (e.g. of a SiO2/Si template) and of the chemistry of the MO precursors. This MO-MBE will be the first equipment of this type in France for the fast growth of epitaxial oxide films. This technique, originally developed in the USA, with a number of breakthroughs over the past 10 years, with most notably that of demonstrating the highest film quality and very recently demonstrating the growth of thick oxide films on silicon, is a milestone for photonic applications. Several MBE manufacturers can provide MO-MBE systems, with the technological maturity stemming from the USA market.

1.2 Advanced Oxide MBE. Advanced in situ control & source optimization (Knudsen cells, e-beam & original strategies for oxygen injection and active flux control) for beyond state-of-the-art oxide thin films and superlattices, structured down to the monolayer scale on Si or III-V. Prototype designed in the framework of the INL-RIBER joint laboratory. This custom-built equipment will implement numerous innovations, and in particular a unique sensor for active in-operando control of growth rates and material composition, an original reactor geometry for oxygen injection, and load protection against oxidation, enabling a level of control of the growth unrivalled at the international level. It will allow users to accurately tailor the optical and thermoelectric properties of their oxides with unprecedented flexibility.

1.3 Gas source III-P MBE on Si. Hybrid integration of III-V structures on Si, using an industry-grade cluster, the first in French academia for integrated phosphorus-based III-V devices. This 3" gas source III-P MBE will be designed jointly with the manufacturer. With its high temperature Si and H* plasma preparation chambers, it will provide a unique opportunity in Europe to transfer state-of-the-art MBE-grown hybrid photonic or energy harvesting III-P/Si devices to other academic and industrial partners or to other technological platforms.

1.4 Multisource ion (FIB) system on nanolithography platform. This system will allow for the fabrication and nanomanipulation of multifunctional 3D nanodevices with high controllability and repeatability. The system combines several advantages: improved and contamination-free FIB milling of both Si and III-V compounds over large areas; simplified and robust workflow for the rapid prototyping of hybrid photonic devices; single-ion implantation offers additional route for on-chip integration of single-photon sources. A « VELION » focused ion-beam deposition/etching/implantation system (only the second of its kind in Europe, according to the RAITH company) will enable - for the first time in France - the complete fabrication in the same machine of ultracompact architectures comprising plasmonic and photonic nanostructures combined with deterministically positioned single photon sources

SPINTRONICS

2.1 Manufacturing line for advanced Spintronics. **Sputter deposition cluster**: two connected deposition modules of ten targets each, co-evaporation and state of the art magnetic tunnel junctions, address the increasing complexity of multifunctional spintronic stacks up to 200mm wafer. Combined with a heated sample holder and in-situ annealing, the cluster addresses challenges in the growth of new materials with high spin polarization and low damping for both more efficient and novel spintronic devices. **RIE etching cluster**: it will be designed for several soft chemistries specific to magnetic materials, on which LTM has an extensive expertise. The cluster will also allow for in-situ encapsulation of the sidewalls to protect them against oxidation and corrosion, specifically required by the magnetic tunnel junction technology.

2.2 MBE cluster will be specially designed to grow heterostructures combining topological, ferromagnetic and/or superconductive materials with perfectly abrupt interfaces and high crystal purity. This cluster will be unique in Europe for provision of high mobility structures and offering model systems to investigate numerous theoretical proposals of physics and practical applications of topological insulators for spintronic devices.

TERAHERTZ TECHNOLOGIES

3.1 THz nanofabrication line. **A semi-industrial PVD chamber**, with high up-time, multi-cathode for high purity metals and in-situ analysis along with standardized processes will allow users to go beyond standard conventional laboratory PVD tools and obtain high purity thin metal films on 4-inch wafers. This equipment is key in reducing contact resistances, the major bottleneck in compact devices. **Atomic Layer Deposition & Etching 4-inch cluster:** (i) a plasma etching chamber for standard processes and atomic layer etching (ALE) allowing for low damage etching of nano heterostructures, (ii) an atomic layer deposition chamber (ALD) for high-quality side-walls passivation layers. This equipment will be the last link that will complete a unique fabrication line in France for the development of next generation THz devices.

3.2 3D metal nano-printer. Full-3D structures are required for the realization of micro/nano antenna arrays or for integration and interconnection of sub-millimeter and THz subsystems, which can only be obtained with a 3D nano-printer. This approach is completely unprecedented in the European landscape, where conventional deposition and etching techniques are heavily relied upon. This equipment belongs to a new generation of sub-µm scale 3D printers. In contrast to polymer 3D structures technologies (see https://www.nanoscribe.com/en/), the targeted nanoprinter (https://www.exaddon.com/) is able to print with sub-micron accuracy 3D shapes in metal directly (without additional coating step). Direct manufacturing 3D complex shapes in metal (Cu, Au, Ag…) is rather unique and provide huge benefits in terms of accuracy, resolution, and conductivity of materials, while keeping the freedom of design expected from additive manufacturing. To the best of our knowledge, this equipment will be the first available in France and the second in Europe (Germany) dedicated to RF applications.

NANO-BIOTECHNOLOGIES

4.1 Nanofabrication line for life science. A fabrication line dedicated to multilevel and 3D architectures based on biocompatible materials will be composed of the following elements:

Microfabrication & micromachining for life science

3D Laser lithography and laser ablation micromachining: these high-resolution 3D machining systems will allow users to create complex 3D architectures (cantilevers, buried microfluidic channels, membranes) in glass, biocompatible polymers (hydrogels, bio-sourced material), metals or photosensitive sol-gel materials with a sub-micrometer resolution and create architectures with controlled topology for cell culture, microfluidic 3D structures and integrated electrodes.

High aspect ratio electroplating: combination of 3D fabrication technologies with a specific electroplating reactor devoted to high aspect ratio structures growth, will enable use for implantable metallic devices (e.g. implantable filtering devices for rare cell capture), 3D sensors (e.g. electrodes for in vivo sensing) and electrical interconnection in multilevel devices.

Integration & assembly

Wafer bonding will be complementary to laser ablation and laser micromachining to provide glass devices integration in silicon/glass microfluidic channels and manifolds.

Flip-chip equipment will enable integration, assembly and interconnection of fabricated devices to holders, microfluidic structures and multilevel electrical interconnection systems.

3D imaging & characterization

Interferometer for non-contact profilometry and dimension analysis of 3D devices.

4.2 Laser ablation & assisted CVD. This 3D microfabrication equipment uses CVD/ALD assisted by a UV or fs-laser, to grow locally electroactive lead-free ceramic layers such as KNN (a lead-free piezoelectric material as efficient as PZT), functional oxides, nitrides and noble metals (TiO_2, ZnO, Pt, AlN, etc.). Laser ablation in the same chamber will allow users to transform these dielectric/piezoelectric/metal structures into full-3D micromechanical structures with submicron (~300 nm) lateral resolution. In short, this new tool allows for the direct microfabrication in the same chamber of complex 3D multi-materials structures - complete micro actuators for micro-robotics, for instance. The equipment will be built to design with a manufacturer and will be a unique instrument in Europe, capable of fabricating ready-to-use micro-actuators (including their connectors) on 3D micro-mechanical structures.

SENSORS IoT & MICRO-ENERGY

5.1 Additive microfabrication for printed sensors. To enable the fabrication of sensors in tight spaces and on complex shapes, including full-3D parts, equipment dedicated to the micro/nanoprinting of materials will be acquired and improved for non-flat substrates. The modifications include soft and hard upgrades of two-photon laser lithography and maskless photolithography commercial equipment to enable direct writing of polymer and hybrid materials and to take into account the shape of substrates before fabrication. Additive processing will also reduce the environmental impact of micro/nanofabricated sensors as well as their fabrication cost.

5.2 Reactor for Diamond with Boron doping capability. Diamond material is not conventional in microelectronics, but its intrinsic properties make it very attractive for many applications. The development of diamond for research and industrial applications requires the setup of a pilot line in a clean-room environment along with standard micro-machining processes and materials to be able to combine classical semiconductor technology and diamond material. This equipment will complement existing equipment to enable the usage of diamond (intrinsic and doped) instead of silicon to achieve new sensors. This equipment will specifically be used for chemical vapor deposition of diamond with in-situ insertion of boron, and will enable conformal coatings on patterned silicon. It will be a unique tool in France and Europe where researchers and industrial partners will find all ecosystem to develop their diamond sensors.

5.3 Reactor for Plasma Enhanced CVD deposition of SiC/Si/SiN. In contrast to epitaxy (MBE, MOCVD), the tool targets (i) the engineering of polycrystalline materials with low stress, and (ii) carbide heterostructures conformal growth on high aspect ratios features (up to 100:1), retaining capabilities only known in ALD techniques but with too thin layers for sensors processing. The maturity we target is to be able, within 5 years, to master these poly-heterostructures as a reliable brick in TRL above 6 for researchers and industrials willing to integrate them into their process. This equipment will enable users to engineer polycrystalline mechanical and optical materials required for MEMS in harsh environments and micro-energy sources. The tool is crucial to the development of multilayers and poly-heterostructures: SiC/Si, SiC/AlGaN/GaN/Si, SiC/C=C, each having new advantages: high velocity of mechanical parts, yield strength increased above 250°C, hardened surface passivation.

NANO-MANIPULATION & NANO-ASSEMBLY

6.1 Micro-transfer-printing station. A Micro Transfer Printing (MTP) equipment will allow the formation of van der Waals heterostructures not directly compatible with epitaxy, and more importantly their transfer onto non-native host substrates, with a scalability from the transfer of unique structure at predefined location to a collective, wafer-scale, transfer/ stacking process. It will be a unique tool for the fabrication of 2D heterostructures free from surface contamination, and posing the capability to orient 2D layers “at will”, a feature of great importance for the development of topological electronics, and of new functions in PICs (Photonic Integrated Circuits). MTP was initially developed for the hybridization of III-V devices on ICs/PICs with first commercial stations released from ~2016, but it has a great potential for the transfer of van der Waals materials and the fabrication of 2D stacks. MTP allows the handling of µm-size to mm-size flakes, with controlled position/orientation between 2D layers. There is no MTP station in France, and only few systems installed in Europe to our knowledge (Cork Univ. & Tyndall Inst. - Ireland in relation with X-Celeprint, and Ghent University-Belgium). This MTP station will be modified to offer transfer of layers under controlled atmosphere and controlled substrate temperature. A specific stamp technology will be developed to avoid surface contamination during the transfer and stacking of several layers.

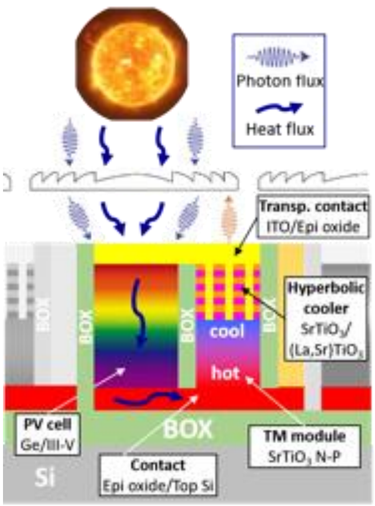
6.2 Bottom-up & maskless nanofabrication platform. A 3D printing tool with a resolution in the tens of nanometer, i.e. much below the microscale resolution usually available, will be a crucial pillar of our infrastructure and will be used to process colloidal and organic nanostructures. It will thus lift the main roadblocks of the community for exploring and exploiting the physics of nanodevices (defining clean and abrupt interfaces down to a few atoms, addressing individual nanocrystals). The platform will consist of an inert atmosphere environment for the fabrication of devices based on nanocrystals, molecules and 2D materials. These materials are subject to oxidation and are hard to shape with lithography. The platform will include new technologies tailored to handle 2D materials. One key feature will be the ability to print 2D materials with a resolution of 20 nm, i.e. 100 times better than anything currently existing in the world. It will allow users to print stacks of nanostructures without worrying about material compatibilities and alignments.

6.3 MBE-CVD cluster tool for 2D materials & vdW heterostructures. We plan to go beyond the standard approach to fabricate van der Waals (vdW) heterostructures, i.e. exfoliation and manual stacking, by developing an MBE-MOCVD cluster tool that will allow us to select the best growth conditions to engineer sharp interfaces between various 2D layers, including graphene, h-BN, and TMDs. Growth of 2D materials is usually performed either by CVD or by MBE. The cluster tool will allow one to combine both techniques, using their specific advantages (e.g. sharp interfaces, high purity materials with MBE, versatility of materials, industrial transfer perspectives with CVD) and complementarity depending on material choice in order to fabricate innovative 2D materials and vdW stackings. MBE and CVD reactors will be connected through a chamber under controlled atmosphere. This cluster tool will be unique in France.

I.3.5 Potential to generate ambitious projects & complementarity

To showcase the originality, breadth, and variety of benefits from NANOFUTUR, 8 ambitious projects are described below, highlighting what can be done with potential partners and the help of the requested equipment:

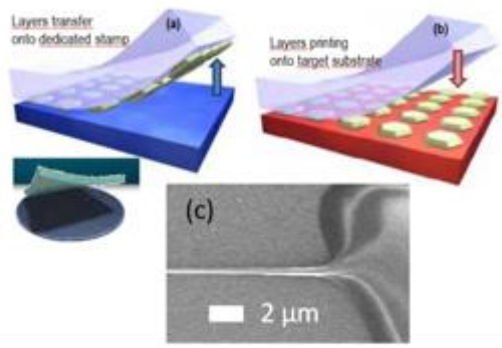
Combined Photovoltaic-Thermoelectric energy harvester integrated at device level (INL, FOTON, C2N, FEMTO-ST, CRHEA, CETHIL, ILM, RIBER, IPVF, CEA, IMEC, IBM/Lumiphase)



PV-TM harvester epitaxied on SOI: lenses focus sunlight/ heat on PV cells and heat is channeled by boxes to the hot side of the TM module. Nanostructured oxide hyperbolic metamaterial ensures radiative cooling of the TM cool side.

Combining photovoltaic (PV) and thermoelectric (TM) energy harvesting is very efficient at the **macroscopic** scale. We propose the first demonstration of a **nanoscale** PV-TM energy harvester, for local renewable energy production at device level. This may be a breakthrough for self-powered IoT devices in which major actors (IME, IBM…) invest considerable effort. Integration will also enable implementing novel designs (e.g. for radiative cooling) for unrivalled performances. The unique advantages offered by the combination of the gas source MBE for III-V on Si, advanced Oxide MBE and multisource FIB system will allow us to face the challenge of integrating by epitaxy a Ge/III-V multijunction solar cell, an oxide thermoelectric micromodule and an oxide superlattice based hyperbolic metamaterial structured in photonic crystal to boost performances thanks to radiative cooling. The project will involve NanoLyon, NanoRennes, C2N and FEMTO-ST from the NANOFUTUR consortium and federate actors of energy harvesting, at the national (IPVF, CEA, CETHIL, ILM, CHREA, Institut d'optique, III-V lab) and international level (partners of former EU projects in this field, such as IBM Zürich, Tyndall, IFW, IMB-CNM, DUT, Univ. Gröningen, MESA+ Institute).

On-chip photonic integration with nanoscale materials (C2N, MPQ, CRHEA, FEMTO-ST, UMI GT, ONERA/LEM, ESPCI, INSP, LP2N, LPENS, L2n, IPVF, Thales R&T, PSA, STMicro, Hong Kong uni., MIT)

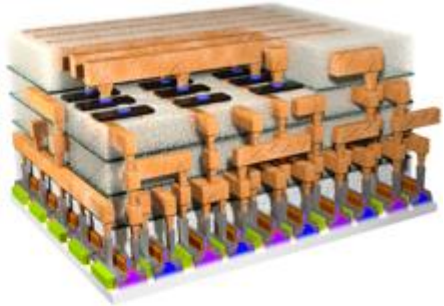


(a,b) Accurate release-and–transfer of 2D materials (courtesy X-Celeprint Ltd), (c) Submicron additive printing for superradiant 0D-2D devices (courtesy nano3dprint)

Low-dimensional materials hold great promise for photonics, e.g., (quantum) communications, integrated sensing from the visible up to the far-infrared range, and the future of human machine interfaces. Most of the heralded properties of 2D layers and colloidal nanostructures stem from their interfaces, because their surface/volume ratio is larger than conventional materials. These interfaces, though fragile, are host to informal of novel phenomena that give rise to innovative devices (e.g. novel excitons in moiré heterostructures). **In this context, the challenge that we will address is the demonstration of integrated devices that do not destroy the rich interface physics of low-dimensional materials.** We will demonstrate (i) silicon-based photonic integrated circuits (PICS) with encapsulated optically-active 2D layers for NIR to mid-IR detection and on-chip generation of frequency combs; (ii) integrated single-photon sources at room temperature based on perovskite nanocrystals and (iii) sources and detectors of coherent but non-lasing superradiant states based on the combination of 0D objects (for electron/photon conversion) and 2D layers (for establishing the coherence through long-range correlations). These feats require tools that are currently lacking in the French academic and R&D landscape; the tools proposed for the nano-manipulation and nano-assembly platform will guarantee reproducibility, especially at the crucial level of the interfaces, and defect-free fabrication in controlled environments.

The synthesis of 2D layers will involve CRHEA, C2N, LEM/ONERA, and UM GT-Lorraine while ESPCI and INSP will be involved in advanced colloidal synthesis. The design of PICS will be done by C2N with inputs from Hong-Kong University, MIT and LP2N. LPENS will coordinate the developments of single photon sources and MPQ will lead the superradiance thrust. Processes developed at CRHEA, C2N and MPQ will be compared to other techniques explored at UMI GT-Lorraine, at ONERA, and FEMTO-ST. Potential applications will be reviewed by TRT, STMicro, PSA and IPVF.

SOLARIS: SpintrOnics based uLtrA-low poweR bio-inspired electronIcS (SPINTEC, LTM, C2N, UMPhy CNRS-Thales, IJL, ETH Zurich, ICN, LIRMM, IM2NP, KIT, FRAUNHOFER, SYNOPSIS, SpinIon, Hprobe, Crocus, ANTAIOS)

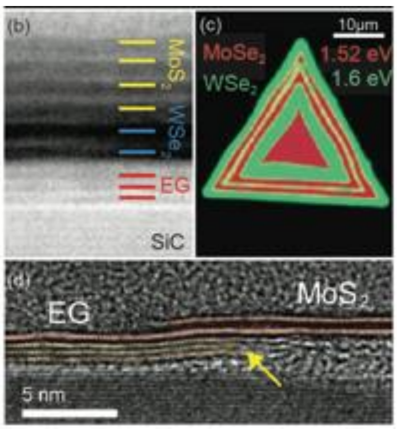

Hybrid CMOS-spintronic chip array for neuromorphic computing

Since its birth in Europe in the late 1980s, spintronics has been an extremely vibrant area of research, development and applications, this dynamics being mainly driven by several scientific breakthroughs in which teams and labs from France have been at the forefront. Thanks to the intrinsic non-volatility of nanomagnets and their compatibility with CMOS processes, spintronics can bring massive embedded memory to unconventional circuits and generate novel physical effects for brain-inspired computing, such as tunable fast non-linear dynamics, controlled stochasticity and multifunctionality. Spintronics promises both immediate gains and long-term groundbreaking changes in processor core and system architectures.

The main objectives of the SOLARIS project are the following:

- to decrease by thousand-fold the energy cost of Artificial Intelligence (AI): Spintronics is the ideal platform, exploiting intrinsic non-linearity, time nonlocality hysteresis, and stochasticity of magnetism.
- to boost “spin-charge interconversion”, a key for low-power communication, as well as a paradigm-shift in logic such as the. MESO Intel concept, with the potential to reduce the switching energy per bit to near thermodynamic limits for GHz logic (60 k_BT/bit switching at 100 ps delay). The proposed academic spintronic pilot line brings breakthrough specifications for innovative spin-based devices with unprecedented high reproducibility and the tight tolerances required for practical manufacturing. This can be realized only by integrated deposition and etching clusters, not available so far in the French academic environment. The project will directly benefit from the complementarities between the partners in spintronics (SPINTEC, UMPhy CNRS-Thales, C2N, ETH Zurich, IJL, …), material etch (LTM, …), circuit design (LIRMM, KIT, SYNOPSIS, …) and industrial partners for dedicated applications (ANTAIOS, SpinIon, Hprobe, Crocus). Beyond this consortium, the platform will be opened to outside users from the academic or industrial worlds. A strong structuring effort has been made in recent years both in France and at the European level (SpinTronicFactory) to establish a consortium of complementary skills in the field of spintronics. The universities / research centers will benefit from the versatility and the uniqueness of the upstream research system, while research centers involved in circuit design and test will find a way to test their ideas as they usually do with classical semiconductor devices through multi-project wafers with leading semiconductors foundries.

Next generation electronic devices with van der Waals (vdW) heterostructures (CRHEA, C2N, MPQ, IMS, IEMN, LPENS, LPCNO, IPCMS, NEEL, CEA-IRIG, STMicroelectronics, SOITEC, RIBER, AIXTRON, ANNEALSYS, CNR-IMM)

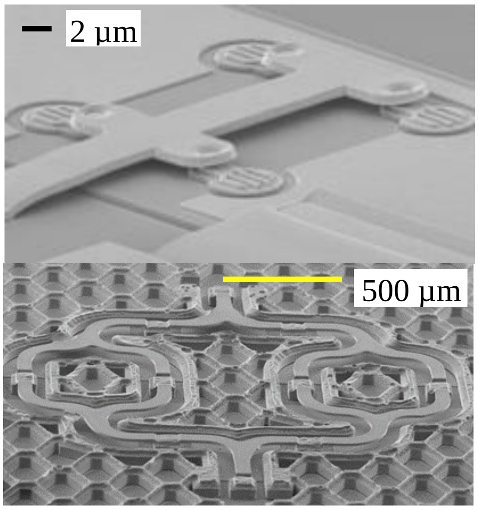


Examples of 2D heterostructures. From Briggs et al., 2D Mater. 6 (2019) 022001

Integration of 2D materials and vdW heterostructures for electronics applications has become a hot topic. A roadmap for electronic grade 2D materials has been recently presented. The identified challenges are the development of proof-of-concept devices and how they could complement or improve existing Si-technology. **The objective of this project is to demonstrate advanced electronics devices with 2D and vdW heterostructures**. We will address synthesis of heterostructures, contact, doping, mobility, defect control, engineering of interlayer couplings and intercalation, as well as the integration of 2D materials with 3D structures. Transistors and high-frequency devices will be developed to optimize post-CMOS ultrafast devices (post 6G). The MBE-CVD cluster tool for 2D material growth at CRHEA combined with the micro-transfer tool at C2N will allow investigations into innovative material combinations using TMDs, h-BN or graphene and to engineer optimized interfaces, with the ultimate goal of achieving superior performances. Device processing using these multilayer materials will be done within the

RENATECH network. Beyond proof of concept and prototyping, we will develop a strategy for integration with our industrial partners. By building a long-term vision, possible routes to lead vdW heterostructures to industrial maturity will be explored, either for internet of things, flexible electronics, back-end of CMOS lines, or post-CMOS electronics. CRHEA and C2N will contribute their expertise in materials growth. MPQ, C2N, and IEMN will be in charge of advanced processing and electrical characterizations. LPENS, LPCNO, IPCMS, NEEL, CEA-IRIG and CNR-IMM are among the best international experts to investigate the properties of these heterostructures. A study led by IMS will be dedicated to reliability. STMicroelectronics and Soitec will provide guidelines for the heterogeneous integration of vdW heterostructures, either in lateral, vertical or FinFET architectures and cluster tools manufacturers (Riber, Aixtron, Annealsys) will also be involved.

Solid-state/photonics-based high-power THz devices and Interconnects for next generation wireless communications (IEMN, XLIM, FOTON, C2N, CRHEA, IETR, IES, LERMA-Paris Observatory, Rohde & Schwarz, OMMIC, MC2 Technologies, ST Microelectronics, Univ. Nice, iXBlue, V-Micro, Lytid, T-WAVES Technologies, AIRBUS, AIRMEMS, Thales Alenia Space, Ghent Univ.-IMEC, Thales TRT/DMS, Fraunhofer HHI Berlin)



(a) 4-elements array of THz photodiodes (IEMN)
(b) 3D THz interconnects (XLIM)

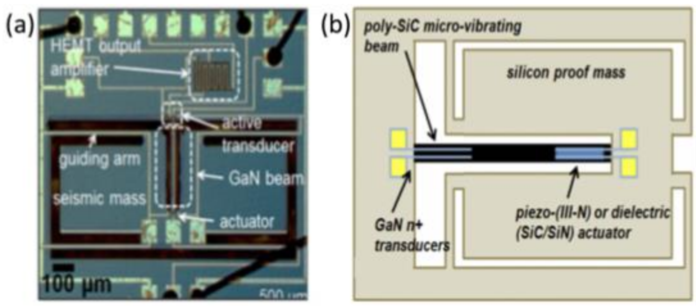
By 2030, the THz spectrum will be explored for 6/7G to support the data traffic increase, mainly on wireless channels. The size of THZ sources should be a few 100 nm while keeping excellent access resistances. Current ICP dry etching or PECVD oxide tools strongly limit the surface state quality and degrade access elements for all THz devices (diode, photodiode or transistor). A new PVD tool will enable reaching 100 nm / high aspect ratio devices, by depositing highly pure & dense metals, with high-resolution, abrupt interfaces, low-damage and contamination-free surfaces. Then, etching by using an ALE tool with a precision of a few monolayers will also provide very low surface damage for the contact layer and the device edges, lowering leakage currents. This will enable a 10-fold increase on source power and receiver, which ends-up with a **100-fold gain** on the complete system. **Moreover, future THz subsystems will also rely on the development of low-cost, flexible, THz integration platforms**. Interconnecting chips and building passive components (like antennas or transmission lines) are key aspects for the successful development of this technology that XLIM will address with stacked layers stemming from micromachining technology. Core devices from IEMN (InP/InGaAs UTC photodiodes, GaAs photoconductors and GaN Schottky diodes) integrated by XLIM will position the NANOFUTUR consortium as a world-class leader in the field of THz subsystems. Among external partners we can cite mm-wave/THz noise sources (ST Microelectronics, Rohde & Schwarz), high-power THz sources (Thales, Lytid), satellite-to-satellite applications (AIRBUS) and the Jet Propulsion Laboratory (NASA) for new generations of GaN Schottky-diodes.

Development of 3D microphysiological systems (MPS) for colon cancer diagnosis (LAAS, FEMTO-ST, CRCT, StromaLAB, IRSD, IPGG, Fluigent SA, Microresist)

Microphysiological Systems bridge the gap between traditional in vitro cell culture, animal models, and patient samples

The failure of pre-clinical cell culture and animal models to predict drug safety and efficacy in humans impedes the development of treatments for patients and the understanding of the biological processes at the origin of pathologies. The engineering of new model systems devoted to the diagnosis, analysis and modelling of living systems is thus a strategic objective in the field of life science. The combination of microtechnologies and microfluidics has opened new routes for the development of Microphysiological Systems (MPS or « organs-on-chips ») that provide new in-vitro models to mimic the key physical, chemical and biological cues of living tissues found in vivo. Our aim is to focus on the etiology of inflammatory bowel diseases (IBD) and colon cancer which is the second cause of death by cancer worldwide. We wish to develop an integrated MPS combining 3D architectures mimicking the specific intestine and colon morphology, microfluidic perfusion, mechanical actuation and in situ sensing capabilities to control dynamically culture condition and monitor tissues in physiological, inflammatory (IBD) and pathological (cancer) condition. LAAS CNRS will address the challenges imposed by MPS development by implementing new high-resolution 3D new laser ablation and 3D printing techniques adapted to biocompatible materials and novel flip-chip systems permitting the integration of sensors in microfluidic culture chambers for metabolism monitoring. Development of the microfluidic device design will be done in collaboration with FEMTO-ST and Institut Curie/IPGG (RENATECH+ network). Microresist GmbH will provide its expertise in material development. Stromalab, IRSD and CRCT, experts in the fields of organoid models and cancerology, respectively, will provide their expertise in cellular models. Fluigent SA will promote the industrial transfer of MPS as in vitro device for medical applications.

MEMS multi-sensors for combined measurements in harsh environments (IEMN, ESIEE, IMS, FEMTO-ST, CRHEA, C2N, ONERA, Vmicro, SENSECITY, CEA-List, SCHLUMBERGER)



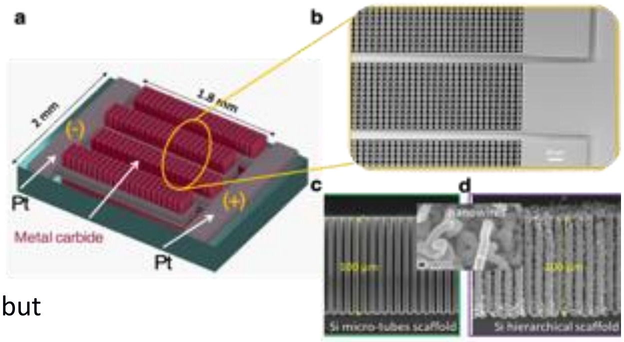
Concept of a vibrating inertial sensor based on SiC and wide bandgap materials for extreme environments (a) first GaN/Si MEMS accelerometer (b) future SiC based architecture for High Temperatures operation.

The proof of concept micro-resonators and transducers based on wide bandgap nitride heterostructures have opened the path toward new hybrid MEMS sensors able to work at very high accelerations (100-1000g). The next challenge is to combine such ranges with temperatures above 250°C. However, nitrides alone cannot fit the MEMS or NEMS requirements since many obstacles are present with the epitaxial approach (dislocations, substrate dependent stress). Polycrystalline **silicon carbide** and **diamond** appear to be more promising, especially because they keep a large Young modulus at high temperature. **The objective is to demonstrate MEMS/NEMS multi-sensors (accelerometers, flow hot-wire sensors and gravimetric sensors that keep their performance in combined harsh conditions (high g, high T, corrosives/toxic**

gases). The « Reactor for Plasma Enhanced CVD deposition of SiC/Si/SiN » and the «CVD reactor for boron doped diamond» will enable to engineer materials not accessible to standard approaches. For example, SiC has a high acoustic velocity, enabling high-frequency mechanical microstructures and by using SiC/SiN/C=C poly-heterostructures combined to silicon, mechanical stress will be managed to increase the temperature range of vibrating sensors like the architecture of fig 11. Finally, doped diamond will unlock new piezoresistive/piezoelectric concepts for implementing the transducers.

Next generations of micro-energy sources based on wafer level fabrication strategies. (IEMN, LAAS, INL, IMN, CIRIMAT, ICGM, UCCS)

IEMN and coll. have demonstrated the fabrication of high energy density Li-ion micro-batteries (MB) and high-power micro-supercapacitors (MSC), which are required for powering future sensors and emerging IoT microdevices (Fig 12). MB offer high energy (1 mWh cm^{-2}) and moderate power densities (0.5 mW cm^{-2}) and MSC are particularly attractive for high power applications (> 10 mW cm^{-2}) but suffer from a lack of energy density (< 0.1 mWh cm^{-2}). To reach values above 50 mWh cm^{-2}, while keeping high the rate of the miniaturized energy storage devices, a new paradigm for the fabrication of 3D miniaturized batteries and super-capacitors is needed (fig. 12a-b). Here we propose to combine hierarchical 3D scaffold made from top down and bottom up approaches with metal carbide films deposited by CVD or (PE)-CVD. The corresponding area enhancement factor (AEF) of the 3D scaffold moves from 50 for straight Si micro-tubes (fig. 12c) to a value of 1000 (fig. 12d) for the hierarchical template. Metal carbide is a class of material suitable for microelectronic applications (sensors, actuators) and for miniaturized electrochemical capacitors. Those films are not only attractive for academic and industrial partners working in microelectronics but also for those involved within the energy storage community such as the RS2E and the Store-EX labex, where IEMN is a key leader able to make the connection between microelectronic and energy storage communities. Titanium carbide (TiC) is one of the best precursors used to fabricate carbon-derived-carbide (CDC) nanoporous electrodes for MSC. The TiC film is transformed on nanoporous carbon electrodes based on a recently reported process for planar MSCs. TiC films could then be deposited on 3D scaffold by ICP PECVD, allowing - for the first time - the fabrication of 3D MSCs based on nanoporous carbon (CDC) electrodes.



(a): Electrochemical Energy Storage miniaturized devices based on 3D interdigitated electrodes coated with metal carbide films (b) zoom on the 3D Si micro-tubes (c) and (d) New paradigm shift from Si straight micro-tubes to 3D hierarchical scaffold

I.3.6 Opportunities

New technical capabilities and expertise stemming from NANOFUTUR will foster new academic/ industrial partnerships, leading to more publications, patents and technology transfer to the industry:

For **Photonics**, NANOFUTUR will enable the co-integrating of different materials (e.g. III-V semiconductors or functional oxides) on silicon - a major technology challenge – for academic projects such as optical neural networks, solar energy harvesting or quantum nano-systems. Hydrid III-V/oxide devices on Si will also attract the interest of companies already working with the consortium: THALES, ALMAE, 3SP, LUMIBIRD-SENS'UP or SILTRONIX for photonic processing and AIR LIQUIDE, EDF & TOTAL for solar energy.

For **Spintronics**, a quantum leap is expected through the access to new classes of materials, stemming from exploration of new materials/nanostructures with proper growth control to optimize lattice matching between layers. Academic users will use this opportunity for improving non-volatile spin transistors with atto-Joule switching energy, reconfigurable metamaterials for high-frequency signal processing, innovative neuromorphic architectures or quantum processors using spin qubits. Together with companies like CROCUS, spintronic sensors will be further improved (e.g. signal-to-noise ratio) for electric cars or health applications markets. With ANTAIOS, HPROBE and SPIN-ION, the integration of magnetoresistive memories into CMOS circuits will dramatically decrease the power consumption for computing. The global environmental impact may be huge since a 1000-fold energy consumption decrease is possible for all electronic devices. Radio-frequency spintronics (with NANOSC) may lead to embedded devices for RF signals processing at nW levels, for on-chip communication. Improved magnetic sensors, ultralow power memories and spintronic based wake-up receiver functionalities for the IoT market may attract interest from ST-Microelectronics, SOITEC, EM Marin or TRONICS.

For **THz Technologies**, NANOFUTUR will build a unique expertise in Europe for the fabrication of sources/detectors and their hybridization to waveguides/antennas for demonstration of new THz communication or imaging systems. End-user laboratories working in many different fields (e.g. terrestrial/space communications, radar-based environmental monitoring or medical imaging, etc.) may then use the technology to experiment specific building blocks (modulators, beam forming systems etc.) or new system architectures for their own research field. A joint lab between IEMN and ST-Microelectronics already addresses mm-waves Datacoms, and various projects have been carried out with THALES, MC2 Technologies, Paris Observatory, Rhode & Schwarz, iXBLUE, LYTID, V-MICRO or T-WAVES TECH. New partnerships are expected with other divisions from THALES or AIRBUS in the field of communications and with MC2 Technologies in the field of THz imaging.

In the field of **Nano-biotechnologies**, the setup of a fabrication line for the prototyping of fully packaged micro-fluidic devices will attract scientists involved in regenerative medicine, in-vitro diagnosis or environmental health, whereas scientists working on in-vivo diagnosis (e.g. probing with micro-electrodes or optical fibers) or minimally-invasive therapy/surgery will benefit from new ultra-miniaturized probes/robotic arms with sub-mm diameters. Over 20 companies are working with NANOFUTUR partners, of which 2 joint labs with LAAS (ESSILOR on vision devices and INNOPSYS on biomolecular arrays). The project will benefit to current partners and will attract new ones like ROCHE, HORIBA, NEMERA, MIMETAS and INOREVIA for in-vitro drug screening or regenerative medicine markets and like OTICON, Medical/Neurelec or PHONAK for e.g. new hearing aid implants. In the field of environment, new devices are already being studied for pollutants analysis (e.g. with DCU and Tel-Lab in Ireland) and new projects may develop significantly in the future.

For **Sensors**, NANOFUTUR will allow going beyond the "silicon-only" roadmaps by fostering new materials (e.g. diamond, SiC/SiN), for high-temperature environments where the performances of silicon are limited. These chemically resistant and stable materials can also be used for new electrochemical sensors (for monitoring of air, water, soil or biomedical analysis) or to store more energy in micro-batteries. Organic materials are also studied for sensors integration on flexible substrates in tight spaces. New collaborations are expected with academic labs working on micro-batteries, combustion machines, chemical plants pollution monitoring or biomedical applications (Paris Vision Institute, Brain Tech, Sense city, and Systems research department (COSYS)). SCHLUMBERGER has been collaborating with ESYCOM for 15 years on sensors for oil fields monitoring (high-temperature/pressure environments) as well as IEMN with its joint Lab with ST-Microelectronics. New collaborations are also expected with SMEs (ZYMOPTIQ, JMH CONCEPTION, THURMELEC, V-MICRO, Pixium-vision, MISTIC, NEURALLYS).

For **Nano-assembly and Nano-manipulation**, the ability of growing innovative 2D materials at CRHEA (using a unique combination of MBE and CVD), the ability to print 0D or 1D nanostructures using organic and colloidal m aterials at Paris Centre (with a world-record resolution of 20 nm) and the ability to assemble different 2D or 3D-on-2D heterostructures onto non-native platforms using a MTP transfer tool at C2N (with only 2 existing in Europe) will enable realizing a very wide variety of new multifunctional devices integrated at µm scale. These abilities will attract worldwide academic users wishing to study new functional nanostructures infeasible to date. Major companies like THALES, STMicroelectronics or SOITEC are regular partners of the consortium and are already interested to investigate new disruptive concepts. RIBER, VINCI-Technologies or ANNEALSYS have proposed to develop jointly a dedicated reactor and AIXTRON wishes to establish a joint laboratory on 2D-material growth.

I.3.7 Fostering dissemination & exploitation

NANOFUTUR targets competitive sectors of nanotechnologies driven by sobriety and better energy harvesting, reduced consumption/footprint, longer lifetime and social welfare. To maximize its outcomes, it will be necessary to communicate both at national and international levels on its offer of service and obtained results by organizing annual information meetings for potential academics/industrial partners or new cleanroom users.

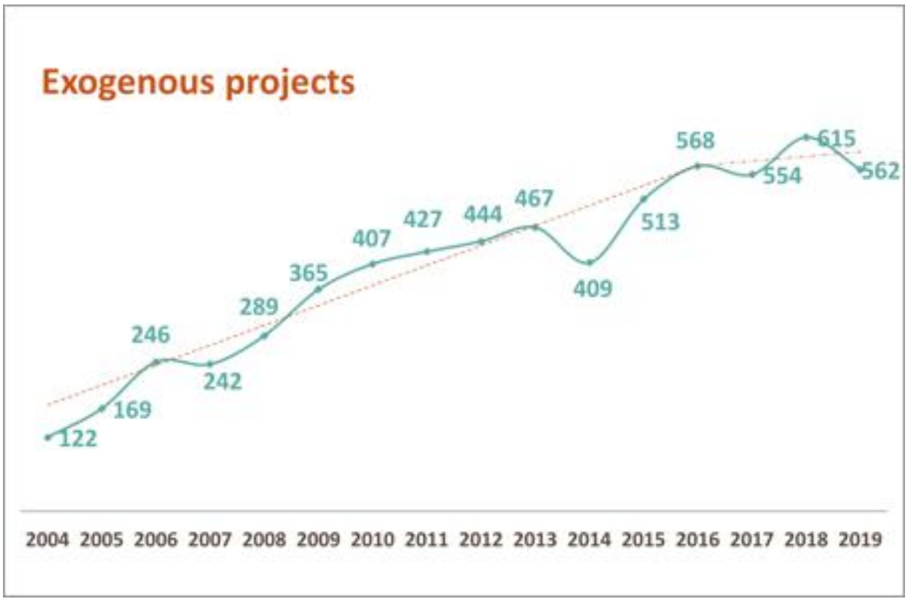
Academic outcomes. Thanks to NANOFUTUR equipment, the range of services and trainings offered to users will be expanded and will allow better addressing current challenges, thus opening the way to new academic partnerships with internal or external cleanroom-users. As illustrated above, many opportunities will be offered to increase the number and quality of publication or patents for various ecosystems such as energy, electronics, communications, health and environment.

Industrial partnerships. Requests from companies for collaborations or nanofabrication service (through RENATECH open-access portal) will increase, thanks to state-of-the-art equipment. RENATECH has already over 170 industrial partners and aims at increasing this figure by 50% during the project, thanks to better visibility and regional anchoring stemming from the network enlargement. Creating a club of industrial users of RENATECH+ will enable more confidential communication with industrial partners. Sub-groups of NANOFUTUR comprising academic/industrial members as well as RTOs (such as CEA-Leti) will be created to work on roadmaps for each challenge and will increase the number of national/European R&D projects with industrial partners or transfer projects to industry. For companies (e.g. startups but not only) a specific access to device-oriented pilot-lines will be available for R&D and small volume production. This kind of access already exists in RENATECH (at IEMN and FEMTO-ST) and will be extended when possible (e.g. for the SPINTEC/LTM spintronics project of NANOFUTUR).

Industrial transfer. The NANOFUTUR management will monitor indicators of scientific/technological output (publications, patents or industrial transfers) and stimulate the creation of startup companies that could exploit the innovative results of NANOFUTUR. The associated legal issues (IP, patents, and non-disclosure agreements) will be managed by legal departments of SATTs and partners’ institutions (CNRS, Universities, Schools). In terms of patents, the estimated goal is to increase the figure by 200% in 10 years.

II. Activity indicators of the Renatech network for the year 2019

Since the begining of the investment project, the upgraded Renatech's facilities are shared with the acamedic and private community that involved in micro and nano technology/sciences.
The number of exogenous project have been account for since 2004 as described in the graph. An exogenous project is a project carry out for the account of one (or several) external laboratory (academic or private) such that the driver of the project is not from the laboratory supporting the technological facility.

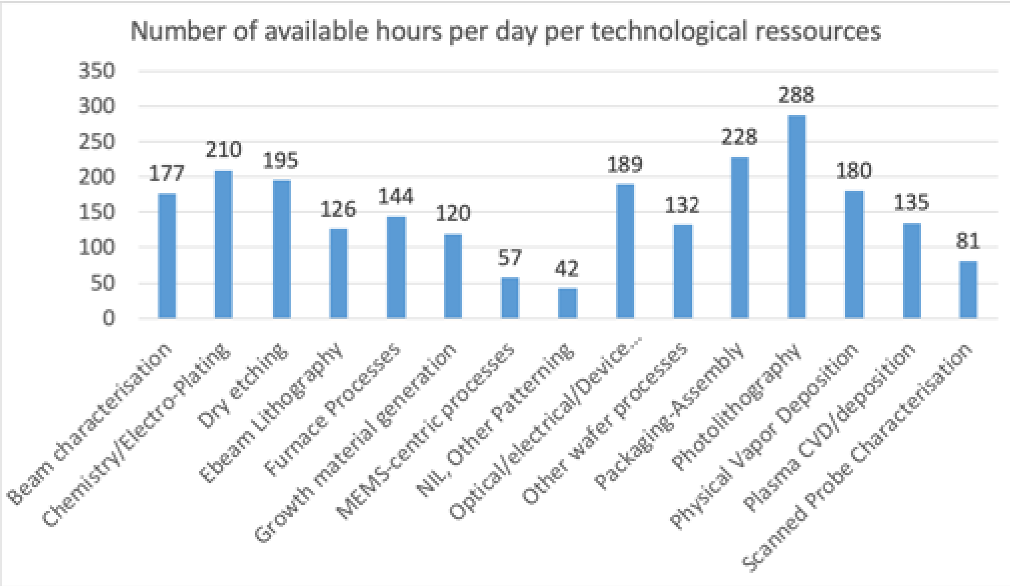


Since 2004, the number of exogenous projects has been raising constantly and was multiplied by 3.6 from 2004 to 2019. Since 2016, this number remains stable around 600 exogenous projects per year which seems to be the maximum project number that Renatech network can manage taking into account the human and technical means.
The 10% decline, compared to 2018, in the Renatech activity in 2019 is explained by the C2N move in his new building in Palaiseau. The C2N facility was closed during more than one year.

The number of internal projects is accounted since the network uses the national Renatech web portal i.e. since 2014. In 2019, a total of 1008 projects were carry out in Renatech's clean rooms, from which 59% were exogenous.
This high value of exogenous projects demonstrates the relevance of the creation of the open access network that shares a set of state-of-the-art equipment for carrying out research projects.
With the integration of the small clean rooms into the Renatech+ network, we will increase the facilities offer and increase the territorial coverage.

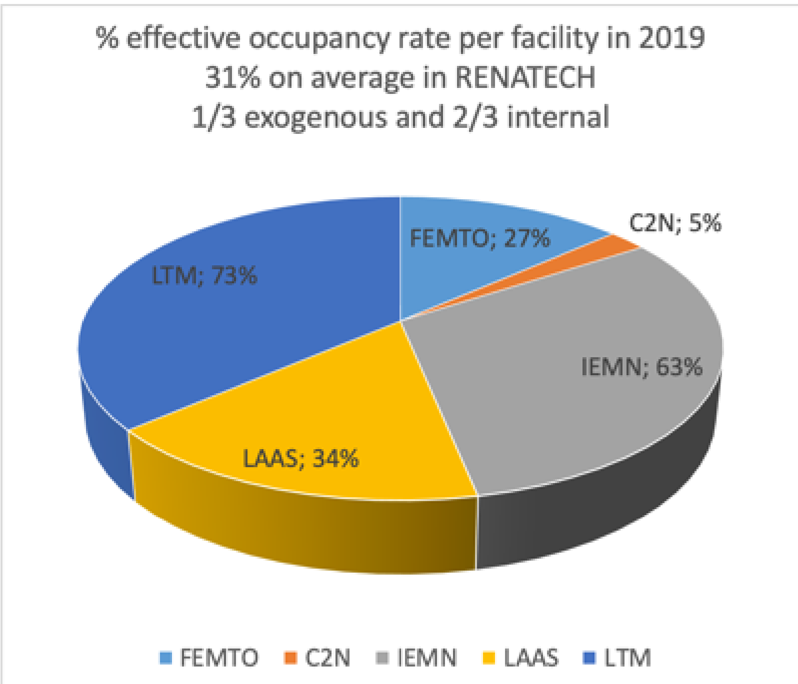
II.1 Opening rate

We have first estimated the number of available hours per day for all technological ressources that are present in our 5 facilities.

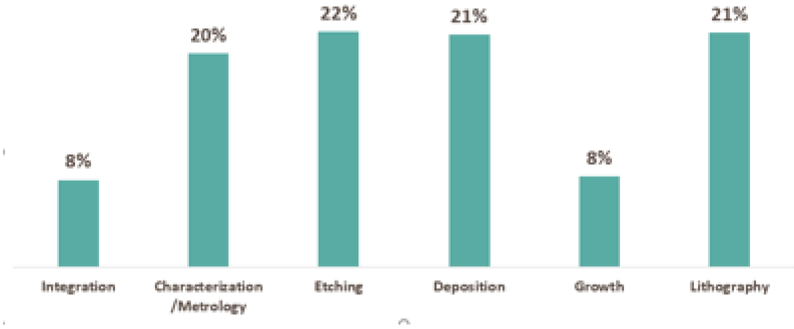


As reported in the following graph, the effective occupancy rate varies from one facility to another, which can not be explained easily (depends on how is counted the time in front of an equipment).

Note that in average in RENATECH, a value of 31% of effective occupancy rate is observed despite the shutdown of the C2N due to its relocation. 1/3 of the time is devoted to the realization of exogenous projects.



II.2 Main equipment required



The graph above represents, for all projects carried out in 2019, the proportion of technological resources used to carry them out. It can be noted that the most requested technological resources are, since the beginning of the BTR program, lithography, etching and deposition. Although the percentage of their used can vary from year to year, we always find that e-beam lithography is the most requested technique after the standard lithography. We point out that the occupancy rate of growth equipment is not negligible and is a key to go from material to devices. This is specific to RENATECH and its policy to maintain on the same site a complete process flow towards integration.

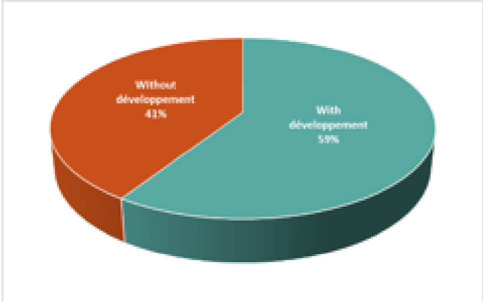
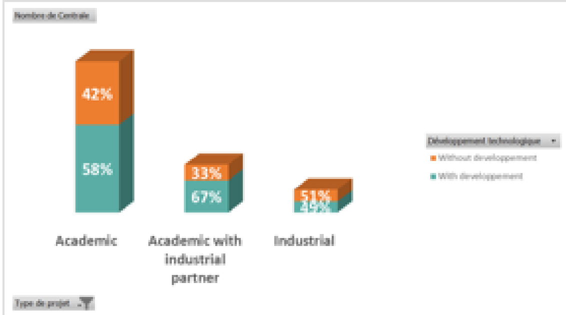
II.3 Projects characterization

This section aims to present the Renatech projects specificities (internal and exogenous) carried out in 2019.

II.3.1 Industrial innovation is mostly carried out in academic and industrial partnership projects

In term of innovation, on all the projects, we observe that almost two thirds of them require development. That's the specifity of Renatech, from the beginning of BTR program, since people are attached to developed fabrication processes to the benefit of the community. If we have a look to the distribution per type of project to discrimate where a lot of development is required, we see that:

- More than half of academic projects require development
- 2/3 of academic/industrial projects make innovation (with development)
- 1/2 of industrial projects require development

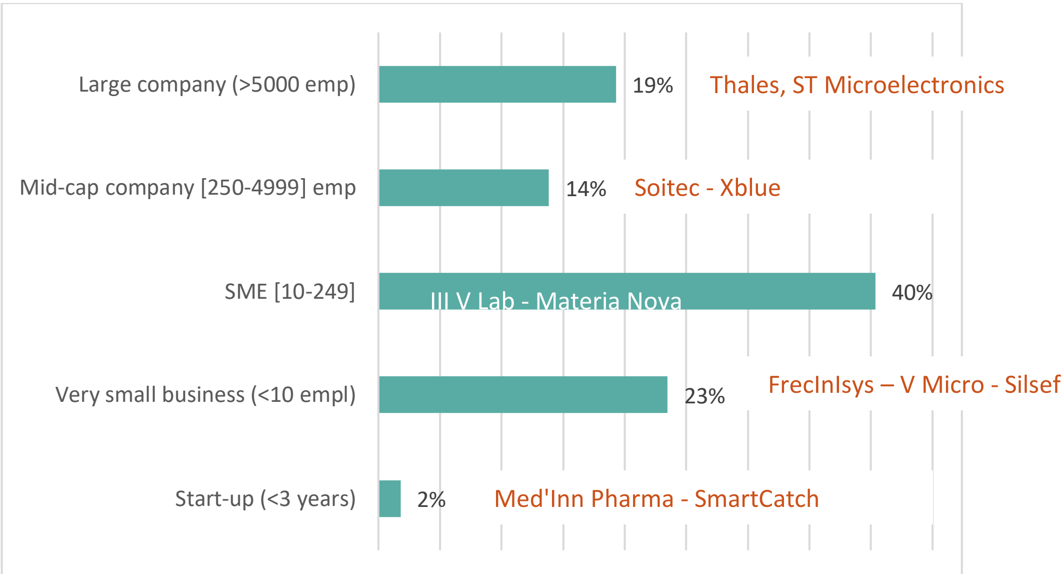
 	
Distribution « without and with development » for all the projects (academic/industrial/in partnership)	*Distribution « without and with development » by type of projects*

II.3.2 Industrial partnership

Renatech worked with 165 companies.
In France, large companies account for the majority of R&D expenditure (60%) and Mid-cap companies account for just under a quarter. Microenterprises (MICs), when they are active in R&D, represents the category of company that devotes the largest share of its turnover to R&D.
Concerning R&D requiring developments in nanofabrication, the trend is reversed. The investment costs are too high so that small and medium-sized companies collaborate more than large companies with public research, including Renatech. In 2019, 65% of industrial projects are carried out with small and medium companies.

Number of projects with type of companies

- *Main partner companies*



The four biggest industrial partners are:

- Thales, involved in 18 projects
- ST Microelectronics, involved in 13 projects and 4 Renatech/STM joint lab
- Frec'N'Sys, involved in 10 projects. Note that Frec'N'Sys has just been buying out by SOITEC
- III-V Lab, involved with 6 projects

Renatech and STMicroelectronics reinforced their collaboration through three joint labs:

- STM-IEMN on high-frequency characterization platform
- STM-LN2 (Canada) – LTM on energy management of low power electronics
- STM-LTM on plasma processes for etching in nanofabrication.

A short survey gave us a better understanding of the industrial user needs and why they use our facilities:

- The systematic and relevant feasibility study undertaken by the technical staff who evolves in a high-quality scientific ecosystem and profits to the last scientific and technical advances.
- An access to a wide range and cutting-edge equipment
- An access to a wide range of technical processes
- A high fabrication flexibility
- A high configurable equipment
- A gain of machine. They don't have to stop manufacturing machine
- Training on nanofabrication equipment and processes
- The possibility to fabricate by themselves
- The housing equipment

The survey also highlights specific needs according to the company type. The needs of start-ups are rather linked to proof of concept while SMEs ask for manufacturing of measurement systems, filters or electronic systems integrated

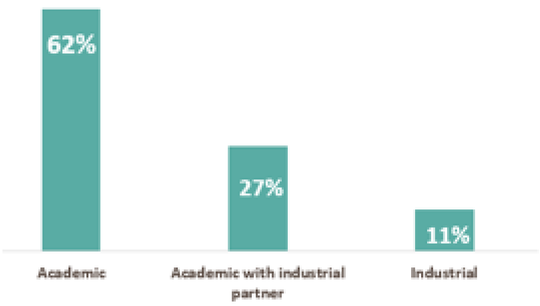
II.3.3 Internal Renatech or Renatech+ projects

For the third year, we count the projects involving several Renatechs' clean rooms and the projects between Renatech and the 27 French small facilities (which are joining Renatech+ network).
In 2019, we counted 22projects in which more than two Renatech facilities worked in partnership and 84 projects between one or more French small facilities named "regional facilities" and one or more Renatech facilities

II.3.4 International projects

The scientists belonging to Renatech have a lot of international collaboration on individual basis. In 2019, 19% of total number of projects were carried out with one or more international partner(s). Partners are mostly academic and these projects required developments.

International project type



Percentage of international projects for each project type

In 2019, Renatech network has worked with 34 different countries that are mainly European. Note, that the EuroNanoLab network was naturally created with our historical European partners and is strategic for the future European investment plan in nanotechnology.

Countries involved in projects

Specific international collaboration

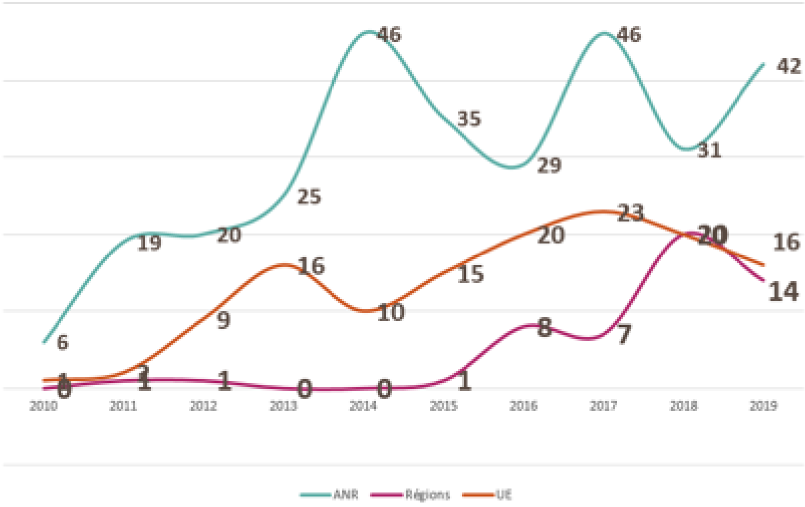
Canada – LN2

At the Renatech network level, a strong collaboration was existing since 2012 with the University of Sherbrooke (UdS) in Canada, in the framework of the joint laboratory named "Laboratory of Nanotechnologies and Nanosystems" (LN2) between CNRS and UdS. This collaboration involves exchanges of scientists and PhD students between UdS on the Canadian side and the five Renatech facilities on the French side.

USA - Applied Materials

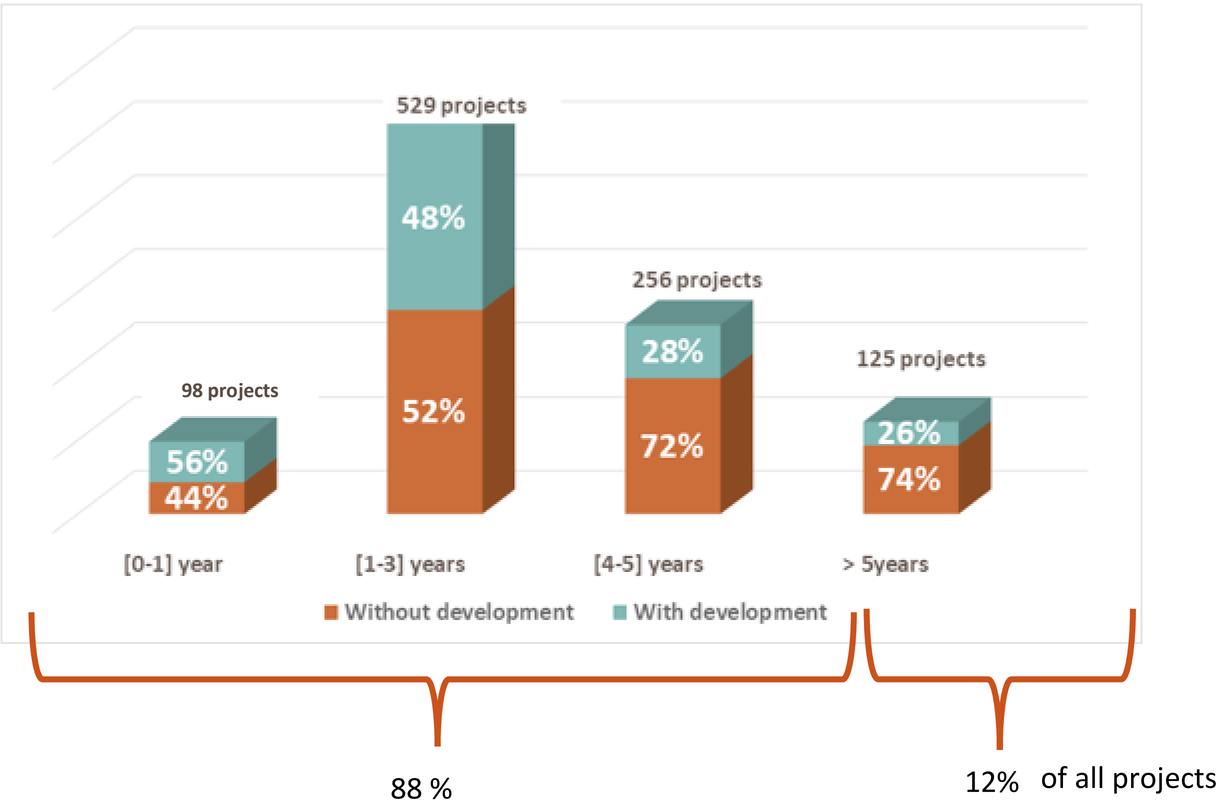
Moreover, a joint laboratory with the US Company "Applied Materials" has been created with LTM/Renatech, and is dedicated to the development of plasma technologies.

II.3.5 ANR/EU projects



For both programs, EU and ANR (national program), the trend is growing since 2010. After a constant increase until 2014, the number of ANR projects strongly decrease from 2014 to 2016 and in 2018. These decreases are correlated with the decrease of ANR budget.
Even if the number of EU projects are increasing, this number is still law. We think that French people are not in well know networks or are shy and not sure of them. Scientific contact in international conferences doesn't sufficient to create long term collaboration. Since a few years, the CNRS has been encouraging the submission of European projects and has set up training workshops.

Project duration

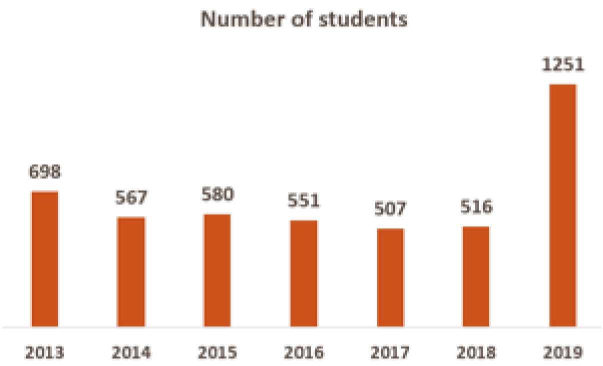


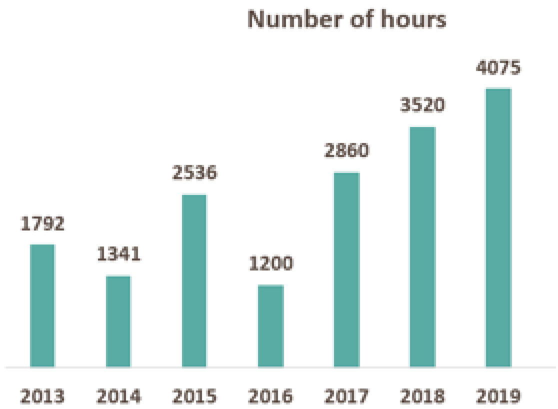
The duration of projects varies from a few days to several years:

- 52% of them last between 1 and 3 years. It corresponds to ANR and EU projects that need developments.
- 25% of them last up to 5 years. It corresponds to internal scientific project with a challenging development.
- 13% of them are very long-term projects (>10 years) and corresponds to scientific specifity of the laboratory. They contribute to the technological high-level expertise of the staff.
- 10% of them are short projects and pure services. These projects require little development.

II.4 Education

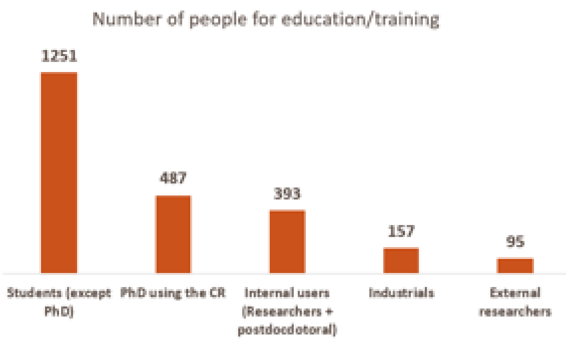
Education activities are carried out thought the C2N, Femto-ST, IEMN and LTM contributions to undergraduate courses from University and Grandes Ecoles. They are involved in Licence and Master courses on physic and chemistry, material, nanosciences and technologies, electronic, micro-electronic (microsensors, on-board systems….) industrial IT, telecommunication, (…) LTM is also involved in a summer school on European School on Nanoscience and Nanotechnology (https://www.esonn.fr/).
Renatech trained 1251 students in 2019 and 487 PhD which is more than the double compared to 2018. This increase in the number of students is due to the training in micro and nanotechnologies provided by the IEMN to master students from local schools and Universities.

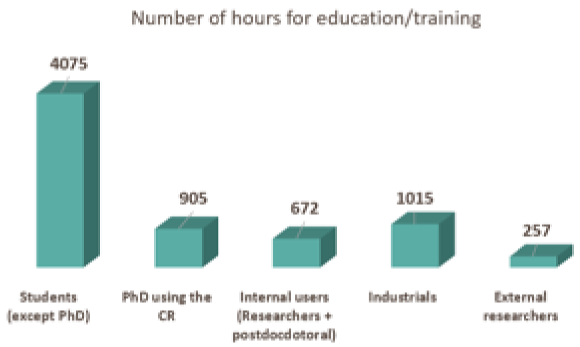




Note that 4 apprentices are trained in Renatech clean-rooms. In their future working life, these students will become the best communication medium of our expertise on nanotechnologies.

Training
Clean-room training is also an important piece of the education role of the network. In 2019, 645 persons were trained in our clean rooms. These trainings are mostly dedicated to new users of the clean room in order to get access to clean room and conduct by themselves their own project. At the end, the "student" obtains operator's licenses for the tools he plans to use. Train covers safety, cleanroom behavior and practical matters such as how to use to book a tool.



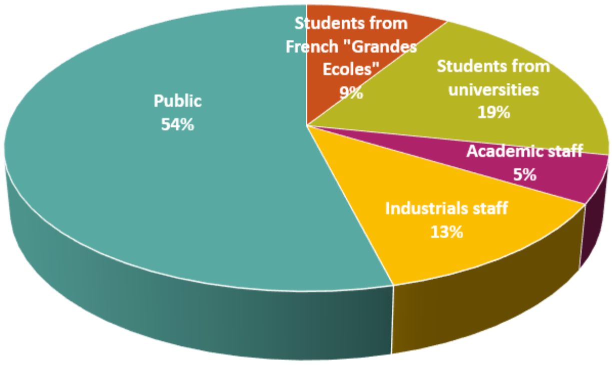


These programs provide the students an opportunity to work across disciplines and develop a common language between different scientific backgrounds. This enhances the students' ability towards problem solving and generation of novel ideas. After their master, students can either pursue a doctoral work in a laboratory or begin a professional activity.

Visits of the facilities

Hundreds of visitors, researchers, scientists, students and industrials are invited to visit the BTR facilities in order to be acquainted with the latest equipment and its capacities.

Main indicators: in 2019, Renatech facilities welcomed 884 visitors. Two third are students from school and university. The different types of visitors is given in the graphic below.



Renatech Thesis Prize

Following a previous recommendation of the evaluation panel, a Renatech thesis Prize was created in 2012 in order to reward outstanding work in micro-nanofabrication accomplished by a PhD student during his thesis work. The thesis had to be defended in the two years before the JNTE symposium. The work must have been carried out in any French academic or industrial laboratory, possibly in collaboration with foreign partners.

A board of experts gathering each Renatech laboratory Director, taking into account the importance and novelty of the technological achievements has evaluated the applications. Therefore, the evaluation was not focused on the scientific results obtained from the fabricated device/material/instrument and their impact for the community: it was only concentrated on the technological achievements.

In 2019, 20 proposals were submitted. Two ex-aqueous were selected as laureates of this PhD award:

Loic Berthod: "Cylindrical photolithography based photosensitive sol-gel" - Laboratoire Hubert Curien (Université Saint-Etienne) & Laboratoire des Matériaux et du Génie Physique

The aim of this thesis is to analyze the photolithography tools used to print diffraction gratings and to identify those that are sufficiently flexible to be adapted to unconventional substrates such as cylinders or tubes. The photolithography tools developed have also been adjusted in order to write directly a diffraction grating in a functional layer of TiO_2, supplied by the sol-gel pathway. This thesis is a prospective study because the periodicity or the pattern of the registered diffracting structures has not been defined for a specific application. Two photolithography tools have been successfully adapted to cylindrical substrates. They will be presented here and will be accompanied with a perspective for a specific application. Finally, the last chapter is distinct from the previous ones because it does not concern the development of a photolithography tool but on the chemical transformation of TiO_2 (dielectric) into TiN (metal), it nevertheless remains in the continuity of its thesis because this transformation is adapted to all types of substratestransformation is adapted to all types of substrates

Ludovic Marogo-Lombart: "Vertical integration of an electro-absorption modulator onto a VCSEL for high-speed communications" - LAAS-CNRS / TONA VUB Brussel

The aim of this thesis is to analyze the photolithography tools used to print diffraction gratings and to identify those that are sufficiently flexible to be adapted to unconventional substrates such as cylinders or tubes. The photolithography tools developed have also been adjusted in order to write directly a diffraction grating in a functional layer of TiO2, supplied by the sol-gel pathway. This thesis is a prospective study because the periodicity or the pattern of the registered diffracting structures has not been defined for a specific application. Two photolithography tools have been successfully adapted to cylindrical substrates. They will be presented here and will be accompanied with a perspective for a specific application. Finally, the last chapter is distinct from the previous ones because it does not concern the development of a photolithography tool but on the chemical transformation of TiO2 (dielectric) into TiN (metal), it nevertheless remains in the continuity of its thesis because this transformation is adapted to all types of substrates

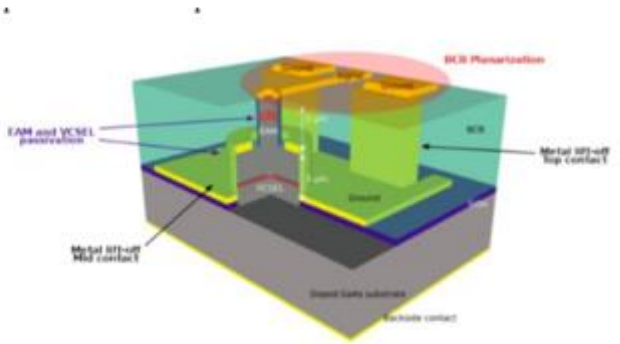


Figure 1: Technological locks for the vertical integration of an EAM onto a VCSEL

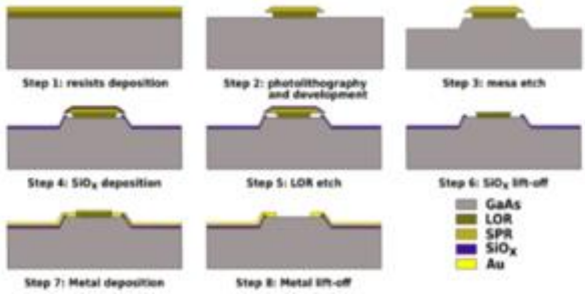


Figure 2: Self-aligned process step for EAM or oxide-free VCSEL fabrication

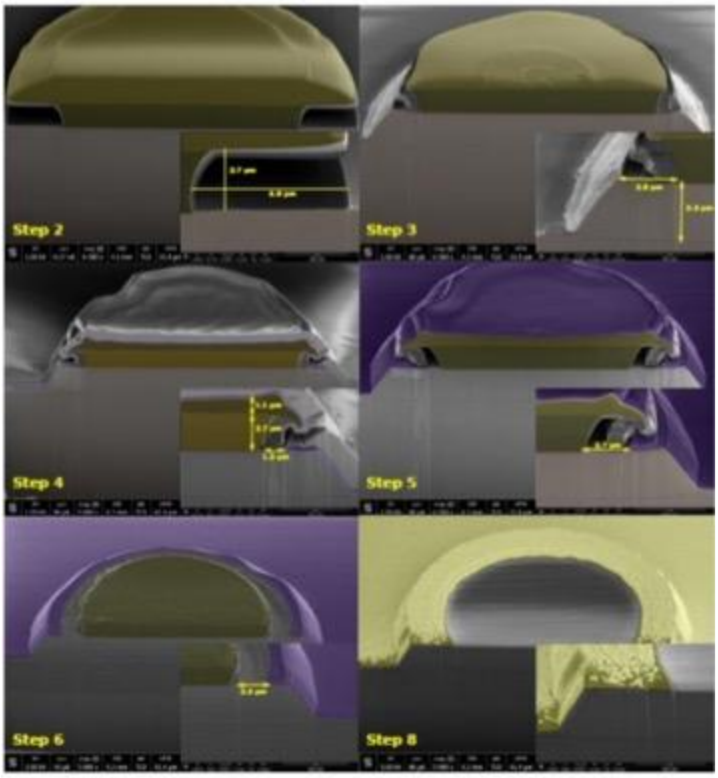


Figure 3: Focus Ion Beam Cross view of a VCSEL fabricated with one single photolithography step

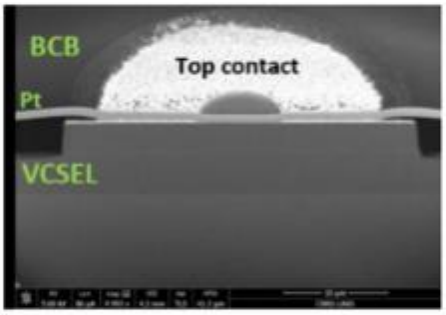


Figure 4: Cross view of a VCSEL planarized with BCB using nano-imprint tool as mechanical press

III. Scientific results & outreach activities

The promotion of the BTR program is based also on the scientific production of the network members and its dissemination.

Renatech's figures

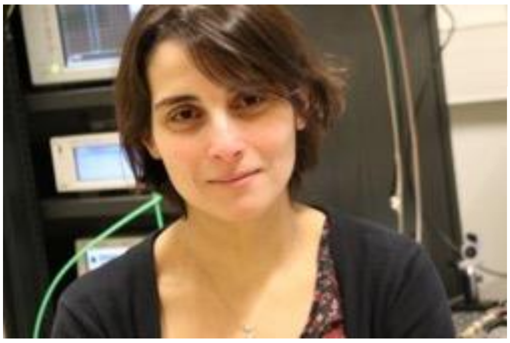
	2013	2014	2015	2016	2017	2018	2019
Scientific prizes	6	11	9	16	12	13	25
Patents files	29	28	28	17	12	30	28
Total number of patents and patents extension	165	170	177	147	159	207	
Invited conferences	143	166	154	306	47	51	95
Total number of conference (with invited conferences)	522	625	572	346	470	592	493
Number of thesis	76	85	120	107	77	160	285
Number of postdoctoral fellowship	-	-	-	-	87	131	86
Number of masters	-	-	-	-	47	45	36
Number of intership in clean-room				42	5	6	4

The BTR facilities are essential tools of national research in nanosciences and micro- and nanotechnologies. The equipment and the know-how of facility staffs allow each year the fabrication of devices, circuits and systems that are presented in renewed or are published in scientific journals.

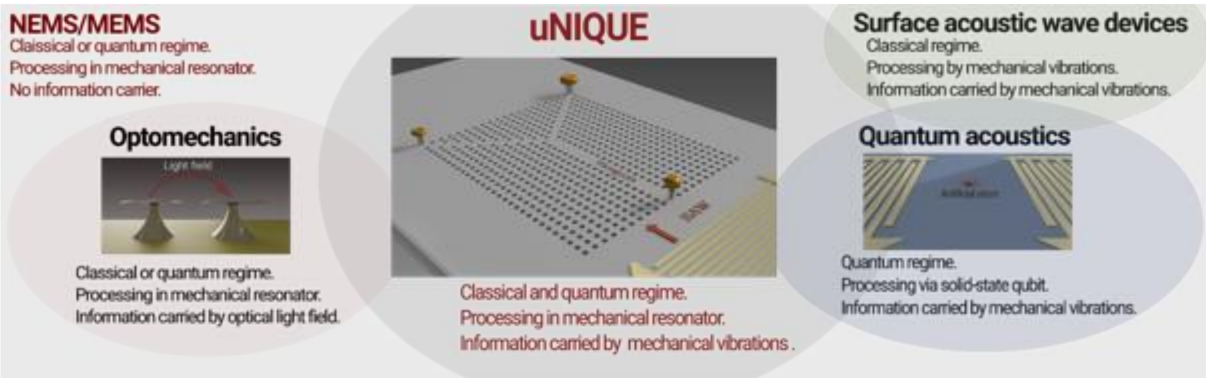
III.1 Prizes

III.1.1 ERC Consolidator grant

Sarah Benchabane (**FEMTO-ST**), obtained a prestigious €2M European Research Council (ERC) consolidator grant for her project uNIQUE: Nanophonics for Quantum Information Processing. The project aims at the development of an all-electro-acousto-mechanical quantum information platform exploiting the full potential offered by surface acoustic waves in the single-phonon regime, and by mechanical resonators beyond the standard quantum limit.



European Research Council
Established by the European Commission



David Pech (**LAAS**): 3D micro-supercapacitors for embedded electronics

The realization of high-performance micro-supercapacitors is currently a big challenge but the ineluctable applications requiring such miniaturized energy storage devices are continuously emerging, from wearable electronic gadgets to wireless sensor networks and the upcoming Internet of Things (IoT).

Here we propose a 3D paradigm shift of micro-supercapacitors design to ensure increased energy storage capacities [1]. Hydrous ruthenium dioxide (RuO_2) is a pseudocapacitive material for electrode well-known for its high capacitance. A thin-film of ruthenium will be deposited by atomic layer deposition (ALD), followed by an electrochemical oxidation process, onto a high-surface-area 3D current collector prepared via an ingenious dynamic template built with hydrogen bubbles

We obtained 3D electrodes exhibiting unprecedented high capacitances per surface area, in excess of 5 F/cm^2 using porous gold current collectors and RuO_2 [2] for an energy of 329 mJ/cm^2 in an interdigitated device . These first results undoubtedly demonstrate the high potential offered by 3D micro-supercapacitors to obtain high-energy storage components for embedded electronics.

Micro-energy autonomy solutions based on these components will play a decisive role for long term autonomy of embedded electronics and will significantly shape the future of IoT in our everyday environment

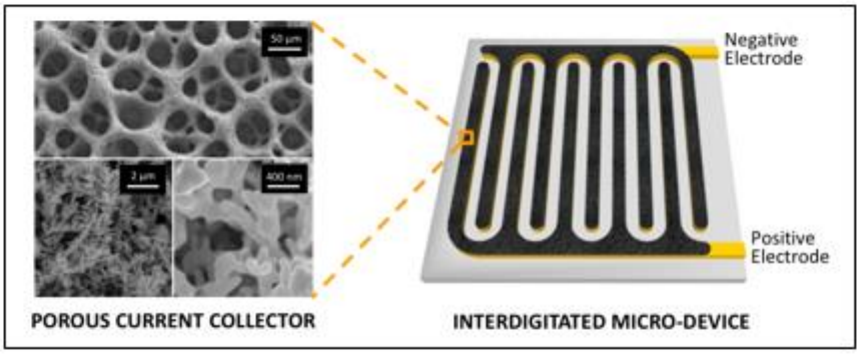


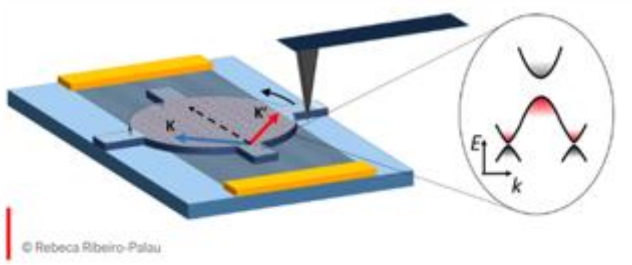
Figure: Interdigitated micro-supercapacitor based on 3D porous electrode

III.1.2 ERC Starting Grants 2019

Rebeca Ribeiro-Palau is laureate of an ERC Starting Grants 2019 for her project Twistronics

Rebeca Ribeiro-Palau, CNRS researcher at the Department of Nanoelectronics of **C2N** (PHYNANO team), is laureate of an ERC Starting Grants 2019 for her project Twistronics (Probing topological valley currents by layer alignment in van der Waals heterostructures).

Rebeca is an experimental condensed matter physicist. She obtained her PhD at the Universite Paul Sabatier in Toulouse. She did a postdoc at the French National Metrology lab (LNE) and then at Columbia University. In November 2017, she got tenured CNRS researcher at C2N to investigate the generation and control of different topological orders in van der Waals heterostructures.



III.1.3 Outstanding Career Award

Alain Cappy (IEMN), received the *Outstanding Career Award*, at the European Microwave Week, on the 1st of octobre 2019 in Paris. This international outstanding award was attributed by the European Microwave Association due to his outstanding carrier in the domaine of microwaves.

III.1.4 Jacqueline Bloch (C2N)

Jacqueline Bloch is awarded with the "prix Ampère de l'Électricité de France", and is elected at the French Academy of sciences.

Jacqueline Bloch, CNRS Senior Researcher at **C2N**, has been awarded the "prix Ampère de l'Électricité de France" 2019. The French Academy of sciences honored her during a solemn presentation of her prize under the Coupole of the Institut de France on October 15. 18 new members of the French Academy of sciences were elected in December 2019, including Jacqueline Bloch who joined the section of physics.

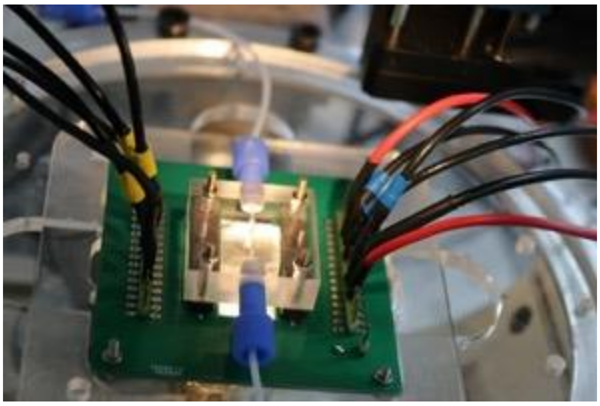
Jacqueline Bloch's work is pioneering in the field of cavity polaritons in semiconductors. Early in her career, she became interested in the ultimate confinement of electrons and light in nanostructures, in order to exalt and control light-matter interaction. Thanks to her experimental breakthroughs, together with her deep understanding of a subtle subject, she is now a world leader in the field of polariton quantum fluids. Her research on this system added an invaluable contribution to a broad field of physics, that ranges from liquid helium to ultra-cold quantum gas.

The impact of her work is evidenced not only by the high number of citations of her publications, but also by the many requests she received for collaboration coming from experimenters and theorists, in France and abroad (Spain, Italy, Israel, Germany, United Kingdom ...).

She actively participates to the management of research, at the local level in her laboratory, at the national level at the comité national du CNRS, at the international level in the ERC panels. She is renowned for the clarity of her lectures, and students can benefit from her teaching skills, especially at the Institut d'Optique and the Ecole Polytechnique.

III.1.5 CNRS bronze medal 2019

Aude Bolopion (FEMTO-ST) was awarded the CNRS 2019 Bronze medal for her work in microrobotics. Her research focuses on the non-contact manipulation of objects at micrometric scales whose main application framework is the ultra-precise positioning of biological cells. She has proposed many original methods of actuating and controlling micro-object trajectories using various remote force fields.



III.1.6 The French University Institute

Loïc Lanco, Assistant Professor at Université de Paris and researcher at **C2N**, is selected **member of the "Institut universitaire de France"**!

By order of the French Minister of Higher Education and Research, Loïc Lanco, Assistant Professor at Université de Paris (Université Paris Diderot) and researcher in photonics at C2N, was nominated junior member of the "Institut universitaire de France" (IUF) for five years, starting from the 1st October 2019. He is the second C2N researcher to receive this recognition after Delphine Marris-Morini in 2013.

The research activity of Loïc Lanco at C2N focuses on light-matter interfacing at the single-photon level, using semiconductor quantum dot / cavity structures. He headed the Physics BSc of University Paris Diderot (Université de Paris) from 2014 to 2018.

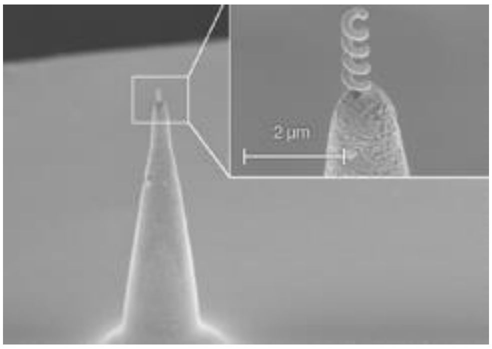
The role of the IUF is to foster the development of high-level research in universities and to reinforce interdisciplinarity. Thus, it encourages the dissemination of knowledge, contributes to the increased number of women in the research sector and promotes a policy of a national scientific networking. University lecturers and researchers who are nominated are distinguished for the excellence of their scientific activity, attested by their international influence.

III.1.7 IFCS Cady Award 2019

Serge Galliou (FEMTO-ST), was awarded the **W. G. Cady Award** is to recognize outstanding contributions related to the fields of piezoelectric or other classical frequency control, selection and measurement and resonant sensor devices.

III.1.8 Raith Micrograph Award - Special Art Award 2019

Roland SALUT (FEMTO-ST) won the special art award from the company Raith Nanofabrication, a world leading manufacturer of nanofabrication instrumentation. The presented work concerns a nano-helix placed on a fiber tip for a novel chiral fiber nanoprobe.



III.1.9 Start up Prizes

Grand prix i-LAB: The startup Spin-Ion Technologies, co-founded by Dafiné Ravelosona, CNRS Senior Researcher and Deputy Director at **C2N**, was awarded with one of the 10 Grands Prix of the French national competition to support the creation of innovative technology companies "i-LAB 2019" from the hands of Frédérique Vidal, French Minister of Higher Education and Research.

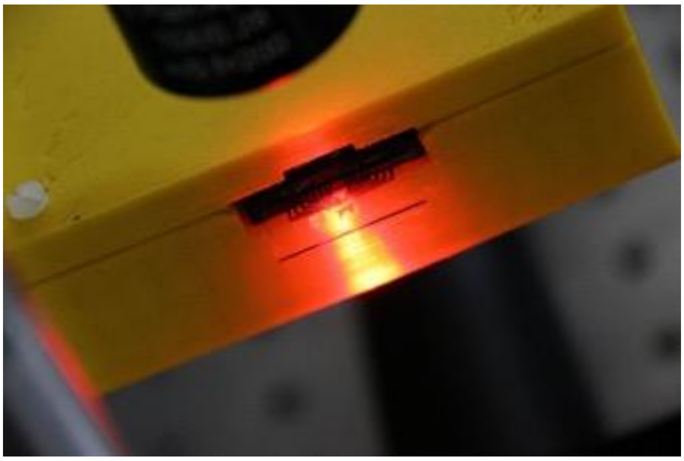
The start-up provides an answer to the challenge of the digital transformation. It has developped an innovative process to be integrated on the production lines of MRAMs (Magnetic Random Access Memory), a new memory with the potential to replace all existing memories that reach their limits.

The solution is based on the use of a specific ion beam to treat ultra-thin magnetic films in order to improve their structural properties. The performance of MRAMs, which use these materials, are thus increased. Spin-Ion Technologies has initiated partnerships with several global industry leaders in the development of MRAMs and related equipments.

The Grand Prix i-Lab is accompanied by a significant R&D funding. This grant will allow Spin-Ion Technologies to accelerate the process of maturing technology towards industrialization.

III.1.10 MESR/BPI France PEPITE Prize 2019

Vladimir GAUTHIER (FEMTO-ST) won the PEPITE Prize of the Ministry of Higher Education, Research and Innovation and the public investment bank BpiFrance for young creators of innovative companies. His project Cell-Select concerns microrobotic sorting of biological cells and will make possible to sort 1 million cells per hour with a degree of precision never achieved before.



III.1.11 I-PhD Innovation competition prize 2019

Maya GEAGEA (FEMTO-ST) won a prize at the I-PhD innovation competition sponsored by BPI-France for projects of new start-up. Her project ANIOPAC developed with the SATT SAYENS concerns the development of a new hydrogen fuel cell technology powered by its own integrated hydrogen production system. Intended to power nomadic applications (laptops, smart cards, sensors, etc.), this mini fuel cell is made from silicon and machined using micro-manufacturing processes that are easily transposable and low cost.

concours d'innovation i-PhD

III.1.12 Thesis Prizes

Valentin Goblot is awarded the thesis prize 2019 of the EDOM Doctoral School

The thesis prize 2019 of the Doctoral School "Ondes et Matières" (EDOM) of University Paris-Saclay was awarded to Valentin Goblot, PhD Student in the team GOSS (Photonics Department) at **C2N**, for his thesis about "Polariton quantum fluids in 1D synthetic lattices: localization, propagation and interactions", defended on January 31st, 2019 and supervised by Jacqueline Bloch.

université PARIS-SACLAY | ÉCOLE DOCTORALE Ondes et Matière (EDOM)

Chaymaa Haloui (LAAS), A phD student in the third year of her thesis in the Energy Integration team (ISGE) and at CEATech Occitanie, supervised by Josiane Tasselli, Frédéric Morancho and Mathieu Gavelle, was awarded the prize for **the best oral presentation at the National Days of the Doctoral Network in Micro-Nanoelectronics** (JNRDM 2019), held in Montpellier from 3 to 5 June 2019. This award recognizes her work on the technological development of a normally-off HEMT in Gallium Nitrure (GaN) with a p-GaN barrier grid.

Lya Fontaine (LAAS), A phD student in her third year of thesis in the Energy Systems Integration team - ISGE, supervised by Karine Isoird, Josiane Tasselli and Patrick Austin, was awarded the **Michel Amiet Grand Prize at the Young Electrical Engineering Researchers Conference** (JCGE 2019) held on Oléron Island from June 11 to 14, 2019.The award recognizes her work on "the development of technological bricks for the production of diamond-powered components."

Benjamin BOISNARD (LAAS). Award for the **best presentation of the GEET doctoral school**. April 2019 "Designing and building a VCSEL source tuned to CL for a microsystem of skin analysis by Optical Coherence Tomography (OCT)"

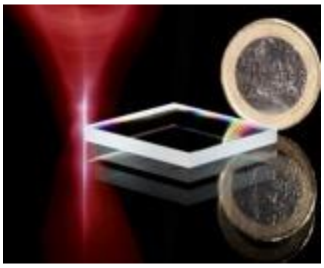
Marianne Elias (LAAS) : **Best Poster Award at BioPhee** Conference (Membrane Biophysics of Exo-Endocytosis: From Model Systems to Cells), Mandelieu, Avril 2019, for her work « Biomembrane mechanics tested in a microfluidic configuration: towards on-chip micropipette »

Bayan CHAMI (LAAS) :**Young oral presentation award** ITP Conference (International Symposium on Electroseparation and Liquid Phase Séparation Techniques), Toulouse, Sept 2019, for her work « µLAS Technology for RNA Separation »

Audrey CAYRON (LAAS) has received the "**Young Engineer Prize**" during European Microwave Conference 2020 in Paris

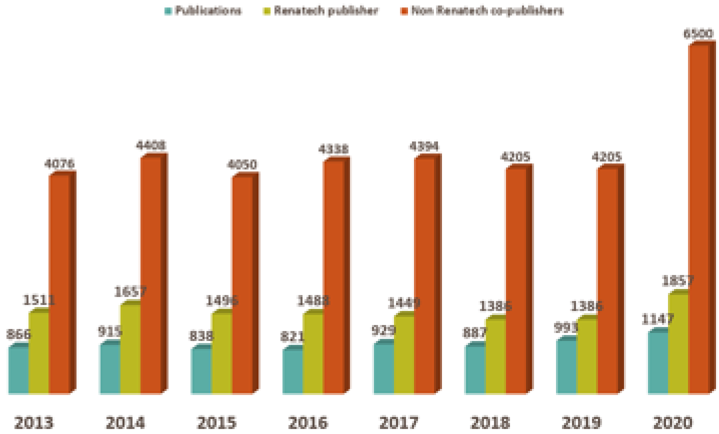
Sarah Brotman (LAAS), **Best Oral Presentation** at the MRS Boston Fall Meeting

Rémi Meyer (FEMTO-ST) won **the best student paper award** category "Frontiers in Ultrafast Optics" for his work on ultrafast laser machining of thick glass substrate using Bessel beams at the Photonic West conference, San Francisco, USA in February.



III.2 Publications

The number of publications is representative of the activity of the network, the best way to promote a network and to measure its outreach. To show the impact of Renatech network, we consider all publications in ISI Web of Science where at least one co-author is a permanent people of the 5 laboratories of Renatech. On average, we found 924 papers per year; 88% are peer-reviewed papers and 17% are papers issued from conferences.



In 2020, 1147 papers were published in international journals of which almost half of them were in strong impact factors journals (rank A).

If we have a look on all co-authors of international papers, we count 8357 co-publishers of which 77% aren't from Renatech laboratories and 25% are in Renatech+ labs. This high number shows Renatech outreach in the world. More precisely, you will find the repartition on the world map of 1110 co-authors, which are outside France.

Diversity of the facilities users is illustrated by the diversity of the journals in which work is presented (physics, engineering, electronic, photonic/optic, microsystems, and biology).

One point we always have to further improve is the mention of Renatech in the aknowlogement section of international papers. On the graph below, we show, from 2011 until now, the number of international papers, which thanks Renatech for funding. The sentence "this work was partly supported by the French Renatech network" has to be added in the same way that researchers thank the various funders. For Renatech, to not be referenced by researchers, gives a negative image of the French network and does not evidence the crucial role of infrastructures to reach scientific results at state of the art.

Networking activities

Networking is an important activity of Renatech and various actions have been implemented to promote communication and cooperation between members of the network. Technical staff members have often some opportunities to visit each other (on a case-by-case basis), to work on joint developments of specific processes that are not available in their own clean room. Such technical exchanges have been extended by the creation of several "technical expert groups" that gather clean-room staff on the main categories of clean room processes:

- *lithography,*
- *deposition technic,*
- *etching technics and epitaxial/material characterizations.*

One new technical group was formed in 2018 about crystal growth & caracterization.
These groups meet regularly (about once a year) to exchange on new technologies and on new available equipment. The group members will thus be able to share best practice and their knowledge on the usage and reliability of the various micro-fabrication machines. They also invite equipment suppliers to present their products to the group and have even negotiated network rates for the purchase of clean-room products.

Last "Days":

- *Lithography days, October 2018, in Grenoble with 35 attendees*
- *Etching days, November 2018, in Grenoble with 27 attendees*
- *Etching Days, March 2017 in FEMTO-ST (Besançon) which launched a new formula.*
  One day dedicated to process, manufacturer presentation and a roundtable.
  Half a day on one subject "etching" in Renatech.
- *Deposition days, 15-16, November in Orleans after the JNTE symposium with 29 attendees*
- *October 2019 in Marseille for Deposition. It will be co-organized between one Renatech laboratory – C2N and a regional clean-room-Fresnel (Marseille).*
- *November in Grenoble for etching technics and epitaxial/material characterizations, co-organized between LAAS and C2N.*

After noting that technical staff doesn't use to participate to national or international conferences we try to reverse this assessment. We foster their participation supporting the registration fees to one technical staff per laboratory in selected events:

- *MNE (Micro and Nano Engineering), 23-26, September 2019 in Rhodes (Greece) with almost ten talks or posters presentation from Renatech clean room.*
- *JNTE (National days of emerging technologies) in Grenoble from 25 to 27 November. For technical staff presented their technological development.*

III.3 Start-up

Since 2000, 21 start-ups were created. Seven of them shutdown which is a good result. A recent survey shows that between 466 - 918 jobs were created. In the following, we only retain last start-ups created.

CRYOHEMT

Founding in 2019

Activity

In the fields of electronics for scientific research, CRYOHEMT SAS, co-founded by Yong Jin, CNRS Senior Researcher at C2N, provides specially designed cryogenic HEMTs and associated PnP preamplifiers working at 4.2 K or lower temperature, for low-frequency , ultra-low noise cryogenic readout electronics.Their implementation in experiemnts or systems has already resulted in 3 publications in Science; 8 publication in Nature journals.

Market / potential customers

The products by CRYOHEMT are used in Mesoscopic Physics, Dark Matter search, low temperature STM, low temperature nano-mechanical resonators and low temperature detectors. Customers that have already used the products by CRYOHEMT come from France, Spain, the Netherlands, Germany, Japan, China and the United States.

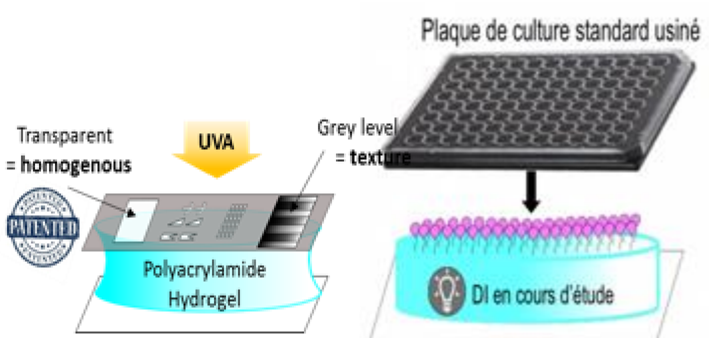
Cell&Soft

Founding in 2019

Activity

Most of the in vitro cell-based assays performed in research laboratories, pharmaceutical industries or screening platforms are operated on plastic dishes which rigidities are a billion times stiffer than the in vivo environment. This shortcoming is a true limitation, as many studies have proved that the mechanical properties of the microenvironment deeply impact almost every aspect of cell behavior. Thus biological results obtained from standard cell culture assays are biased by the lack of mechanical relevance of the in vitro culture devices.

Cell & Soft provides ready-to-use mechano-mimetic culture plates, called Mecachips, that imitate the mechanical properties of the in vivo microenvironment. Using technologies derived from the microelectronic field, Cell & Soft elaborates soft, elastic and flat hydrogels which can exhibit either uniform or patterned rigidity properties. Mecachips culture plates assume the chemo-mechanical robustness of the culture environment as they combine a micron scale control of the plate mechanical properties with an independent control of the surface chemistry.

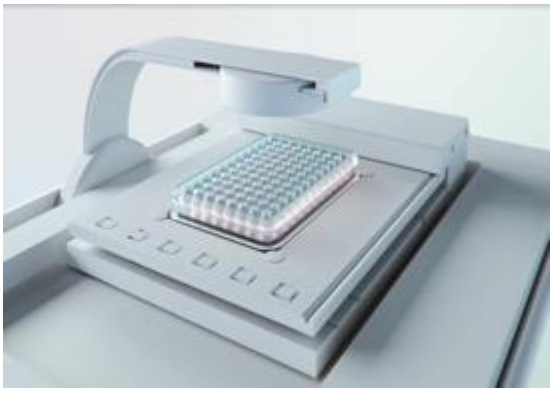


Inputs of the laboratory: 4 patents (CEA/UGA/CNRS)

Market / potential customers: Cell & Soft culture plates are intended for 1) cell-based assay, 2) drug discovery 3) stem cell differentiation and 4) cell engineering.
Contact: C. MIGDAL CAMILLE.MIGDAL@CELLANDSOFT.COM

ZYMOPTIQ
Understanding Enzymes

Founding in 2019
Activity: New technology to measure the enzyme activities
Inputs of the laboratory:
Patents : 3
PhD : 1
Market / potential customers:
Food/Feed
Nutrition
Detergent
Biofuel
Biomedical
Contact:
philippe.pebay@zymoptiq.com



III.4 Renatech impact: Key indicators

		2012	2013	2014	2015	2016	2017	2018	2019
Leverage for industry	Number of R&D projects with industrial partners								
	national	65	150	244	144	250	259	270	263
	international	6	48	17	18	22	66	56	56
	Number of exogenous projects	444	467	409	513	568	554	615	562
	Number of publications	655	867	915	838	821	929		924
Research excellence, research relevance and visibility	Number of PhD student	104	73	85	120	107	77	160	285
	Number of post-doct	92	50	68	73	60	87	131	86
	Number of training hours	3119	3200	3804	4562	3100	5303	4025	4075
	Number of patents and patents extension	-	165	170	177	147	159	207	235
Impact on the research and development activity	Number of common labs	13	10	10	12	10	10	15	13

IV. Prospects and evolutions

The BTR program was launched in 2003, planned for a period of 4 years, with a budget of 100 M€ and renewed each year since 2006 following the recommendation of the international panel. In this section, we will first overview recent investments of the BTR network over the last period beginning in 2006. Then, we will remind how the investment plan is elaborated, and how it feeds up the BTR funding request. At the end of the section, two tables will summarize the funding request for 2018.

IV.1 Presentation and recent evolutions in Renatech clean rooms

The Renatech netwok went through a change in 2018 with the move of the 2 two ex-laboratories: IEF (Orsay) & LPN (Marcoussis) in the new building in Palaiseau. This new lab named C2N has the biggest clean room area of the network with its 2200 m². We not that during this year, IEMN and the other clean rooms hosted people from C2N, which included researchers, PhD students and post doctoral fellow to aid them with their projects.It shows that Renatech members are integrated into the network.

On the other hand, we note a reduction in the number of the cleanroom technicians and engineers. This drop is more serious at IEMN and FEMTO-ST clean rooms and weakens them. It became more difficult to deal with demand of the community and more problematic because we have lost some technological expertise.

IV.1.1 C2N

In June 2016, Laboratory for Photonics and Nanostructures, located in Marcoussis (LPN) and the Institute of Fundamental Electronics in Orsay (IEF) merged together to create the Centre for nanosciences and nanotechnologies (C2N). This new laboratory is a joint research unit between CNRS and University Paris Saclay. It is affiliated with two CNRS Institutes «INP» (Institute of Physics) and «INSIS » (Institute of Sciences of Engineering & Systems). C2N main research topics are organized in 4 departments: nanoelectronics, photonics, microsystems-and-nanobiofluidics, and materials. C2N cleanroom is organized in 3 plateforms: 1- micro and nanotechnologies, 2- materials growth and 3-structural analyses platforms. From year 2016 to 2018, clean room facilities were located on ex-LPN (Marcousis) and ex-IEF (Orsay) sites. In Marcoussis, 700m^2 were dedicated for process and 350m^2 for material growth and epitaxy. In Orsay, 700 m^2 were dedicated to process in a clean room environment, and 300 m^2 for material growth in laboratories unclassed areas. In fall 2018, both facilities have moved into a new 3000 m^2 clean room on plateau de Saclay. After some delays in the Palaiseau site work, the cleanroom infrastructure has restarted in September 2019, and today 50 % of the tools are operational.

<u>The micro and nanotechnologies platform (PIMENT)</u> is composed of 28 engineers and technicians. They are in charge to keep more than 150 equipment (25 M€) at the state of the art, develop processes for the laboratory research activities, external users, small and medium companies, industries. Furthermore, the have an education and training mission. More than 220 students from masters, licences, engineer's schools are trained each year thanks to micro and nanotechnologies platform technical staff involvement. This platform is organized in 4 poles: lithography, deposition and growth, etching, characterization and back-end. These 4 poles are covering 9 resources:

- Optical lithography (UV mask aligners…), direct writing lithography (e-beam, laser, FIB…), alternatives lithography (nanoimprint, 3D lithography…)
- Metallic deposition and electrolytic growth (sputtering, e-gun evaporation…), dielectric deposition and thermal treatments (PECVD, ALD, furnaces…)
- Dry etching (RIE CCP, RIE ICP…), wet etching and chemistry
- Electronic and atomic force microscopy (MEB, EDX, AFM…), back-end (dicing, wire-bonding, polishing…), electric physic and chemical characterization (prober, ellipsometer, FTIR…)

- **The materials growth platform (POEM)** is coupled to C2N materials department. A technical staff of 7 engineers is in charge to develop materials and thin layer heterostructures for scientific projects. This experimental platform is dedicated to the development and the fabrication of the wide range of materials which are studied at C2N: IV-IV and III-V semiconductors, two-dimensional materials, functional oxides, metals. It relies on different advanced growth technologies based on the following equipment maintains (10 M€) and operates by the technical staff:

- 5 molecular beam epitaxy (MBE) systems dedicated to the elaboration of III-V compounds and heterostructures
- 1 metalorganic vapor phase epitaxy (MOVPE) reactor which fabricates advanced III-V heterostructures for photonics
- 1 UHV cluster tool which includes 1 chemical vapor deposition (CVD) reactors, 1 chemical beam epitaxy (CBE) reactor and several characterization tools (RHEED, SEM, AES, XPS)
- 1 pulsed laser induced epitaxy (PLIE) (very high local doping levels in Si or Ge)
- 4 Chemical Vapor Deposition (CVD) reactor to growth 2D materials (graphene on metallic substrates, hBN, graphene on SiC and WSe2)
- 1 pulse laser deposition (PLD) cluster to growth epitaxial oxide thin films (Perovskite oxides, YSZ, VO2 …)
- 1 sputtering system for the deposition of metals (Co, Pt, Ni, Cu, Au) and oxides (Al_2O_3…) for spintronic applications
- In-situ growth capabilities and their developments connected to a transmission electron microscope (HRTEM)
- Several in-situ or systematic characterization facilities: XPS, AUGER, AES, Raman Spectroscopy, FTIR, electrical measurements & in-situ surface characterizations.

As C2N concentrated high tech equipment into materials growth platform, one of its important missions is to provide state of the art samples and structures to the other physics laboratories, at a national level.

- **The structural analyses platform (PANAM)** is included into materials department. A technical staff of 3 engineers is responsible for the maintenance and the operation of state-of-the-art equipment and know-how in X-ray diffraction (XRD), transmission electron microscopy (TEM), microanalysis and atomic force microscopy (AFM). These facilities offer a wide range of structural, chemical and morphological analyses of materials at the nanoscale.

- Atomic Force Microscopy: basic analyzes of surface characteristics (topography, roughness, film thickness) with monoatomic resolution and studies using the magnetic (MFM) or electric modes (EFM/KFM) are possible. AFM can also serve as a nano-tool to modify the surface of a sample by local anodic oxydation (LAO). Three equipments operating in contact and tapping modes are available. One AFM can be used under controlled atmosphere, another enables nanomanipulation

- X-Ray Diffraction: crystalline phases, relative orientations, structural defects and alloy composition can be precisely analyzed in a non-destructive way using X-Ray powder diffraction, pole figures measurements, reflectometry, high resolution diffraction, grazing incidence diffraction. These techniques are applicable to thin films and ensembles of nanomaterials (nanowires or quantum dots). The facility includes tree multi-configuration diffractometers. One is equipped with a rotating anode and a goniometer dedicated to the diffraction of crystallographic planes perpendicular to the sample surface
- Transmission Electron Microscopy: transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM) are the most powerful techniques to characterize nanomaterials. The platform includes two (S)TEM with spherical aberration corrector on the STEM probe. They can operate with a very intense electron current focused in a beam of 0.1 nm diameter (smaller than a single atomic column). Scattered electrons are collected for the image formation and the detection of X-rays produced by the electron/matter interaction enables chemical cartography at the atomic scale.

NEW-EQUIPMENT

- **Micro-PL /micro-Raman Spectrometer – LabRam / Horiba)**
  - Co-Funding : 70 000 €. 70% RTB – 30% internal resources (ANR research projects).

The LabRAM HR Evolution Raman/photoluminescence (PL) microscope is suited for both micro and macro measurements, and offer advanced confocal imaging capabilities in 2D and 3D. The Photoluminescence-Raman microscope at C2N enables images and analyses with three lasers (633, 532 and 325nm) and different objectives from x100 to X10. The spectral range is from 325nm to 1.2µm. Gratings are 300, 600 and 1800 grooves/mm, enabling a spectral resolution of 0.7cm-1. The xyz platform has a step resolution of 100nm. The instrument has intuitive and simple use. It is mainly used to measure micro-PL /micro-Raman cartographies of 2D materials and semiconductors emitting from the UV to NIR.

The system was installed in C2N cleanroom in July 2019. It is open to users after a dedicated training. External users have also access to the tool (e.g. Alcatel III-V lab in 2019). The responsible for this equipment is Julien Chaste (julien.chaste@universite-paris-saclay.fr) from the group mat2D and dept Material, and the system is attached to the POEM platform.

Long-term strategy : to extend the PL detection up to 1650nm ; to install a customized micro-photocurrent mapping into the system ; to adapt a cryostat on the sample holder for measurement at various temperatures.

- **Raith EBPG 5200 – a 100keV E-beam nano lithography system.**
  - Co-Funding : 2 480 000 €. 5% RTB – 85% CPER, Regional SESAME Ile-de-France.

The EBPG 5200 presents high performances in e-beam writing: pattern with critical dimensions below 10 nm can be realized at high speed (writing frequency 125 MHz) and with full 200mm capability. Furthermore, it offers the possibility to write along the Z-axis (non-planar samples), such property is unique in France for this kind of system working at 100keV. This technical innovation has a real impact along several studies such as the fabrication of diffracting surface dedicated for synchrotron radiation on very thick sample (1cm) or the realization of adaptative optic system (3D lens). Those two examples are the core of our scientific collaborations with historical partners such as SOLEIL or Thalès.

- **Evaporator for teaching [T. Baptiste, G. Agnus**]
    - Co-funding : 5% RTB - 95% other resources (national programmes, and Université Paris-Saclay)

The dedicated zone for clean room training courses in C2N purchased a new deposition chamber by e-beam evaporation (Plassys MEB300S). It’s been delivered in fall 2019 and allows the deposition of either single films or multi-layers stacks in the 10nm-100nm range of thickness. This equipment was primary aimed to fulfill teaching purposes but the 6-crucibles turret and range of materials (Ti, Au, Cr, Al, Ni and Ge) would fit the different technological and research needs in the lab as well (photonics, nanoelectronics, microsystems and biological devices). This equipment will be indeed suitable for lift-off processes and structurations.

- **Rejuvenation PEVCD - APSY [F. Maillard]**
    - Co-funding : 150 k€ - 100% RTB.

PECVD is a chemical dielectric deposition tool. By injecting precursor gases (SiH_4, N_2, N_2O and/or NH_3), it allows thin layers (typically 20 nm to 5 µm) to be produced on samples of 2 to 8 inches and thickness of 200 µm to 5 mm. A plasma helps in the decomposition of these precursors and this machine has the particularity of having the choice between two generators to favor certain types of reactions (allowing among other things to play on the stress of the deposits).
The rejuvenation of the tool allowed the updating of the electronic components, the computer, but also the addition of a mass flow allowing to inject pure silane as well as helium. This will make it possible to control the dilution of the silane in nitrogen, or to produce depositions of hydrogenated silicon.

- **UPGRADE - Time-resolved cathodoluminescence with a streak Camera**
    - Co-funding : 200 k€ - 75% RTB - 25% internal resources (ANR research projects)

The cathodoluminescence (CL) set-up at C2N has been upgraded with a Steak Camera used as a detector in the time-resolved cathodoluminescence mode (TR-CL). The TRCL temporal resolution is now ~ 10 ps (limited by the pulsed electron beam dynamics) in the 250 nm-900nm spectral range. This make the TR-CL set up unique in France and Europe for spatially and time-resolved CL analysis of materials over a wide temperature range (10nm, 10ps, 10K-300K), and with a large measurement dynamics (~ 3 decades in photon counting mode). The upgraded setup is dedicated to the determination of the minority-carrier lifetime, and analysis of the recombination mechanisms in various nanomaterials including wide bandgap semiconductors (ZnO, GaN, AlGaN), materials emitting in the visible and NIR (GaN/InGaN quantum wells, II-VI nanostructures, CIGS, perovskites, GaAs-based heterostrutures). This qualification is required for their further integration in optoelectronic devices (e.g. laser diodes, LEDs and micro-displays, photovoltaïc cells and energy recuperators).
The TR-CL upgrade has been installed during September-November 2019 and is operational since December 2019.
The CL -up is attached to the PHOTONICS Dept and its responsible is Stephane Collin (stephane.collin@c2n.upsaclay.fr). The CL set-up is open to C2N projects and users as well as

external projects and users (10 projects running in 2019). The TR-CL extension is under qualification and will be open under the same mode from 2021.

Long-term strategy : our next objective is to integrate a pulse peaker in pulsed e-beam set-up, in order to extend the temporal range of the luminescence decay from 10 ps to 100 ns range (presently limited to 10ps-12ns), for a refined analysis of the fast / slow carrier recombination mechanisms in nano- or polycrystalline materials.

- **AFM (ICON BRUKER) with nano-manipulation capability, and manual transfer station**
  - Co-Funding: Total Cost = 261 500 €. RTB: 43% - DIM SIRTEQ (Mi-Lourd Topo2D - 2018, PI: Rebeca Ribeiro-Palau): 57%.

The atomic force microscope ICON from Bruker is suited for AFM multimodes operation (topography, nanomanipulation and electrical measurement) at nanoscale level. This equipment has both a high stability (0.03 nm resolution in vertical direction) and an easy graphic interface, which grants access to a highly performance equipment by a large amount of "non-experts" users. Another advantage of this AFM it is the easy ScanAssist mode combine with Peak Force mode which allows topography access to soft sample (polymers, organic materials) without tip or sample damage, this is achieved by controlling ultra-low interaction forces and automatic force and scanning control. The system was installed in C2N cleanroom on April 2019 and it is open to users after a dedicated training. The responsible for this equipment is Christophe David (christophe.david@universite-paris-saclay.fr) from dept Material, and the system is attached to the PANAM platform.

The 2D materials transfer station has the possibility to transfer 2D materials from the monoatomic thickness to few hundred nanometers, its spatial resolution if better than 5 um. This station can be used to transfer 2D materials and nano-objects from one substrate to another or to build ultra-clean van der Waals heterostructures and dynamically rotatable structures, that later can be manipulated with the previously described AFM. This station is operational since July 2018.

Around 50 % of its use time is dedicated to the project Topo2D concerning assembly and nanomanipulation of 2D materials.

Long-term strategy : to upgrade the transfer station towards a collective, parallel transfer, to explore the transfer under controlled atmosphere.

IV.1.2 FEMTO-ST

The technology center "MIMENTO" of FEMTO-ST is a state-of-the-art multi-user facility for micro and nanofabrication, specialized in micro-nano-acoustics, micro-nano-optics and MOEMS and more recently in microrobotics. MIMENTO facility is housed in its 850 sq. meters clean room in class 100, 1000 and 10000 and includes both the micro- and nanofabrication facilities and characterization instruments. This includes a technical staff of 12 engineers/technicians. All the equipment of MIMENTO facilities is worth about 17 M€.

The R&D activity at MIMENTO follows the main points described below:

• Technological research: micro- and nano-structures for research in physics, chemistry and biology, microstructures for the characterization of new materials.

- Manufacturing processes: new manufacturing processes in silicon and other materials (lithium niobate, glass, piezolectric materials such as zinc oxide or AlN), new processes for microelectronics, silicon post-processing.
- Integration and encapsulation techniques for microsystems.

The clean room is organized in 7 working areas:
- lithography (laser pattern generator, spray and spin coaters, single & double side aligners),
- physical deposition (sputtering&evaporation, low stress&temperature ICP PECVD, cluster for AlN deposition, diffusion and thermal oxidation furnaces, RTP)
- plasma etching (Silicon DRIE and RIE, quartz & niobate & glass DRIE, different RIEs),
- wet processes (electrodeposition, wet etch for Si, quartz, niobate, metals, etc..),
- packaging and 3D integration (wafer bonders,wire-bonder, flip-chip, megasonic cleaner, plasma activation,…)
- dicing and polishing (high precision dicer with cut&polish, wafer polishing)
- nanotechnology (FIB, E-beam lithography)
- characterization tools.

One of strategic objectives of MIMENTO is to reinforce the excellence of our research combining basic science and microtechnology in the frame of several structuring projects such as Labex ACTION focusing on the development of smart systems where the innovation is accompanied by a strong collaboration with local industries (Frec|n|sys, IX-Blue, Crystal Device Technology, Robotics Percipio, Lovalite, Silmach, Sonaxis, SENSeOR…) directly processing in our clean room. Several industrial boxes are available for renting.
The spin-off Frec|n|sys, created by a former CNRS researcher at FEMTO-ST, is operating a pilot line at MIMENTO, making the design, the fabrication, and the commercialization of advanced SAW (surface acoustic wave) and BAW (bulk acoustic wave) devices, such as filters for telecommunication applications. The pilote line includes the stepper, automatic coating system and piezoelectics deposition cluster. Another spin-off company Silmach, in the field of MEMS devices for innovative hybrid integrated sensors, is closely collaborating with the FEMTO-ST institute together with Frec|n|sys and Percipio Robotics, on novel process and products based on Silicon MEMS sensors involving deep plasma etching, in the framework of a regional FEDER program in Smart Specialization called 3S-MEMS.
The operating budget of MIMENTO clean room is about 900 k€ / year. In 2019, MIMENTO received 76 internal projects and 76 exogenous projects (including 44 industrial projects) for a total amount over 14765 hours of equipment usage, including around 130 hours dedicated to training of students (bachelor, master).

IV.1.3 IEMN
Micro & Nano Fabrication Center (MNFC) and Nano-characterization and Scanning Probe Microscopy Platform (SPMP) are both parts of IEMN Renatech facilities.
Since September 2015, a new building was opened to host the scanning probe microscopy and the EQUIPEX LEAF (Laser procEssing plAtform for multiFunctional electronics on Flex) facilities in an area of about 700 m2 (ISO 8 class). This new building has been designed to achieve good temperature stability and to avoid to be disturbed by external and internal vibration. Thanks to this building, the expected scientific and technical equipment performances can be reached.

The clean-room is a complete fabrication line for high speed III-V micro, nano and optoelectronic devices but also RF and Bio-MEMS devices. The cleanroom facilities missions are to be at the best international research level in micro and nanotechnology and to support academic organizations and industries that require the use of large clean-room infrastructures. 2300 m2 of clean-room area and 23 high skilled engineers and technicians are devoted to support the research activities in those innovation areas to be at the state-of-the-art scientific activity of researcher from basic physics to industrial applications.

Organization of the Micro & Nano Fabrication Center (MNFC)

In order to satisfy the user needs, 19 engineers and technicians are assigned to the clean room. This clean room (ISO 6 class) has a total area of 1860 m2. The structure is organized in 8 technological resources: material growth, physical deposition, chemical deposition, lithography, etch, integration, scanning probe microscopy and characterization. Each resource is constituted by a coherent set of equipment devoted to specific process steps. All facilities are under the responsibility of one specific engineer for the maintenance and the control of process step quality. Part of the technical staff has also the entire responsibility of devices processes for research contracts, for external project through academic or IEMN-industry collaboration. The wafer diameter is usually 2'', 3'' with some equipment suited for 4'' wafers. The total equipment represents, in 2019, a total value of about 32 M€. Some equipment are in self-service, and then used by the scientists and students while other are not and only operated by the technical staff. Any user has to follow a training performed by the technical staff in charge of the equipment. More than 750 h of training are provided to new academic users and PhD students.

The IEMN clean-room facilities have many equipment. Most of processes developed in lithography (standard resist processing, ...), deposition (LPCVD doped polysilicon, Metal evaporation, atomic layer deposition, ...) and etching (III-V material reactive ion etching, ...), process control (MEMS inspection, ...) have an excellent level compare to laboratories working in the same field. Two facilities have got world class capabilities with some outstanding processes. Those processes are e-beam writing and ion implantation. The accuracy of the e-beam and the e-beam proximity correction system allow to write reproducible 10-nm structures. The implanter of IEMN has a large variety of possible implantable elements. Samples could be tilted in any directions, substrate holder is heated up to 500°C and a deceleration of the ion beam down to 5 keV is available. All those knobs give the opportunity to finely tune any processes for advanced research applications.

Organization of the Scanning probe microscopy facilities:

4 full time equivalent engineers are dedicated to this 440m2 large platform (ISO 8 class). The structure is organized in 2 technological resources: ultra high vacuum and ambient air microscopes. Some equipment are in self-service, namely used by the scientists and students while others are not and therefore only operated by the technical staff. Any user has to follow a training performed by the technical staff in charge of the equipment.

10 scanning microscopes such as AFM (Atomic Force Microscope) and STM (Scanning Tunneling Microscope) are available to observe, manipulate and study atoms and nanoscale devices. Thanks to these resources and expertise, physical properties (topography, mechanical, electric, thermal, magnetic, …) at nanoscale could be obtain in a large temperature range and with magnetic field.

Planned Acquisitions 2020/2021

- FIB: 1.300 k€

IV.1.4 LAAS

LAAS conducts research activities on different type of systems: micro and nano systems, embedded systems, integrated systems, large scale systems, biological systems, mobile systems, autonomous systems et critical information systems, with application domains such as : aeronautics, space, transportation, energy, services, health, telecommunications, environment, production and defense.
There are 8 research topics in the LAAS animating the activities of the 22 Research Teams of the laboratory:

- Critical Infomation Processing
- Networks and Communications
- Robotics
- Decision and Optimization
- MicroNanosystems RF and Optical
- Nano-Engineering and Integration
- Energy Management
- MicroNanoBio Technologies

A 1600m² clean room (ISO 5-7) support micro and nanotechnologies research projects from the entire french and foreign communities. In this clean room the main technological know-how are focused on

- Optics / Photonics
  - Photonics on transparent substrates/opticals
  - III - V multifunctional integrated components
  - Optical sensors
- Micro nano electronic
  - Nanowires nanocomponents
  - Power Micro Electronics
- bioelectronics, Biosystems, biophysics
  - Micro/nano fluidics
  - Micro sensors
  - Advanced Micro Nanostructures for bio detection technology
  - DNA technology for advanced materials and sensors
- Micro Nano device, micro Nanosystems
  - RF Micro switches with capacitive and resistive contact
  - Passive wireless sensors with electromagnetic transduction
  - Micro energy storage
  - Pyrotechnic actuator based on reactive nano materials
  - Integrated systems on flexible substrates
  - Llow temperature process for 3D Integration and interconnection

In the technological platform, it is all the equipment needed for components prototyping. From mask design and fabrication up to the characterization; through optical, laser or electron beam lithography, wet and dry etching, thermal processes, electroplating, vacuum depositions, molecular beam epitaxy, ion implantation, chemistry, packaging and innovative technologies such as ink jet, screen printing, surface treatment and nano replication. These 200 equipment (> 35 M€ value) support more than 150 projects/year.

Beyond the aspects of infrastructure and equipment, a main strength of the platform is the technical human resource. The TEAM technical staff (https://www.laas.fr/public/en/team) of 34 persons is in charge of the platform, the equipment and supports the research activities. To carry out its missions, the TEAM department is organize around Technical Area Leaders (TAL) and Project Coordinators (PC). A TAL is in charge of a group of equipment, or of homogeneous technologies; a PC is leading the technological part of a project in collaboration with researchers. This organization with specialists allows developing the technological knowledge.

An online application (https://lims.laas.fr/default.aspx) allows the management of the activities, equipment, projects and users. The operations are payed through auditable fees.
External demanders can apply either on Renatech web site or through email : renatech@laas.fr.

New equipment

- **PE-ALD (285k€ ERC3D cap and RTB)**

Since January 2020, the CVD area has been hosting a new chemical deposition equipment with plasma assistance from SENTECH.
This machine is intended for the atomic layer deposition of RuO2 (ruthenium oxide) or RuOxHy (hydrogenated ruthenium oxide).
The diameter of the substrates varies from 100 to 150 mm but with a suitable support, samples with variable geometry of less than 50mm size can be processed.

- **RIE ICP avec option DRIE (340k€ RTB)**

Since January 2020, the plasma etching area host a plasma etching machine such as GIR-PCI or RIE-ICP from Sentech. This machine inted to etch silicon, silicon nitride, silicon oxide for thicknesses between 100nm and 5m. It has the DRIE option for deep silicon etchings up to 600 µm

- **PECVD 100 ApSy (100 k€ RTB)**

This CCPECVD NOMOS equipment was partially retrofited by the Application-System company during the year 2018.
It can make siO2, Si3N4 and SiON materials deposits in CVD mode assisted by a capacitive plasma at 13.56MHz or 380KHz for temperatures of 200 degrees Celsius or 300 degrees Celsius. The substrates used are Si, glass, of different sizes up to 150mm in diameter, which are place on an aluminum tray.
A single-wavelength tool with an OES filter connected to the control automat allows you to track the cleaning of the deposit chamber in real time.

- **Finalizing glove box for hydrofluoric acid and derivatives manipulation (16k RTB)**

The transformation of the chemical bench for hydrofluoric acid manipulation into a glove box has been finalized,. This bench post now allows a safe treatment of substrates (treatment and rinsing in vertical bins, with resistance-based monitoring of the rinse). The operator's protection is significantly enhance, while reducing the wearing of PPE. This closed system is similar to the legally confined systems payable for non-permanent personnel handling hydrofluoric acid.

IV.1.5 LTM

The LTM facility, located in Grenoble, runs a clean-room with a total area of 1200 m2. PTA (700 m²) is devoted to upstream research using 100 mm state of the art equipment whereas 500 m² of LTM cleanroom facilities are embedded in 200-300 mm LETI platform. This section of the cleanroom is used for the development of technological processes on 200 mm and 300 mm silicon wafers dedicated to micro- and nanoelectronics research programs. Main fabrication equipments are devoted to plasma etching and III-V deposition using MOCVD. The IMPACT platform, combining both advanced characterization techniques (pARXPS, IR-VUV Ellipsometry and Polarimetry, IR-UV Raman and PL) and very versatile sample loading capability (from small sample to 300mm), establishes a very specific and unique set.

PTA platform is located in the 1005 CEA building (350 m²) and in the BCAi cleanroom (350m²) localized in a Grenoble-InP building. The PTA offers the technical capabilities needed to cover a wide range of projects in nanosciences and micro- nanotechnologies: complementary methods and equipment facilities for lithography, deposition or etching enable reliable integration of nano-objects and nano-materials or patterning of thin layers in the nanometric range. The PTA can accommodate all types of substrates from small 5 x 5 mm² sample up to the 100 mm wafers. A huge diversity of materials can be processed within a reasonable approach of contamination management. The research fields are numerous: nanoelectronics, MEMS & NEMS, magnetism and spintronics, integration of nano-materials and nano-objects, photonics, ... The purpose of the facility is both to provide the needed means and skills to researchers, and to welcome industrial companies looking for a place to develop their projects. 19 engineers and technicians are assigned to LTM facilities.

New equipment

- ZEISS EVO 10 SEM

The Zeiss EVO 10 Scanning Electron Microscope (SEM) is located at 40.06 building. This SEM offers the functionality of a conventional SEM while also providing the speed and ease of use commonly associated with tabletop solutions. As a user-friendly equipment, this SEM is well adapted for many users.

- AFM Icon

Bruker’s Dimension Icon AFM offers excellent resolution, reliability and productivity. It is used in Tapping and PeakForce Tapping modes by many researchers that want to determine at the nanometer scale the surface roughness and/or nanostructure sizes on a large variety of samples in order to get a rapid feedback on their growth or etching process. One main particularity of this system is that it allows large sample analysis up to 200mm wafer size.

- DLS MalvernPnanlitycal

LTM bought a Zetasizer Ultra from Malvern Panalytical that measures by Dynamic Light Scattering the particles and molecules sizes (from 1 nm to 10 µm) in suspensions and measures by Electrophoretic Light Scattering the zeta potential of particles and molecules of colloidal suspensions. This tool is the most advanced combined DLS and ELS system with Multi-Angle Dynamic Light Scattering technology that insures higher resolution of the size distribution. Proteins and nanoparticles sizes are commonly measured.

V. Funding request for 2019 and investment policy for 2019-2020

V.1 Critical impact of continuous reduced funding (2007-2014)

The continuous reduction in BTR funding, since 2007, results in a noticeable slowdown of new technological developments. The research centers and associated laboratories must therefore have to make priorities and arbitration, resulting in the inability to start some new research subjects. Today, the situation is critical when we received requests on subjects for which the institutes and research centers are clearly behind the rest of the world.

V.2 Last equipment and the strategic funding request

V.2.1 C2N

- **NEW – 2nd MOVPE reactor**

A second MOVPE reactor operated by C2N will be installed at Thales R&T, in Palaiseau. It will be dedicated to the growth of III-V heterostructures such as GaAs-based VCSEL or microcavities, InP/InGaAs membrane laser heterosttuctures, InGaP/GaAs membrane heterostructures for non-linear photonics, .. The previous reactor will be devoted to the development of research on GeSn/Si materials and heterostructures for light emission.
Applications/Domains: quantum optics, nanophotonics, and photonic integrated circuits
Funding : 2 800 k€ (obtained) - 17% RTB – 28% regional Ile-de-France (SESAME programme) – 53% internal resources, CNRS, and CPER 2015-2020.
Delivery : expected 2021

- **UPGRADE – Bonder**

Hardware upgrade or our SUSS-MICROTECH and EVG bonders. The SUSS-MICROTECH bonder is no more operational after the move to Palaiseau site
Applications/Domais: MEMS and hybrid photonics
Requested Funding : 53 k€ - 100% RTB.

- **UPGRADE – RAITH ElectronBeam lithography (EBPG5000)**

Hardware /software upgrade or our ebeam lithography EBPG5000, in order to be compatible with the new EPBG files format.
Applications/Domains: nanoelectronics, spintronics, nanophotonics
Requested Funding : 83 k€ - 100% RTB.

- **UPGRADE – JEOL transmission electron microscope (TEM)**

Hardware /software upgrade of our JEOL TEM. The acquisition electronics and PC interface is obsolete and no more supported by JEOL. The new system could be compatible with the installation of Precession Electron Diffraction Tomography on the microscope in a near future.
Applications/Domains: Materials
Requested Funding : 50 k€ - 100% RTB.

- **UPGRADES – several upgrades after the move to Palaiseau sites**

Several tools have suffered from the move, they are no more operational, and need to be repaired : HF6vapor etching tool, Ellipsometer, XPS detector (channeltron) installed on the CVD cluster.
Requested Funding: 68 k€ - 30% RTB – 70% internal resources

- **NEW – Electrochemical C-V profiler**

To acquire an ECV profiler dedicated to the control of doping and to dopant depth-profiling in IV-IV and III-V semiconductor heterostructures grown at C2N. Our lab is not equipped with any C-V system for doping control.
Requested Funding (estimated): 110 k€ - 100% RTB

- **NEW – CVD deposition of parylène**

To acquire a CVD chamber devoted to the deposition of C-Parylene films with films thickness from ~ 100nm to tens of microns. It will be mostly devoted to the fabrication of bio-compatible sensors. Our objective is to replace part of our PDMS technology with parylene. Conformal deposition of parylene will also be explored for the encapsulation or passivation of nanostructures (e.g nanowires, ..)
Requested Funding (estimated): 220k€ - 80% RTB – 20% other resources.

V.2.2 FEMTO-ST

- **Participation in CO2 laser processing station (New, 78 k€ HT)**

Description of the equipment: This tool is a CO2 laser source with a galvanometric laser scanning system for laser material processing. The galvanometric head coupled with an XY table allow high speed scanning with a precision that may reach 1.5µm. The station includes 2 cameras for precise positioning of the sample with complete software control of the beam motion.
Justification: The laser station is targeting different uses in the cleanroom. First it is designed to complement our 3D laser glass patterning tool (FEMTO-Print) for controlling reflow of glass and smoothing the etched surface. The new opportunity will help extend the application of this innovative technique to the realization of micro-optical elements like micro-lenses and micro-axicon, as required for example, for new integrated biomedical optical sensors. The laser will also be used for marking the back of wafers, allowing to fully track the wafers in the cleanroom. This will open the way to automatic logging of process steps for decreasing source of errors for the benefit of all users. Finally the laser will be used to free fragile structures by allowing to zap supporting bridges without any mechanical contact.
Direct & indirect cost & sources of funding: The total cost of this machine is 134k€ (HT) that will be covered by the RTB grant and by the region Bourgogne-Franche-Comté CPER fund. The cost of installation is minimal and will be supported by the platform.
Incomes related to the investment: The different use of the machine ensures a steady return on investment, and for example the laser marking will be added to the wafer cost, generating already several k€ of revenue per year.
Risks: There is a possibility that the glass reflow process does not bring as much revenue as planned, but the versatility of the tool will help open new opportunities for supporting its operation.

- **Participation in Metal-Glass-Piezoelectric material plasma etching (New/Renewal, 111 k€ HT)**

Description of the equipment: This tool is a plasma etcher with fluorine and chlorine chemistry dedicated to non silicon materials etching.

Justification: We need to replace an aging STS ICP fluorine plasma etching tool that has about 15 years and has seen a high rise in maintenance fee in the past 2 years. This tool is used for etching hard to etch materials like glass, quartz or lithium niobate for photonics, acoustic wave and microfluidics applications. Moreover, we want to be able to etch metals and some new materials that require a chlorine chemistry. Accordingly, we propose this new tool that will allow to propose the two chemistries etching in the same chamber. The tool will also be able to accommodate large substrate (up to 7”) for etching of photolithography mask after photoresist patterning. The tool will complement the two ICP DRIE tool dedicated to silicon etching we have in the cleanroom.

Direct & indirect cost & sources of funding: The total cost of this equipment is about 450 k€. The RTB funding this year will be completed by CPER funds from the region Bourgogne-Franche-Comté.

Incomes related to the investment: From past usage of the existing STS tool, we project a minimum use of about 400h, that does not take into account the new capability linked with the chlorine chemistry. Although the cost of ownership of etching equipment is in general rather high, by using a versatile tool attracting more users and by discarding an aging tool, we will minimize the overall cleanroom cost for the users.

Risks: The identification of the FEMTO-ST facility as a resource for non-silicon plasma etching lower the risk for this equipment, which will be used to reinforce the piezo-electric and electro-optic etching capabilities, directly in line with two important scientific domain of the FEMTO-ST institute.

Process development (21 k€ HT)

In order to develop new processes on newly acquired equipments, we need one additional research engineer on a fixed-term contract. The staff will develop new standard processes, and will promote these new technologies to internal and external users. Specifically, we need an engineer for developing new process on the new SEM with material characterization probes and the surface profile characterization equipment that we have recently bought.

Total 210 k€ HT

V.2.3 IEMN

IEMN have decided to continue their policy of upgrading existing equipment that is in great need of upgrading. They will also by a new FIB to replace the only one for Renatech network (**1,3 M€**).

V.2.4 LAAS

Optical profilometer/vibrometer (330 k€)

Optical profilometry is an essential micro and nanofabrication characterization technique. Based on a non-contact method, the system allow three dimensional image reconstruction of components with fast and precise roughness and thickness step measurement, without contamination and preparation. At LAAS, we have two outdated systems (interferometry and confocal) used by nine research TEAM to perform their research. A new generation equipment would make possible both optical profilometry and movement analysis (vibrometry), which is a great evolution. All researches about MEMS (Micro Electrical Mechanical System), a key expertise at LAAS, need this tool to analyze their running sample.

Direct cost of the equipment with both capabilities (profilometry and vibrometry) at a world-class level is 330 k€ and will be funded by RTB program. The indirect cost for installation (10 k€) and running (10 k€/year) will be funded by LAAS clean room budget. Users through auditable billing will then pay these running costs.

V.2.5 LTM

More and more research activities are emerging in the fields of sensors and microsystems at the PTA. In this context, we need to replace the DRIE etching tool, which is outdated without technical support from the supplier. The new DRIE equipment will have new capabilities leading to better Si etching performances in terms of depth, selectivity and uniformity. This tool should also be able to etch other materials such as Ge, Diamond and SiC addressing the new needs emerging at PTA in the fields of photovoltaic and power electronics. The new equipment will be based in place of the old one leading to a low cost for the hook-up. The yearly activity is expected to be enough to cover at least the running cost. The global budget is estimated to be around 900 k€ and we plan to combine the RTB of two years to partially pay this equipment.

Summary

Clean-room	Investment name	Amount k€
C2N	2nd MOVPE reactor	2 800 000,00
	Bonder	53 000,00
	RAITH ElectronBeam lithography (EBPG5000)	83 000,00
	JEOL transmission electron microscope (TEM)	50 000,00
	several upgrades after the move to Palaiseau sites	68 000,00
	CVD deposition of parylène	220 000,00
	Electrochemical C-V profiler	110 000,00
	TOTAL	3 384 000,00
FEMTO-ST	Participation in CO2 laser processing station (New, 78 k€ HT) - 134k€ (HT)	134 000,00
	Participation in Metal-Glass-Piezoelectric material plasma etching (New/Renewal, 450 k€ HT)	450 000,00
	Process development (21 k€ HT)	21 000,00
	TOTAL	605 000,00
IEMN	FIB	1 300 000,00
	TOTAL	1 300 000,00
LAAS	**Optical profilometer/vibrometer**	330 000,00
	TOTAL	330 000,00
LTM	the DRIE etching tool	900 000,00
	TOTAL	900 000,00
TOTAL		6 519 000,00

VI. Conclusions

Nanosciences and micro/nano technologies place the French public research at the 6th world position in a highly competitive ranking that affects all economic sectors (aeronautics, automotive, health, manufacturing processes, household and leisure equipment, defense and security, etc...). This context leads to two large challenges for public research laboratories, in France:

- Maintain an upstream research at the best international level to support the industry of microelectronics on miniaturization technologies for microcontrollers and memory for the Big Data and Cloud Computing,
- Acquire a leadership position in the connected objects to the Internet of Things (IoT), for innovative business and start-ups. These devices integrate complex functions (sensors, actuators, communication, storage, and energy management) involving a multiplicity of materials and co-integration of technologies.

The acceleration vectors of these technologies have already been identified. Moving into the future, there are trends of developing new materials and devices for sensors, actuators and innovative energy generators. Upstream R&D, ranging from 1 to 6 TRL levels, rely necessarily on heavy equipment, often installed in clean rooms. This is consistent with visions given by ITRS (International Technology Roadmap of Semiconductors) and Horizon2020 programs.

Since the cost of Nanotechnology is growing every year, we are convinced that it is of uttermost importance for developed countries and for EU to rationalize the organization of technological R&D and try as much as possible to manage globally our technological knowledge, our know-how, and our heavy investments. We hope that the RTB structuring action will be able to contribute efficiently to this goal. Moreover, this must avoid reproducing dramatic situations such as those where the network missed new research areas like 2D related materials revolution or the next 3D/4D printing technology.

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