C2N
Centre de Nanosciences & de Nanotechnologies

HIGHLIGHTS 2022

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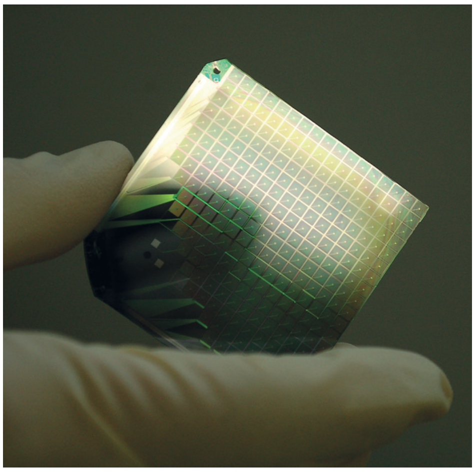
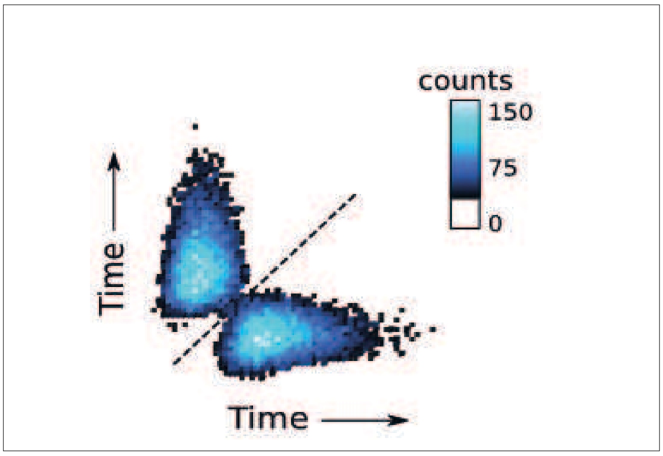
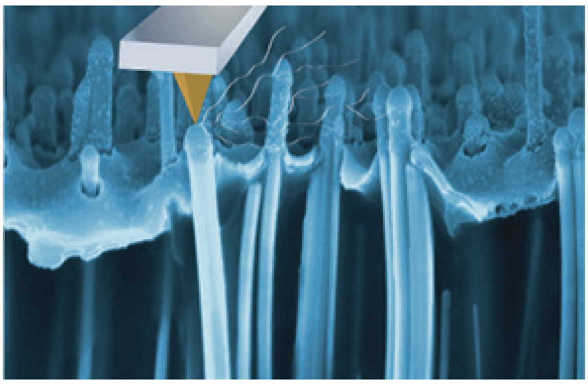
C2N - Avril 2023

SUMMARY







HIGHLIGHTS 2022

FOREWORD

Throughout the past year, C2N has continued its trajectory, once again positioning itself as a leading laboratory in Nanosciences and Nanotechnologies, committed to serving science and the academic and industrial scientific community.

The highlights presented here are one of its signatures. Congratulations to all our research teams for these remarkable results, which contribute to C2N's reputation. I would also like to associate the engineers and technicians of our Nanotechnology Centre and the other three platforms with these results, as they are essential players and contributors to this success.

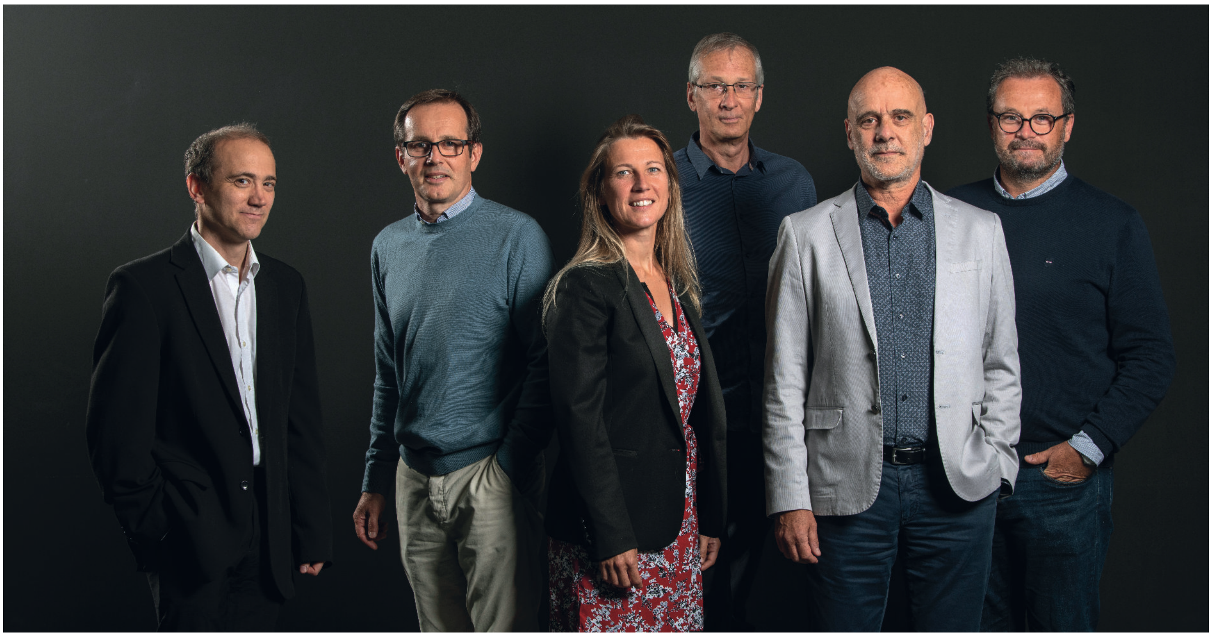
This year, 6 of our researchers and professors have been awarded an ERC grant, which contributes to strengthening our international dimension.

Numerous successful collaborative projects, from fundamental research to industrial breakthroughs, also testify to our dynamism. They illustrate our mission to combine science and innovation in order to respond to the challenges and societal issues of tomorrow (health, renewable energies, etc.). Our laboratory therefore aims to fully develop its role in society. Our aim is to develop our activities in a sustainable manner, by combining research and energy saving actions.

Thanks to the commitment of all its teams, I would like to acknowledge the daily work, skills and dedication of our support services, and the support of our supervisors (CNRS, Université Paris Saclay, Université Paris Cité). C2N's future looks promising.

I would like to express my gratitude to all those who have contributed to this edition of «Highlights 2022» and I would like to thank in particular the C2N communication team for its valuable contribution.

We wish you a pleasant reading.
Giancarlo Faini
Head of C2N
April 2023



@Claudia Bevilacqua

The C2N Management Board
from left to right

Arnaud Bournel, Head of the Nanoelectronics department
Pierre-Yves Joubert, Head of the Micro Systems and Nanobiofluidics department
Cynthia Vallerand, Chief Executive Officer
Jean-Christophe Harmand, Head of the Materials department
Giancarlo Faini, Head of the Unit
Laurent Vivien, Head of the Photonics department

KEY FIGURES*

352 - STAFF MEMBERS

180 - PERMANENTS STAFF

64 - RESEARCHERS

44 - TEACHER-RESEARCHERS

72 - ENGINEERS TECHNICIANS

28 - POST-DOCS

144 - PHD STUDENTS

37 - NATIONALITIES

RESEARCH

2 - HABILITATION TO DIRECT RESEARCH (HDR)

245 - PUBLICATIONS

19 - THESIS DEFENDED

21 - SEMINARIES

* *1st January 2023*

PUBLICATIONS

Electromechanical conversion efficiency of GaN NWs: critical influence of the NW stiffness, the Schottky nano-contact and the surface charge effects

The piezoelectric nanowires (NWs) are considered as promising nanomaterials to develop high-efficient piezoelectric generators. Establishing the relationship between their characteristics and their piezoelectric conversion properties is now essential to further improve the devices. However, due to their nanoscale dimensions, the NWs are characterized by new properties that are challenging to investigate. Here, we use an advanced nano-characterization tool derived from AFM to quantify the piezo-conversion properties of NWs axially compressed with a well-controlled applied force. This unique technique allows to establish the direct relation between the output signal generation and the NW stiffness and to quantify the electromechanical coupling coefficient of GaN NWs, which can reach up to 43.4%. We highlight that this coefficient is affected by the formation of the Schottky nano-contact harvesting the piezo-generated energy, and is extremely sensitive to the surface charge effects, strongly pronounced in sub-100 nm wide GaN NWs. These results constitute a new building block in the improvement of NW-based nanogenerator devices.

The number of “Internet of Things” (IoTs), such as micro-devices (micro-sensors, small nomad electronic, medical implants…) is constantly on a rise both in our daily life and in high-tech applications. To deal with the critical increase of their associated energy consumption, but also to improve their condition of use, especially for those evolving in environment without electrical grid infrastructure or with restricted one, the question of their energetic autonomy is today a key worldwide challenge with strong economic and environmental repercussions. With the recent miniaturization of the electronic devices resulting in the reduction of their energy consumption to mW and even µW, and thank to the micro-nano-fabrication progress, new perspectives appear to develop autonomous power systems based on the renewable energy harvesting. Piezoelectric GaN NWs are promising nanostructures for fabricating efficient piezo-nanogenerators having the ability to convert mechanical deformations and vibrations into usable electrical energy. Thanks to their nanoscale dimensions, their large surface-to-volume ratio and their quasi-lattice perfection, NWs, in comparison with their bulk and 2D-film counterparts, are characterized by : 1) superior mechanical properties; 2) higher sensitivity to applied force; 3) higher piezoelectric coefficients; and 4) the apparition of novel properties, non-existing or non-significant at micrometric scales that can lead to a strong modulation of their characteristics. However, at the nanoscale, it is challenging to characterize these properties and thus fully take advantage of them to improve the performances of the NW-based devices. We use an advanced nano-characterization tool derived from AFM, developed by colleagues from the Materials Team at GeePs, to quantify the piezo-conversion properties of NWs axially compressed with a well-controlled applied force. This unique technique allows deforming axially the NWs and then establishing the direct relation between their output signal generation and their dimensions. It also makes it possible to deform the NWs similarly to the ones integrated into the devices. Then, we have highlighted the relationship between the NW deformation and their piezo-conversion properties. We have also demonstrated that the coupling coefficient is not only driven by the mechanical characteristics of the NWs. Two other parameters, often neglected, play a crucial role: 1) the formation of the Schottky nano-contact allowing increasing the piezo-generated energy harvesting; and 2) the strong influence of the surface charge effects, which under given conditions, are able to remarkably enhanced the electromechanical conversion efficiency of the GaN NWs.

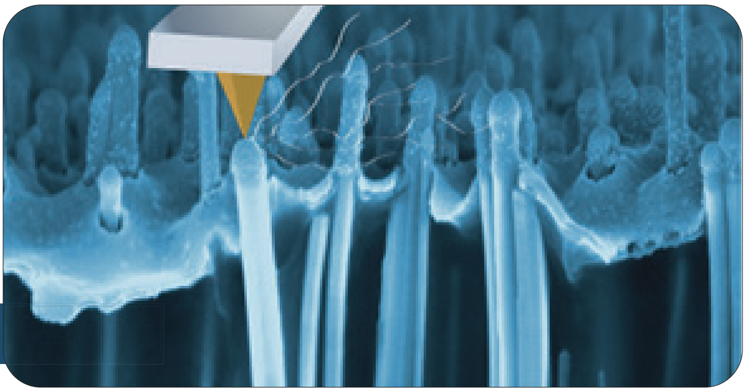


Figure : GaN nanowires for an efficient electromechanical conversion

References

Electromechanical conversion efficiency of GaN NWs: critical influence of the NW stiffness, the Schottky nano-contact and the surface charge effects
Noelle Gogneau, Pascal Chrétien, Tanbir Sodh, Laurent Couraud, Laetitia Leroy, Laurent Travers, Jean-Christophe Harmand, François H. Julien, Maria Tchernycheva, and Frédéric Houzéb

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High piezoelectricity in epitaxial Bi-FeO_3 microcantilevers

Researchers from C2N, in collaboration with colleagues from Université de Picardie Jules Verne, have reported the first investigation of the piezoelectric response in epitaxial $BiFeO_3$ MEMS (micro-electro-mechanical system). The devices demonstrate larger electromechanical performance than that of state-of-the-art piezoelectric cantilevers, including well-known PZT ($Pb(Zr,Ti)O_3$) and PMN–PT ($Pb(Mg_1/3Nb_{2/3})O_3$-$PbTiO_3$). This, combined with the low dielectric constant and lead-free composition, could potentially lead to a replacement of lead-based piezoelectrics by $BiFeO_3$ in many microdevices.

The large switchable ferroelectric polarization and lead-free composition of $BiFeO_3$ (BFO) make it a promising candidate as an active material in numerous applications, in particular, in micro-electro-mechanical systems (MEMS). For device applications with improved performance, BFO is preferred in a thin film form, epitaxially grown with particular crystalline orientations, showing robust ferroelectric and piezoelectric properties. The growth of BFO films on Si substrates is particularly important for the compatibility of the devices with Si—being the basis of semiconductor technology. Among MEMS, cantilevers using transverse piezoelectric response (31 modes) are the prototype device structures for actuation and sensing. Only a few studies have recently reported the integration of BFO films into cantilevers, and they were all focused on polycrystalline BFO films patterned into micrometers-thick cantilevers. The piezoelectric response of MEMS based on epitaxial BFO films has not been reported so far, while epitaxial thin films attract considerable attention in device applications because of their often superior properties over polycrystalline thin films. In this context, the integration of epitaxial BFO into microcantilevers and the investigation of their piezoelectric response particularly appear timely and of technological importance. In this work, 200-nm-thick Mn-doped $BiFeO_3$ thin films have been epitaxially grown by pulsed laser deposition (PLD) on (001) Si substrates using (001) $SrRuO_3$/(001) $SrTiO_3$ buffer layers. The films have been patterned into microcantilevers as prototype device structures for piezoelectric actuation. The devices demonstrate excellent ferroelectric response with a remanent polarization of 55 μC/cm2. The epitaxial $BiFeO_3$ MEMS exhibit very high piezoelectric response with transverse piezoelectric coefficient d31 reaching 83 pm/V. The $BiFeO_3$ cantilevers show larger electromechanical performance (the ratio of curvature/electric field) than that of state-of-art piezoelectric cantilevers, including well-known PZT (Pb(Zr,Ti)O3) and the hyper-active PMN–PT ($Pb(Mg_1/3Nb_{2/3})O_3$-$PbTiO_3$). In addition, the piezoelectricity in $BiFeO_3$ MEMS is found to depend on the ferroelectric polarization direction, with an observed asymmetry of 53% of the d31 coefficient with the voltage polarity. This asymmetric piezoresponse could originate from the flexoelectric effect, which would provide a first measurement of the flexoelectric coefficient μ in BFO (μ= -51 nC.m-1). In addition, this flexoelectric effect could be exploited to further enhance the electromechanical performance of the devices. These results show that by taking advantage of the low dielectric constant of BiFeO3, a promising alternative opens up to develop piezoelectric MEMS that currently incorporate conventional piezoelectric materials from the lead-based perovskite family.

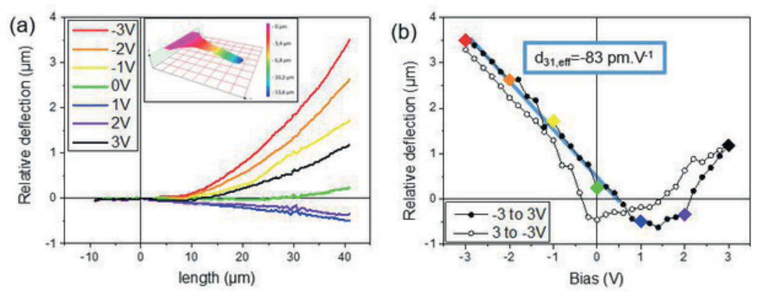

Figure : (a) Deflection under applied voltage of a $BiFeO_3$ cantilever Inset : Optical profilometry 3D image. (b) Extraction of the piezoelectric coefficient

References

High piezoelectricity in epitaxial BiFeO3 microcantilevers
Sylvia Matzen, Stéphane Gable, Nathan Lequet, Said Yousfi, Komalika Rani, Thomas Maroutian, Guillaume Agnus, Houssny Bouyanfif, Philippe Lecoeur

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DOI : https://doi.org/10.1063/5.0105404

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Orientation-patterned Gallium Phosphide: a new material platform for integrated nonlinear photonics

Researchers at C2N and Thalès R&T develop a new material for integrated non-linear optics

Non-linear optics ihave yielded numerous applications in converting the wavelenght of laser light while preserving it's other quantum properties. Interest is now growing in bring these applictations on photonic-integrated circtuits. Demonstrated compact nonlinear photonic circuits requires materials that demonstrate high conversion efficiencies, as a the length of the nonlinear crystal scales in inverse proportion to the square-root of efficiency. Achieving high efficiencies requires one to develop a meta-material that can be tailored to phase-match the frequencies of the waves involved in the nonlinear interaction. A team at C2N lead by Konstantinos Pantzas recently developed one such material : Orientation-Patterned Gallium Phosphide (OP-GaP). Using a combination of metal-organic vapor-phase epitaxy (MOVPE), wafer bonding and e-beam lithography, the team created a meta-material consisting of domains of alternating 001 and 00-1 crystallographic orientations. Using this combination of techniques the dimensions of OP-GaP are well-defined to the level of individual atomic layers. Using this new OP-GaP platform, the team demonstrated conversion of telecom light to visible light, with a record efficiency of 200%/Wcm^2

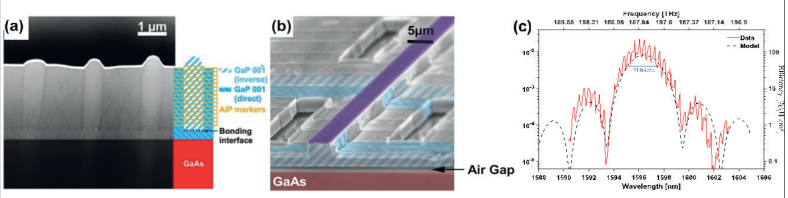

Figure : (a) HAADF-STEM micrograph of a cross-section of OP-GaP showing alternating domains of opposing crystallographic orientation (b) suspended air-clad OP-GaP shallow-ridge waveguide (c) efficiency curve of second-harmonic generation in OP-GaP showing a record efficiency of 200%/Wcm^2

References

Continuous-Wave Second-Harmonic Generation in Orientation-Patterned Gallium Phosphide Waveguides at Telecom Wavelenghts
Konstantinos Pantzas, Sylvain Combrié, Myriam Bailly, Raphaël Mandouze, Francesco Rinaldo Talenti, Abdelmounaim Harouri, Bruno Gérard, Grégoire Beaudoin, Luc Le Gratiet, Gilles Patriarche, Alfredo De Rossi, Yoan Léger, Isabelle Sagnes, Arnaud Grisard

ACS Photonics (2022)
DOI : https://doi.org/10.1021/acsphotonics.2c00156

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Quasi-deterministic nanowire growth

The vapor-solid-liquid growth of a semiconductor nanowire proceeds via the sequential nucleation and extension of biatomic monolayers (MLs) at the interface between the nanowire stem and an apical liquid catalyst nanodroplet. Controlling the length of a nanowire section to within 1 ML is crucial for quantum axial heterostructures, be they based on alternating different materials or different crystal structures of the same material. However, the intrinsic randomness of the nucleation process induces growth rate fluctuations which make such control very tricky. In principle, one may use an in situ instrument which, by combining growth and transmission electron microscopy, provides an instant feedback that allows one to adjust the vapor fluxes. Nevertheless, finding growth conditions that inherently minimize length fluctuations would open the way for tailoring such structures blindly in a standard growth setup devoid of real time monitoring. By combining in situ experiments on the NanoMAX platform and growth modelling, researchers at C2N have progressed significantly in this direction. During the growth of nanowires of III-V materials, the quantity of group V element in the nanodroplet at nucleation may be so low that only a fractional ML can form quasi-instantaneously. Further propagation of the ML is fed by the steady vapor input at a slower pace. After ML completion, a random waiting time elapses before next nucleation (Figure, left). At relatively low growth temperature, desorption is negligible; the group V amount available in the droplet at nucleation then scales with the preceding waiting time. Hence, a short waiting time requires a long propagation time, and vice versa. Growth simulations backed by efficient analytical calculations show that, for certain nanowire dimensions and growth conditions, such complementarity should be quasi-perfect. Computed distributions of the waiting, propagation and ML cycle times have been compared with accurate NanoMAX data. The experiments indeed provide evidence of self-regulation, in that the distribution of the ML cycle times is narrower than expected for non-correlated waiting and propagation times, albeit not as narrow as expected theoretically (Figure, right). This is in large part due to the limited time resolution of our experiments. Other possible experimental and intrinsic sources of fluctuations are currently investigated.

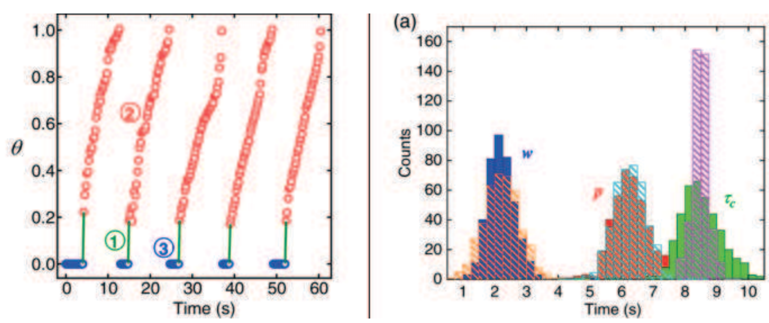

Figure : Left : Measured variation of the fraction q of ML grown (for 5 successive MLs), showing fast partial ML formation at nucleation (1), ML propagation (2) and waiting time (3). Note the random fluctuation of the waiting time between MLs. Right: Histograms of the waiting times w, propagation times p and ML cycle time t_c = w+p, measured (full bars) and calculated (striped bars) at low growth temperature.

References

Statistics of nucleation and growth of single monolayers in nanowires : Towards a deterministic regime
F. Glas, F. Panciera, and J.-C. Harmand

Phys. Status Solidi Rapid Res. Lett. 16, 2100647 (2022)
DOI : https://doi.org/10.1002/pssr.202100647

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High aspect ratio microfluidic devices for long term *in vitro* culture of 3D tumor models

Various tumor-on-a-chip models have been developed so far but the architecture, composition and dialogue between cells still need to be more closely reproduced to obtain valuable answers to questions related to the spatio-temporal evolution of the tumor-microenvironment pair. We have proposed a fabrication process to produce 3D fluidic devices with adapted aspect ratio for long term culture of tumor spheroids. 2PP lithography using the Nanoscribe system was applied for the fabrication of a master mold with different heights, for the fluidic adjacent channels and for the spheroid chamber, up to 500 µm. To ensure large-scale manufacture of series of fluidic devices at low cost, a very simple replication process in epoxy resist was also proposed to produce mold replica on large surface. Then, heterotypic pancreatic cancer tumor spheroids, used as a model of a tumor with a strong fibrotic reaction, have been loaded and cultured in the device. If the height of the central chamber is too small and limited to 100 µm, the spheroid appears flattened and can only grow horizontally due to the restricted space available. Raising the height of the chamber to 500 µm promotes more gradual cell growth and migration, thanks to the availability of space for spheroid evolution. Thus, by adjusting the aspect ratio, we have designed and investigated different devices. And, we have provided a proof of concept of the opportunity for their application for tumor spheroids culture. They might find potential application as a tool to gain in-depth knowledge of how the microenvironment (e.g., biochemical and biomechanical cues) governs tumor function (e.g., growth and migratory capacity) but also how cells affect their 3D environment (e.g., matrix degradation, creation of metabolic gradients).

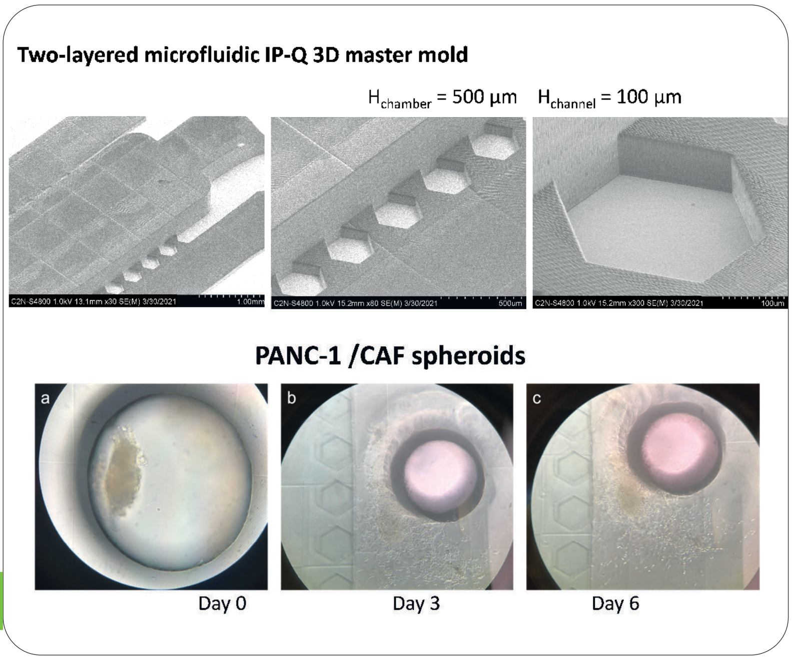

Figure : (a) Side view SEM images of two-layered microfluidic IP-Q 3D master mold with the 500 µm-high central chamber and the 100 µm-high lateral channels, and magnification on the pillar structure; (b) representative images of PANC1:CAF08 heterotypic spheroids cultured in the device over a period of 8 days. Day 0 indicates the day of spheroid transfer via the punched hole (diameter: 1 mm; black border inner ring in the images).

References

Fabrication of high aspect ratio microfluidic devices for long term in vitro culture of 3D tumor models
Martina Ugrinic, Dominique Decanini,, Nad`ege Bidan, Gianpiero Lazzari, Abdelmounaim Harouri, Gilgueng Hwang, Anne-Marie Haghiri-Gosnet, Simona Mura

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Hydrogen sorption in yttrium-based getter thin films

We investigated the sorption of hydrogen by yttrium-based getters for their application to vacuum wafer-level packaging of microelectromechanical systems. Thin alloy films were co-evaporated under ultra-high vacuum on silicon wafers. Getters were activated by annealing during one hour under inert argon atmosphere with traces of oxidizing species, at temperatures ranging from 200 °C to 400 °C. Three complementary techniques of ion beam analysis were performed on the samples: Rutherford Backscattering Spectrometry (RBS), Nuclear Reaction Analysis (NRA) and Elastic Recoil Detection Analysis (ERDA), to quantify metal, oxygen and hydrogen contents, and their in-depth distributions. The results show that oxidation occurs during annealing and prevents or not hydrogen sorption depending on the film composition. Due to its fast diffusion, hydrogen tends to accumulate near the film/substrate interface and starts to diffuse into the substrate as well. The different compositions of getter films are compared in terms of oxygen and hydrogen absorptions.

Some kinds of MEMS need vacuum to operate. This vacuum is commonly achieved by depositing a getter film inside the vacuum package of the MEMS. This film is a metallic reactive film that sorbs gases when it is has been annealed, like H2, N2, O2... The ANR project «Get-Yt» (19-CE08-0011) led by C2N with CEMHTI and IM2NP laboratories studied new yttrium-based getter films. The investigation reported in this article shows that some getter films based on yttrium can sorb H2 and O2 gases at the same time, if specific conditions are met such as getter composition and annealing temperature.

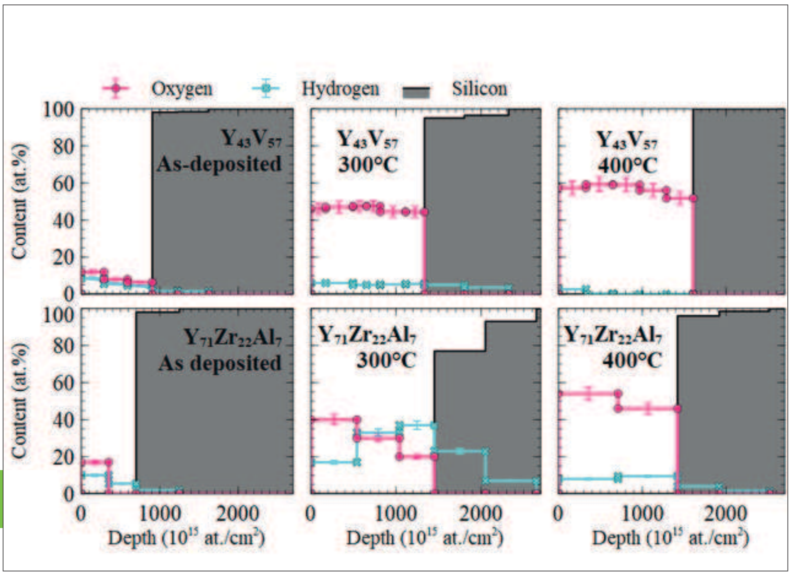

Figure : Oxygen and hydrogen profiles in Y-Zr-Al film before and after annealing at 300 °C and 400 °C

References

Hydrogen sorption in yttrium-based getter thin films
Charlotte Kutyla, Clément Bessouet, Sylvain Lemettre, Laetitia Leroy, Alain Bosseboeuf, Philippe Coste, Thierry Sauvage, Olivier Wendling, Aurélien Bellamy, Piyush Jagtap, Stéphanie Escoubas, Christophe Guichet, Olivier Thomas, Johan Moulin

Vacuum
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Creation of the FESTIN Joint Laboratory between C2N and MISTIC

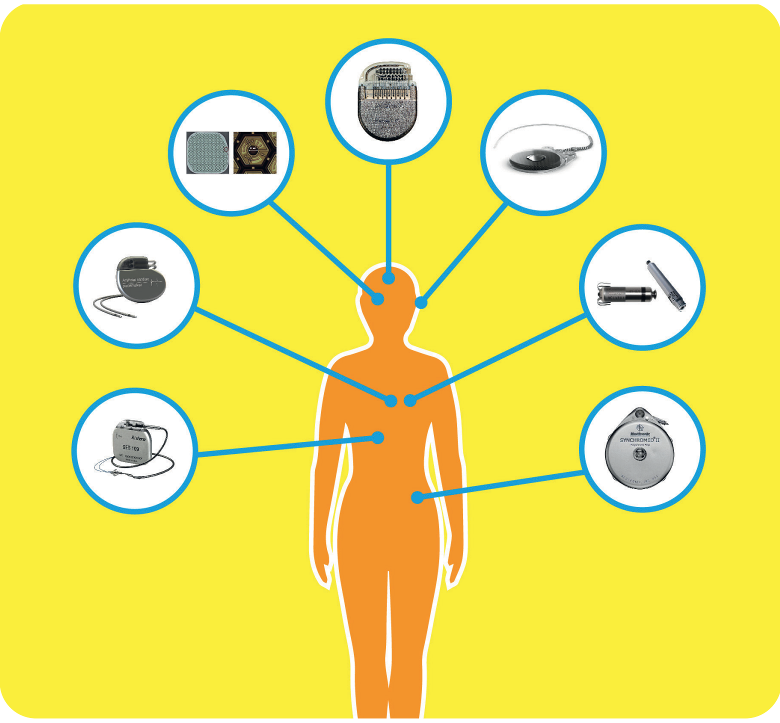
The C2N, Microcapteurs pour le Biomédical team[1] and MISTIC[2] (MIcro Structuration of Titanium for Innovative Components) have created a joint laboratory (LabCom) called FESTIN (Filière Emergente de Systèmes en Titane pour Implants Novateurs) with the support of the French National Research Agency (ANR) to develop innovative titanium-based packaging, thus paving the way for new generations of implantable medical devices (IMDs)

This project is part of the development of a breakthrough technology for the AIMD market. It aims to develop and perpetuate the emerging world leadership in the Ile de France region in the innovative and ambitious field of solid titanium-based microsystems (MEMS). This technological field was born from unresolved and limiting constraints in the design and development of active implantable medical devices (pacemakers, neurostimulators, implantable pumps or cochlear and retinal implants) with a biocompatible and waterproof but non-functional titanium shell. This joint laboratory is therefore intended to manufacture titanium-based MEMS, transferred onto this shell, thus providing intelligence and eliminating various layers of connectivity and packaging. This opens the way to new generations of less invasive implants. To this end, the partners will work on the transposition of MEMS technologies on silicon substrates to titanium substrates in order to elaborate and develop a complete technological toolbox comparable to the state of the art in silicon MEMS. In order to bring to full maturity, in a projection of 1 to 4 years, concepts already studied by the two partners (monolithic implantable feedthroughs, implantable pressure sensor), the two partners will put in place means of testing (specific fatigue benches, accelerated study of the ageing of the structures), characterisation (morphology and surface analysis), in particular in terms of reliability and very long term biocompatibility These devices will address 3 major issues on which C2N and MISTIC members have been collaborating since 2016 :

- An intensification of embedded Intelligence (telecommunication and remote monitoring, increased multiplicity of implanted physiological sensors and interaction / inter-functionalization)
- Responding to the need for a very high miniaturisation of AIMDs to reduce discomfort and risks for patients, address new therapies, and promote gender equality in care
- Manufacturability and cost pressure, especially for access to regions such as Asia or Africa that do not benefit from adequate reimbursement systems

A new scientific and technological approach is being developed to functionalise the purely passive titanium packaging of AIMDs in order to integrate external components and other sensors in the future. As typical thicknesses are in the order of 0.2 to 0.4 mm and dimensional constraints are strong, this intelligent titanium packaging approach is based on a new technological vision: transposing silicon MEMS microfabrication technologies onto solid titanium, which constitutes the new starting substrate (wafer), and thus producing miniaturised electromechanical components based on titanium This titanium MEMS technology is not yet available or industrialised elsewhere.

The Joint Laboratory will benefit from access to our Central Technology Facility, a decisive asset for the development of the new target sector.



[1]Elie Lefeuvre, Fabien Parrain
[2]Bertrand Boutaud, Gwenaël Becan

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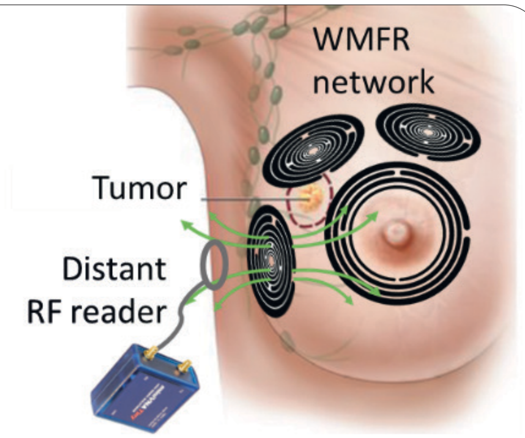
Passive electromagnetic RF sensors, Non-contact organic tissue characterization, Wearable sensors

A multi-frequency passive resonator for the non-contact and non-invasive monitoring of organic materials

The non-invasive characterization of organic matter is a major issue in many fields of activity, such as agriculture, food industry and health. The complex permittivity being a relevant indicator of the physiological state of organic matter, especially in the 10s to 100s of MHz, we have developed a non-contact RF multi-frequency resonant sensor, able to monitor the dielectric properties of the targeted organic media in non-invasive way. This wireless multifrequency resonator (WMFR) sensor basically consists in a set of high sensitivity circular transmission-line LC resonators, arranged in a staggered and monolithic configuration, and deposited on the same low loss substrate. Controlled by the means of a distant and monitoring RF probe by inductive coupling, the WMFR sensor operates as a multi-resonant transmit and receive antenna, able to distantly monitor the dielectric changes occurring in the targeted organic material, with both various investigation frequencies and various penetration depths within the matter. In the framework of the LaSIPS project (ANR-10-LABX-0040-LaSIPS) managed by the French National Research Agency, and in the context of the Ph.D Works of Alexiane Pasquier (Defended January 26th, 2022) we have proposed a proof of concept of the WMFR sensor with our colleagues from SATIE – CYU (Cergy Paris University). A 8-Frequency WMFR demonstrator of 9 cm outer diameter, featuring 8 concentric single-turn LC-resonators was developed to operate in the 22 MHz to 340 MHz bandwidth. It was fabricated on a flexible substrate (Kapton) and an electrical equivalent modeling was proposed. The ability of the sensor to distantly monitor the complex permittivity of biomimetic solutions have been successfully demonstrated within the 0 to 5 S/m conductivity range and the 20 to 80 permittivity range, together with the ability of detecting local dielectric contrasts within a uniform dielectric media, mimicking a tissue anomaly such as a tumor or lesion in a tissue. Monitoring of fruit ripening over a 14-day period and monitoring of muscle tissue alteration over 6 days were also performed, validating the ability of WMFR to detect changes in actual organic matter in a non-contact, non-invasive manner with prospects for low cost and online implementations. A patent application was filed by Université Paris Saclay for the WMFR principle in November 2021, and another patent application was filed for the implementation of WMFR arrays in January 2022. Prospective applications in the field of agri-food industry is the smart packaging of foods, and health-related prospects are the development of non-invasive device such as breast cancer or skin-wound healing wearable monitoring devices.



Targeted application: non-invasive monitoring of breast tissue with wearable WMFR sensor network.

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Towards non-contact characterization of organic tissue changes by multi-frequency RF sensors
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2022 IEEE International Symposium on Medical Measurements and Applications (MeMeA), Messina, Italy, 2022, pp. 1-6.
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Non-contact fruit ripening monitoring using a radiofrequency passive resonator
S. Castanet, A. Pasquier, H. Boukharouba, T.H.N. Dinh, S. Serfaty, P.-Y. Joubert
Sensors and Actuators A Physical, Volume 347, 2022, 113902.
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Perpendicular magnetic anisotropy,
Magnoeto-ionic effect, Annealing

Magneto-Ionics in Annealed W/CoFeB/HfO2 Thin Films

The magneto-ionic modulation of the Dzyaloshinskii–Moriya interaction (DMI) and the perpendicular magnetic anisotropy (PMA), in W/CoFeB/HfO2 stacks annealed at different temperatures and for varying annealing times, are presented in this work. A large modulation of PMA and DMI is observed in the systems annealed at 390 and 350 °C, whereas no response to voltage is observed in the as-grown samples. A strong DMI is only observed in the samples annealed at 390 °C for 1 h, while PMA is present for all annealing times at temperatures of 390 and 350 °C. Magnetic properties including domain wall velocity improve drastically with increasing the annealing temperature and time, while the magneto-ionic reversibility is increasingly compromised. The changes in PMA and DMI induced by the gate voltages in the samples annealed at 390 °C are permanent, while partial reversibility is only observed for the samples annealed at 350 °C for short times. This dependence of reversibility on post-grown annealing has been associated to the influence of crystallization on ion mobility. These results show that a compromise between the enhancement of the magnetic properties and the magneto-ionic performance could be needed in systems requiring annealing to develop PMA and DMI.

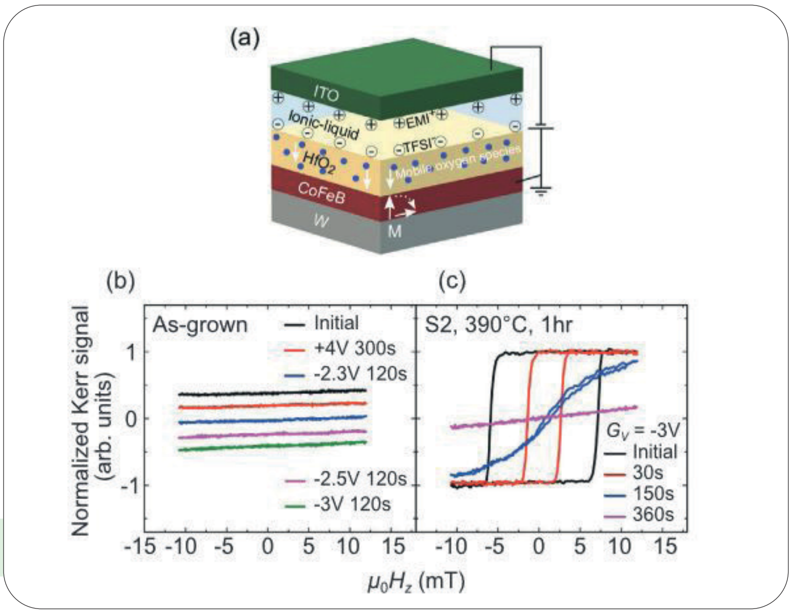

Figure : 1. a) Schematic of the structure of the ionic-liquid gate device and pMOKE signal under an out-of-plane magnetic field (µ0Hz) of the b) as-grown, and c) annealed S2 sample under different gate voltages and gating times

References

Magneto-Ionics in Annealed W/CoFeB/HfO2 Thin Films
Rohit Pachat, Djoudi Ourdani, Maria-Andromachi Syskaki, Alessio Lamperti, Subhajit Roy, Song Chen, Adriano Di Pietro, Ludovic Largeau, Roméo Juge, Maryam Massouras, Cristina Balan, Johannes Wilhelmus van der Jagt, Guillaume Agnus, Yves Roussigné, Mihai Gabor, Salim Mourad Chérif, Gianfranco Durin, Shimpei Ono, Jürgen Langer, Damien Querlioz, Dafiné Ravelosona, Mohamed Belmeguenai, Liza Herrera Diez

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A Memristor-Based Bayesian Machine

Artificial intelligence is making major progress today, but it faces a challenge: its considerable energy consumption, which limits its applications and raises environmental issues. It is now well understood that this consumption comes from the separation, in computers, between calculation and memory functions. As artificial intelligence uses a lot of data, it requires a lot of computer memory, which is costly to access in terms of energy. Our brains are much more energy efficient because the memory functions are integrated as close as possible to the computation functions. Memristors are a new memory technology that uses nanodevices and is integrated at the core of the computation, thus reproducing the brain's energy efficiency strategy. **A team involving three CNRS laboratories (Centre de Nanosciences et de Nanotechnologies, Institut Matériaux Microélectronique Nanosciences de Provence, Institut des systemes intelligents et robotique), CEA LETI, and the startup Hawai.tech has built a «Bayesian machine», a small artificial intelligence with memristors**. The prototype, presented in the Nature Electronics journal, comprises 2048 hafnium oxide memristors and 30,080 silicon transistors (MOSFETs). The machine can recognize a human gesture using thousands of times less energy than a traditional solution based on a microcontroller. The Bayesian machine implements a Bayesian inference model, a type of artificial intelligence complementary to deep learning, today's most widely used AI technique. Bayesian inference excels in situations where little information is available; the Bayesian machine would be particularly well suited for the realization of embedded devices for patient monitoring, or in smart sensors for monitoring the aging of buildings or industrial facilities. The next challenge for memristor-based artificial intelligence is learning, i.e., adapting to new data. It could then, for example, adapt to the evolution of a patient's illness. This challenge will be taken up as part of the PEPR electronic acceleration program, which aims to generate innovations to accelerate growth and relocate production processes in France or Europe using new technological solutions. This project involves the CNRS and the CEA and has just been financed to the tune of 86 million euros.

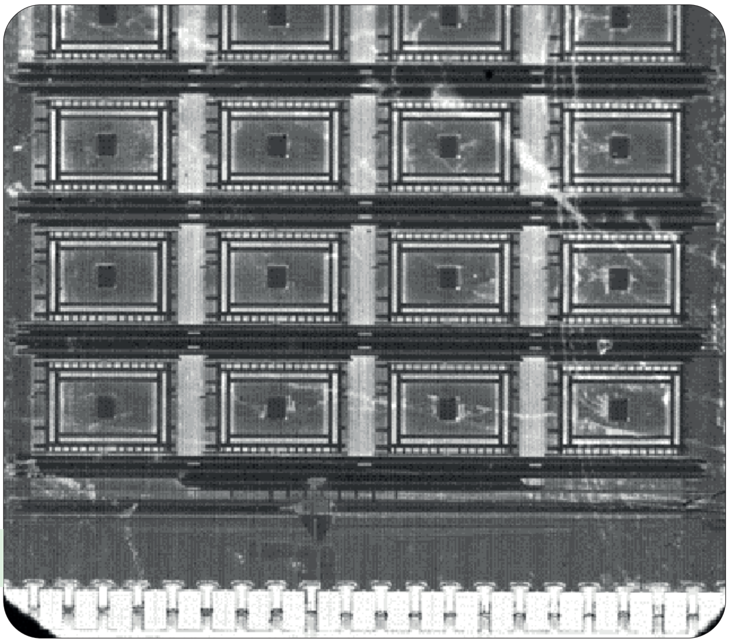

Figure : Photo of the Bayesian machine (size 2mmx2mm). The sixteen blocks of memristors (appearing as black squares) are surrounded by transistor-based circuits performing the artificial intelligence calculations as close to the memory as possible

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A Memristor-Based Bayesian Machine
K.-E. Harabi, T. Hirtzlin, C. Turck, E. Vianello, R. Laurent, J. Droulez, P. Bessière, J.-M. Portal, M. Bocquet, D. Querlioz

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Predicting the results of nanoelectronic experiments with Neural Ordinary Differential Equations

When designing new electronics technologies, it is essential to be able to predict the results of experiments to optimize the technology and design systems that make use of it. For this purpose, a mathematical model of the technology is needed. Electronic devices are usually modeled by ordinary differential equations, which can be found by analyzing and understanding the underlying physics of the technology. However, this process can be difficult, and especially with the complex devices emerging from nanotechnology, is far from always being successful. In this work, we used a novel artificial intelligence technique, Neural Ordinary Differential Equations, to automatically create models of nanoelectronic devices. Based on a limited number of measurements, this technique can find an ordinary differential equation able to model the device in all situations without needing any physical insight. For example, we used this technique to model a spintronic nanoneuron, with highly complex behaviors that resist modeling. The resulting ordinary differential equation correctly predicted weeks of experimental measurements in only minutes of simulation. This work, which is generalizable to multiple physical systems, offers a new way to model and develop new technologies by benefitting from the recent progress of machine learning techniques.

This work involved multiple expertises and is a collaboration between researchers at Centre de Nanosciences et de Nanotechnologies, Unité Mixte de Physique CNRS/Thales, the Albert Fert Beijing Institute at Beihang University, and Université catholique de Louvain.

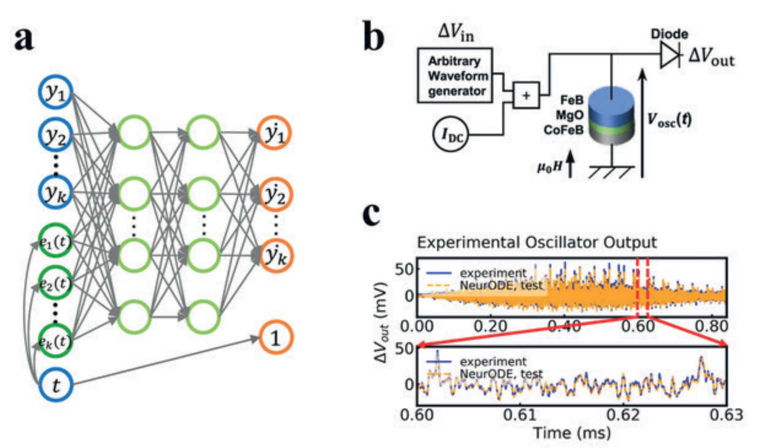

Figure : A Neural Ordinary Differential equation (a) is a specific type of artificial intelligence that can learn to model physical systems. For example, we trained a Neural Ordinary Differential equation to model an artificial nanoneuron (b). This trained equation can then predict of experiments on the nanoneuron with high precision (c). Figure : SEM Picture of the waveguide integrated modulator opera Figure : SEM Picture of the waveguide integrated modulator operating in the mid-IR spectral range

References

Forecasting the outcome of spintronic experiments with Neural Ordinary Differential Equations
Xing Chen, Flavio Abreu Araujo, Mathieu Riou, Jacob Torrejon, Dafiné Ravelosona, Wang Kang, Weisheng Zhao, Julie Grollier, Damien Querlioz

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Integrated electro-optical modulator in the mid-IR spectral range

Spectroscopy sensing in the mid-infrared (mid-IR) range (2–20 µm wavelength) is an unambiguous way to detect and quantify small traces of environmental and toxic vapors. However, current mid-IR devices are often based on a free-space configuration, thus becoming bulky and expensive. Therefore, the on-chip integration of spectroscopic systems would have a major impact in the development of efficient, portable and widespread sensing detectors. In particular, the wavelengths between 5 and 12 µm are of high interest, as many important molecules for pollution monitoring or healthcare (e.g., ozone or alkanes) have strong absorption lines in this spectral band. In this context, the development of integrated electro-optic modulators (EOM) operating in this wavelength range would be essential for sensitivity enhancement via synchronous detection and they are expected to have a major impact in compact and widespread sensing applications. Researchers from C2N in collaboration with Politecnico Di Milano have experimentally demonstrate a broadband integrated electro-optic modulator, based on a graded-index SiGe photonics platform and free-carrier plasma dispersion effect. Optical modulation is reported from 6.4 to 10.7 µm wavelength, with a modulation frequency up to 225 MHz. These results pave the way for the development of multimolecule on-chip spectroscopic systems, operating at the longest mid-infrared wavelengths.

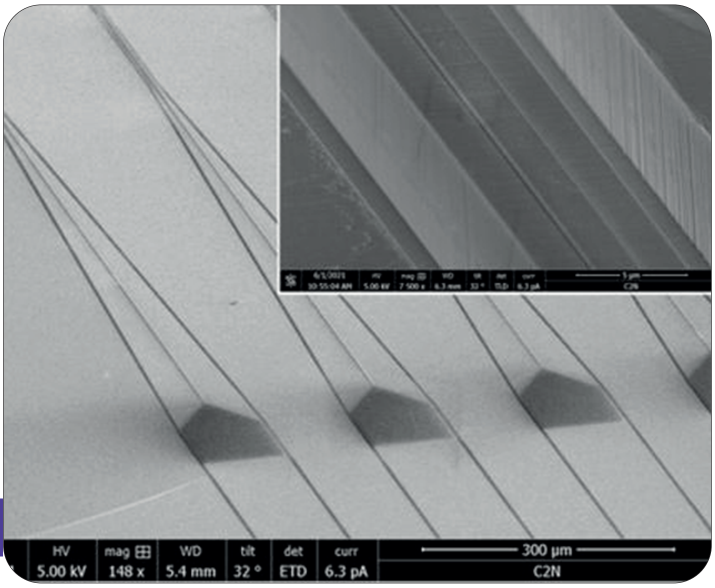

Figure : SEM view of an integrated electro-optical modulator operating in the mid-infrared.

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Mid-infrared Integrated Electro-optic Modulator Operating up to 225 MHz between 6.4 and 10.7 µm Wavelength
Miguel Montesinos-Ballester, Lucas Deniel, Natnicha Koompai, Thi Hao Nhi Nguyen, Jacopo Frigerio, Andrea Ballabio, Virginia Falcone, Xavier Le Roux, Carlos Alonso-Ramos, Laurent Vivien, Adel Boussek-sou, Giovanni Isella, and Delphine Marris-Morini

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Metamaterial-Engineered Silicon Beam Splitter Fabricated with Deep UV Immersion Lithography

Subwavelength grating (SWG) metamaterials have garnered a great interest for their singular capability to shape the material properties and the propagation of light, allowing the realization of devices with unprecedented performance. However, practical SWG implementations are limited by fabrication constraints, such as minimum feature size, that restrict the available design space or compromise compatibility with high-volume fabrication technologies. Indeed, most successful SWG realizations so far relied on electron-beam lithographic techniques, compromising the scalability of the approach. Here, we report the experimental demonstration of an SWG metamaterial engineered beam splitter fabricated with deep-ultraviolet immersion lithography in a 300-mm silicon-on-insulator technology. The metamaterial beam splitter exhibits high performance over a measured bandwidth exceeding 186 nm centered at 1550 nm. These results open a new route for the development of scalable silicon photonic circuits exploiting flexible metamaterial engineering.

Subwavelength grating (SWG) metamaterials consist of periodic arrangements of dielectric structures with a period substantially smaller than the wavelength of the propagating light. Within this regime, the grating effectively acts as a homogeneous material whose optical properties (e.g., effective index, dispersion, and anisotropy) are determined by the ensemble of the constituent materials and can be varied by properly designing the geometry of the grating unit cells. This type of metamaterials have been successfully implemented in particular in silicon photonic waveguides, allowing an unprecedented control over the field distribution and propagation properties of the guided modes, largely increasing design flexibility compared to conventional waveguides most of the successful demonstrations have so far relied on electron-beam lithography that offers higher resolution at the expense of a largely reduced throughput which limits its applicability to research or small volume productions.

Here, we exploit a fabrication technology based on 300-mm SOI wafers and immersion DUV lithography to experimentally demonstrate a broadband integrated beam splitter based on an SWG-engineered multi-mode interference (MMI) coupler. The device has a silicon thickness of 300 nm and nominal minimum feature size of 75 nm, well below the resolution capabilities of dry DUV lithography. We believe that the use of lithographic techniques routinely available in complementary metal-oxide-semiconductor (CMOS) processes will be of fundamental importance to bring the potentialities of refractive index engineering toward commercial exploitation. This will enable the fabrication of high-performance devices for fiber-to-chip coupling, power splitting, polarization management, and spectral filtering, with promising applications, for example, in coherent communications, sensing, and spectroscopy.

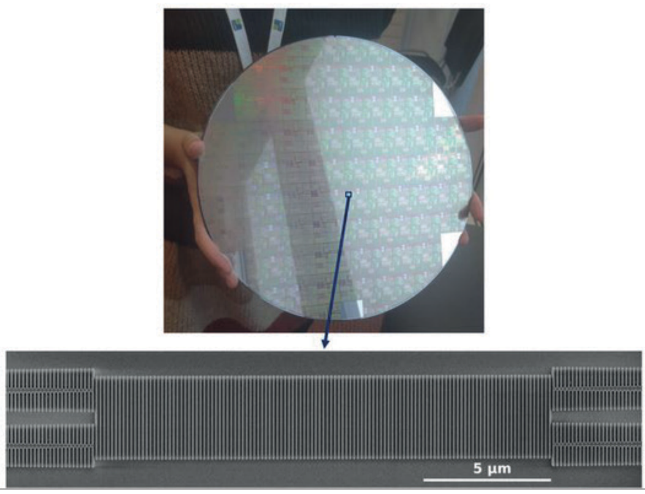

Figure 1 : 1. Top panel : Optical image of 300-mm SOI wafer. Bottom panel : Scanning electron microscope image of the fabricated Metamaterial-Engineered Silicon Beam Splitter. Minimum feature size is 75 nm.

References

Metamaterial-Engineered Silicon Beam Splitter Fabricated with Deep UV Immersion Lithography
Vladyslav Vakarin, Daniele Melati, Thi Thuy Duong Dinh, Xavier Le Roux, Warren Kut King Kan, Cécilia Dupré, Bertrand Szelag, Stéphane Monfray, Frédéric Boeuf, Pavel Cheben, Eric Cassan, Delphine Marris-Morini, Laurent Vivien and Carlos Alberto Alonso-Ramos

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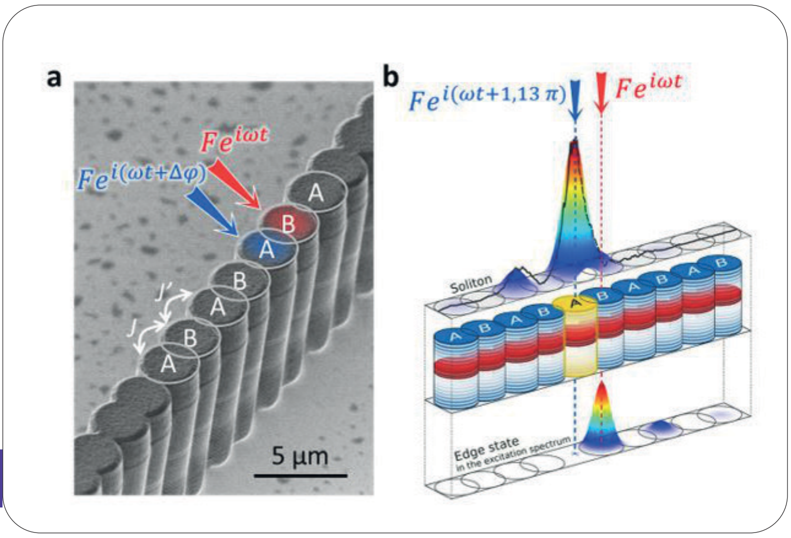
Optical solitons create a topological edge in the bulk of a 1D chain of optical cavities

Optical solitons are highly localized nonlinear states of light, which are named by analogy with solitary waves encountered in hydrodynamics. C2N researchers, with two teams one from the Phlam laboratory in Lille and the other from Institut Pascal in Clermont-Ferrand, have discovered a new family of optical solitons, stabilized by a continuous laser drive of the system, that enable modifying the topology of a one-dimensional topological array of semiconductor nonlinear microcavities. Remarkably, these solitons make possible the generation of an optical interface (an edge) in the bulk of the lattice.

Topology is a branch of mathematics that classifies objects independently of their local symmetries (the detail of their shape), by using global properties characterized by integers called topological invariants. These concepts have proven extraordinary in explaining the deep nature of certain physical phenomena such as the quantum Hall effect of a two-dimensional gas of electrons, in which electrical conduction occurs through edge channels localized at the interface between the material and vacuum. Fabricating synthetic physical systems allow extending the field of topological physics, and tackling one of the major challenges of the field: the influence of interactions on these topological phases. Nowadays, the field of photonics makes it possible to combine topology and non-linear optics. This is what C2N researchers have just achieved in collaboration with a team from the Institut Pascal in Clermont-Ferrand. They studied the non-linear response of a one-dimensional chain of optical resonators under continuous laser drive (see figure a). These chains consist of semiconductor cavities containing an active material (a quantum well) and operating in the strong exciton-photon coupling regime, thus leading to a giant optical non-linearity. By imposing a phase frustration via the quasi-resonant continuous laser excitation, the researchers were able to stabilize a new family of dissipative solitons, which have no equivalent in conservative systems. These solitons inherit the symmetry properties of the lattice, which make them robust against certain types of defects. Remarkably, these new solitons show a peculiar spatial distribution, which optically «breaks» the chain, effectively removing one of the sites from the array (see figure b). This is a striking demonstration that interactions can be tailored to generate a new edge in the bulk of the lattice, and therefore to induce a new topological edge state at a completely unexpected location from the point of view of linear physics. These results open up a new field of research aimed at manipulating the topology of an open system via the optical drive, a promising technique for the future study of the nonlinear properties of two-dimensional photonic topological insulators.



Caption : (a) Scanning electron microscopy image showing a chain of semiconductor cavities. The distance between the cavities is modulated, which gives rise to two different values of the coupling J and J' between adjacent cavities (represented schematically by double white arrows). This modulation of the coupling provides the lattice with topological properties. Two cavities of the lattice are excited by two lasers of amplitude F, angular frequency w and presenting a phase difference Dj . b) For Dj =1.13p the researchers have demonstrated a new family of solitons, which measured intensity profile is shown at the top of the figure. The intensity is very strong on one single site, thus leading to the spectral detuning of this site with respect to the rest of the chain. The chain is thus effectively broken, and an edge state appears in the excitation spectrum, as shown at the bottom of the figure.

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Gap solitons in a one-dimensional driven-dissipative topological lattice
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International team of scientists finds new and simpler way to generate "quantum light"

An international team, gathering scientists from the Centre for Nanoscience and Nanotechnology, the Institut Néel and the University of Calgary, has discovered a new way to generate entangled states of light. This work is published today in Nature Photonics.

Entanglement is a key resource for quantum technologies and most especially for those based on light, where photon entanglement is an essential ingredient of many applications ranging from quantum communications to quantum computing. The generation of photon entanglement is often cumbersome, requiring complex and carefully designed experimental schemes. Here the researchers proposed and demonstrated a new and utterly simple way to generate entangled light. It exploits the light-matter entanglement occurring when an atom emits a photon. In the proposed scheme, the atom is excited with two consecutive laser pulses: the first laser pulse sets the atom on its excited state, preparing the atom to emit a photon via the spontaneous emission. Half-way through this emission process, the atom-photon system is in an entangled state with the atom excited and no photon emitted, or in the atom back to its ground state and a photon emitted. At this moment, a second laser pulse reverts the atom state, i.e., from the excited to the ground state and vice versa. At the end of the spontaneous emission process, both two photons and no photons have been emitted– and the generated light shows entanglement in the photon number basis. These experiments are done with an artificial atom – a semiconductor quantum dot – inserted in an optical cavity, a device that has been shown to be one of the brightest single-photon source. This work beautifully illustrates how fundamental research, boosted by state-of-the-art technology, can lead to new discoveries in physics situation that one thought fully understood and exploited. Moreover, it opens many perspectives to generate more complex and scalable photon entanglement still with a very simple scheme.

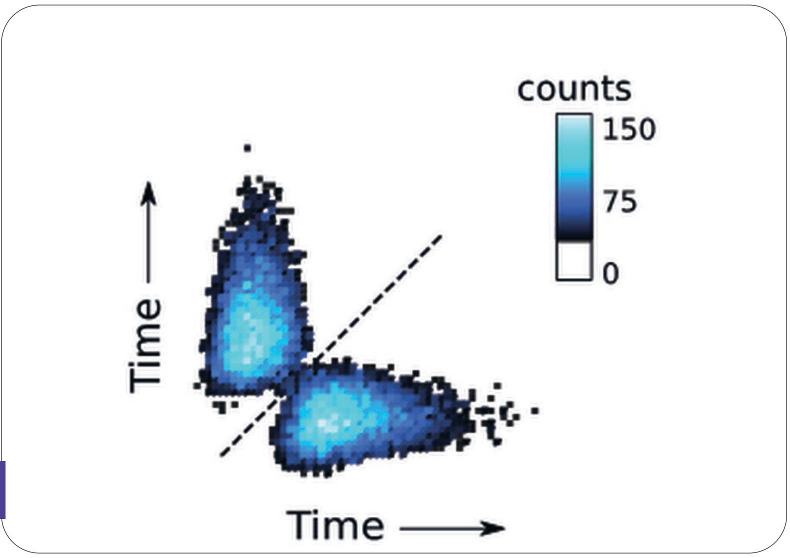

Figure : Second order intensity correlation measurement evidencing the emission of two photons at different times.

Refererences

Photon-number entanglement generated by sequential excitation of a two-level atom
Stephen C. Wein, Juan C. Loredo, Maria Maffei, Paul Hilaire, Abdelmounaim Harouri, Niccolo Somaschi, Aristide Lemaître, Isabelle Sagnes, Loïc Lanco, Olivier Krebs, Alexia Auffèves, Christoph Simon, Pascale Senellart, Carlos Antón-Solanas

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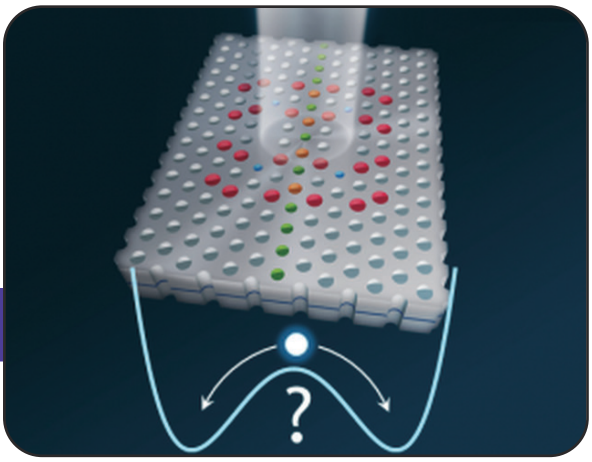
A perfectly symmetric system that ends up in a non-symmetric state: coupled optical nanocavities under coherent excitation

Symmetry governs nature… but not always the way we expect! Although systems tend to respect their initial symmetries in general, sometimes they may refuse. We then refer to "spontaneous symmetry breaking", as it is the case in mechanics, hydrodynamics, or even in particle physics. A team from C2N, together with collaborators from the Netherlands and New Zealand, demonstrated for the first time, spontaneous breaking of mirror symmetry in coherently driven optical coupled cavities.[1] To achieve this goal, two evanescently coupled photonic crystal nanocavities in thin Indium-Phosphide membranes with embedded quantum wells have been realized in the C2N clean-room. Remarkably, such a system operating in the weak coupling regime and at room temperature is shown to be accurately described by the celebrated Bose-Hubbard model, accounting for boson hoping and interaction in optical lattices.

Symmetries play a fundamental role in physics, and often give a handle to predict many observed phenomena. However, some systems can break their symmetry spontaneously,. The hexagonal shapes of salt deserts, the curious geometries of snowflakes, the convection of air masses in the form of rolls in the atmosphere, phase transitions in ferromagnetism… These are some examples of what in physics is called spontaneous symmetry breaking (SSB). One of the model systems undergoing SSB in atomic and condensed matter physics is the double well potential containing interacting bosons, known as the "Bose-Hubbard (BH) dimer". The system has mirror symmetry; yet, the steady state of the bosons, may not respect this symmetry, and may get confined in one of the wells (a single side of the "mirror"). For SSB to occur, the interaction energy U between particles must exceed the "tunneling" energy J which allows the particles to jump between the wells. BH lattices are widely investigated in atomic physics because they enable quantum phase transitions in large-scale systems.

Integrated nanophotonics is an outstanding alternative platform for the implementation of SSB. The particles in question are photons, the wells are "optical cavities", and U is provided by light-matter interactions (optical nonlinearity). The challenge is to realize strong U, in order to reach SSB thresholds with ultralow light intensities. And for this, the engineering of coupled optical nanocavities with III-V semiconductor quantum wells plays a key role, enabling tailoring not only the strength of J, but also its sign! The C2N team, in collaboration with researchers in New Zealand and the Netherlands, demonstrated SSB in a nanophotonic BH dimer, formed by two photonic crystal-coupled nanocavities; unlike a previous demonstration by the C2N team in a laser oscillating regime [2], here the optical excitation is coherent (resonant), and the nonlinearity involved is of Kerr-type. They show that, because of the blue-shift nonlinearity of the quantum wells, the observation of a "pure pitchfork" bifurcation characteristic of SSB is only guaranteed if J<0! Such photonic meta-materials enable artificial situations that can hardly be engineered in the atomic or superconducting counterparts.

[1] Hamel et al, Nat Photonics 2015
[2] Garbin et al, PRL 2022



Two identical coupled optical cavities. (grey areas with missing holes and enclosed by red holes) are symmetrically illuminated by a laser beam. Above a critical intensity, a tiny perturbation can spontaneously break the symmetry of the system; the column of green holes is the symmetry axis. Once the symmetry is spontaneously broken, one cavity becomes brighter than the other.

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Spontaneous Symmetry Breaking in a Coherently Driven Nanophotonic Bose-Hubbard Dimer
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Room temperature GeSn laser

A C2N team, in collaboration with CEA Grenoble (LETI and IRIG) and STMicroelectronics, presents the first room temperature laser with GeSn, a group IV semiconductor compatible with silicon fabrication. This major result is published in Optics Express.

GeSn alloys are the most promising direct band gap semiconductors to demonstrate full CMOS-compatible laser integration with a manufacturing from Group-IV materials. An important milestone towards real-field applications is the ability to operate at room temperature (RT). So far, the highest temperatures achieved for laser operation with GeSn were 273 K at prohibitive power threshold densities of several MW/cm2. Here, we show for the first time that room temperature and above, up to 300 K, lasing can be obtained with GeSn. In addition the threshold densities are reduced to few hundreds of kW/cm2. This is achieved in microdisk resonators fabricated on a GeSn-On-Insulator platform that combine strain engineering with a thick layer of high Sn content GeSn. As previously detailed in recent publication [1] the main assets of this specific laser technologies are, first, to enable the removal of interfacial defect, second, to improve the optical confinement in the gain region as compared to conventional approach based on as grown GeSn /Ge buffer stacks on silicon. Third, the strain transfer from the insulator yields a higher directness of the band structure of the alloy and more robust gain then. Finally the whole structure is fabricated on an aluminum heat sink for improved thermal cooling of the gain media. This achievement published in Optics Express[2] open the route to real field application of CMOS-compatible Mid-infrared lasers. This work has been developed in a collaboration between C2N-University-Paris-Saclay-CNRS and CEA in Grenoble (LETI and IRIG) with STMicroelectronics.

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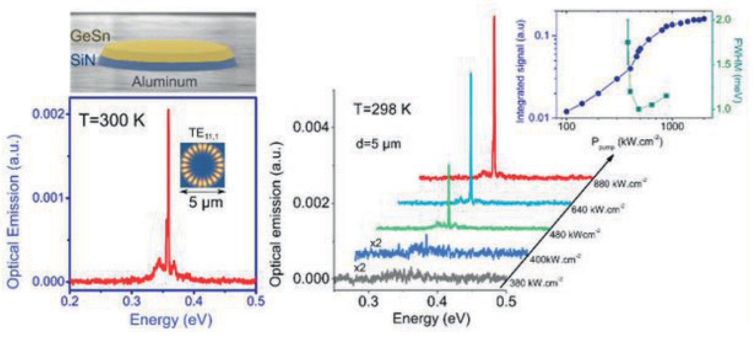

Figure : On the left hand is shown the SEM image of a GeSn microresonator based on GeSnOI platform recently developed at C2N. The emission from such cavities, here with 5 µm diameter shows laser effect up to 300 K with threshold of 500 kW/cm2 under puled optical pumping. The right figure show detailed analysis of laser characteristics at 298 K.

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Up to 300 K lasing with GeSn-On-Insulator microdisk resonators
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Coherent light reveals universal behavior

Universality is a powerful concept in statistical physics that allows understanding critical phenomena and describing them effectively on the basis of a few fundamental ingredients. Systems as different as crystalline surfaces, frost on a window or modern urban skylines under building constraints, can all be effectively described as an interface of height h(r,t), whose dynamics is governed by the same non-linear stochastic equation, named Kardar-Parisi-Zhang equation (KPZ), after the 3 physicists who first introduced it in 1986 [1]. This very simple equation is extraordinarily rich. It predicts the development of spatio-temporal correlations in the interface height: the height observed at time t and position x depends on what was observed at t=0 and x=0. Thus self-similar structures develop in time and space with universal critical exponents that only depend on the dimensionality of the interface. The beauty of frost emerge from these complex structures. An international team of researchers has just demonstrated experimentally that photonic systems also belong to the KPZ universality class, a result theoretically predicted in 2015 [2]. The know-how in nanotechnology at the Center for Nanosciences and Nanotechnologies (C2N) have enabled to sculpt lattices of optical microcavities in semiconductor materials (see Fig.a, bottom panel). Light trapped in these cavities couples to electronic excitations and forms hybrid light-matter quasi-particles called cavity polaritons. These polaritons can accumulate massively in the same quantum state and form a coherent collective state called out-of-equilibrium Bose-Einstein condensate (see Fig.a, top panel). The wavefront of the condensate behaves in time and space as an interface (see Fig.b), and obeys the famous KPZ equation [2].

The team of Jacqueline Bloch and Sylvain Ravets at C2N generated one-dimensional polariton condensates and probed, through optical interferometry experiments, the spatio-temporal coherence of their emission. Very spectacularly, Quentin Fontaine and Davide Squizzato, post-doctoral fellows at C2N and at Laboratory of Physics and Modeling of Condensed Matter (LPMMC) in Grenoble, were able to demonstrate that the experimentally measured and numerically calculated datapoints align perfectly onto a universal scaling curve that characterizes the KPZ universality class in 1D (see Fig.c). The numerical simulations carried out at the LPMMC in the team of Léonie Canet and Anna Minguzzi were able to reproduce the experiments, and then enabled developing a deep understanding of this new system. Indeed, since the variable describing the interface is a phase, defined periodically between 0 and 2π, the interface can wind on itself and form vortices. Such «topological» defects can potentially destroy KPZ correlations. The international consortium discovered that in the regime where the experiments operate, KPZ correlations are resilient to the appearance of vortices, because they appear and disappear in pairs of opposite vorticities, and their density is low enough. This work opens a new avenue for the study of KPZ physics and the exploration of the rich phase diagram of out of equilibrium Bose-Einstein condensates. This very general physics applies to all out-of-equilibrium condensates, and may appear crucial for the optimization of extended solid-state lasers. Finally, all the ingredients are now gathered to probe experimentally, for the first time, the KPZ correlations in a two-dimensional system. This challenge will be attempted very soon in two-dimensional polariton condensates that are routinely realized at C2N.

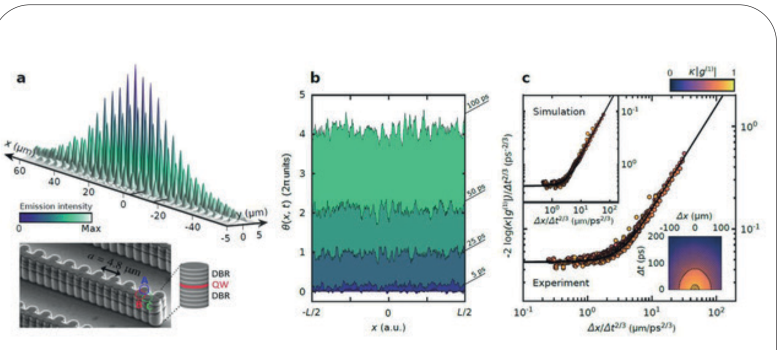

Figure : a. Experimental measurement of the light intensity distribution emitted by the condensate (top panel). The bottom panel shows a scanning electron microscopy image of a 1D array of polariton microcavities manufactured at C2N to perform the experiments. b. Numerical calculation of the phase of a 1D polariton condensate at various instants in time. The temporal evolution of the phase is analogous to the growth of an interface. c. Plotted in a system of well-chosen rescaled coordinates, the points measured experimentally and calculated numerically for the condensate first order coherence (orange-colored disks) align perfectly with the KPZ universal scaling curve (black curve).

[1] Kardar, M., Parisi, G. & Zhang, Y.-C., Dynamic scaling of growing interfaces, Physical Review Letters 56, 889 (1986)

[2] Altman, E., Sieberer, L. M., Chen, L., Diehl, S. & Toner, J., Two-dimensional superfluidity of exciton polaritons requires strong anisotropy, Physical Review X 5, 011017 (2015)

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Kardar–Parisi–Zhang universality in a one-dimensional polariton condensate
Fontaine, Q., Squizzato, D., Baboux, F. et al.

Nature 608, 687–691 (2022)
News and Views : A new phase for the universal growth of interfaces
DOI : doi.org/10.1038/s41586-022-05001-8

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Integrated optoelectronics devices operating in the long wave infra red wavelength

Optical spectroscopy in the mid-infrared (mid-IR) range is an unambiguous way to detect environmental and toxic analytes. Therefore, mid-IR photonics has a great importance for many applications in sensing, imaging or even telecommunication. A challenging task is to make mid-IR spectroscopy accessible in remote areas, driving the development of compact and cost-effective solutions. The development of mid-IR photonics circuits has thus witnessed a burst of research activity in the recent years. In this context, researchers from C2N in collaboration with Politecnico Di Milano have experimentally demonstrated high performance on-chip optoelectronics devices. First, optical modulator based on free carrier plasma dispersion effect in graded SiGe waveguide embedding a Schottky diode have been developed. The main challenges for high-speed operation have been tackled, allowing to demonstrate 1 GHz operation in an integrated device operating from 5 to 9 µm wavelength [1]. Then a waveguide-integrated photodetector has been demonstrated for the first time in a similar wavelength range [2]. A responsivity reaching up to 0.1 mA/W has been obtained at room temperature, which opens strong perspectives for the development of compact and efficient spectroscopic systems exploiting synchronous detection or for on-chip monitoring.

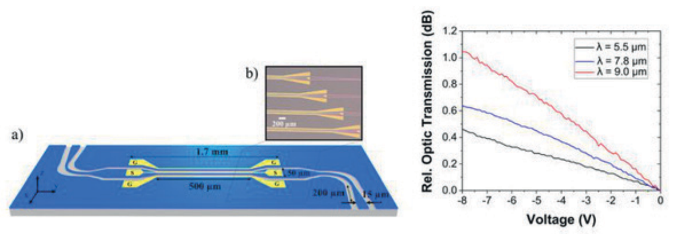

Figure : left : schematic view of an integrated modulator (inset : optical microscope view of the fabricated device), right : characterization of the modulator : extinction ratio as a function of the applied voltage for different input wavelengths

References

[1] ***Room temperature integrated photodetector between 5 µm and 8 µm wavelength***
T.H.N. Nguyen, N. Koompai, V. Turpaud, M. Montesinos-Ballester, J Frigerio, S. Calcaterra, A. Ballabio, X. Le Roux, J-R. Coudevylle, C. Villebasse, D. Bouville, C. Alonso-Ramos, L. Vivien, G. Isella, D. Marris-Morini

Advanced Photonics Research, 2200237 (2022)
DOI : http://doi.org/10.1002/adpr.202200237

GHz electro-optical silicon-germanium modulator in the 5-9 µm wavelength range
T.H.N. Nguyen, N. Koompai, V. Turpaud, M. Montesinos-Ballester, J. Peltier, J Frigerio, A. Ballabio, R. Giani, J-R. Coudevylle, C. Villebasse, D. Bouville, C. Alonso-Ramos, L. Vivien, G. Isella, D. Marris-Morini

Optics Express, 30, (26), 47093 (2022)
DOI : https://doi.org/10.1364/OE.476164

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Toward integrated photonic systems for laser beam control

Free-space laser beams are of core importance in many fast-growing technologies, including optical communications, 3D imaging and mapping, interconnects, and augmented reality. However, state-of-the-art solutions that allow to generate and control such beams typically comprise mechanical assemblies, moving parts and bulk optic components. In this scenario, the use of photonics integration to realize and combine on-chip micron-scale optical components not only offers huge potentialities for the development of compact and lightweight systems but opens the door to unique new functionalities enabled by nanotechnologies.

Here we exploit silicon nanostructuration to demonstrate two key building blocks of integrated photonic system for laser beam control. In the first work, in collaboration with National Research Council Canada and Carleton University (Canada), we exploit metamaterials to demonstrate a fundamentally new concept of a nanophotonic antenna where the far field beam is widened beyond the diffraction limit, a crucial aspect when multiple integrated antennas are integrated in large arrays. We use transversally interleaved subwavelength grating nanostructures to control the near field phase and a Bragg reflector is used at the end of the antenna to increase both the efficiency and the far field beam width. The antenna has a compact footprint of 3.1 µm × 1.75 µm and a broad far field beam width of 52° x 62°.

In the second work, partially supported by the ERC project «BEAMS» and by the RENATECH network, we exploit a flat metasurface to realize an integrated lens with a quadratic phase profile. This type of metalenses provide a point spread function that remains undistorted upon tilted illumination and can achieve a full 180° field of view. In addition, we show that the metalens has also an aromatic behavior over a bandwidth of more tha 140 nm. The combination of such metalens with arrays of nanophotonic antennas could enable the fabrication of high-performance integrated photonic system for the control of free-space laser beams, with promising applications in multispectral lidars and free-space optical communications based on wavelength division multiplexing.

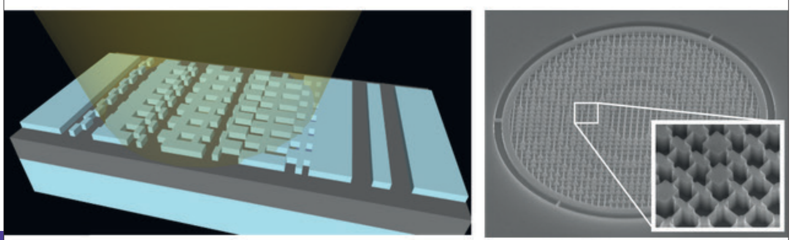

Figure : Integrated systems for laser beam control. (left) The developed nanophotonic antenna achieves a beam width beyond the diffraction limit through subwavelength grating nanostructures. (right) A quadratic metalens is demonstrated to symultaneously achieve an aribtrarily wide field of view and a broadband achromatic behavior over a bandwidth of more than 140 nm.

References

Paper 1
Broadband behavior of quadratic metalenses with a wide field of view
Y. Liu, J. Zhang, X. L. Roux, E. Cassan, D. Marris-Morini, L. Vivien, C. Alonso-Ramos, and D. Melati,
Opt. Express, OE, vol. 30, no. 22, pp. 39860–39867, Oct. 2022,
DOI : 10.1364/OE.466321

Paper 2
Highly efficient ultra-broad beam silicon nanophotonic antenna based on near-field phase engineering
S. Khajavi, D. Melati, P. Cheben, J. H. Schmid, C. A. A. Ramos, and W. N. Ye,
Sci Rep, vol. 12, no. 1, Art. no. 1, Nov. 2022
DOI : 10.1038/s41598-022-23460-x

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Strong light-matter coupling observed with a nanoscale thermal transducer in a single nano-cavity

Researchers at C2N, in collaboration with University of Rome (Italy), Istituto Italiano di Technologia (Italy), Rice University (USA) and University Leeds (UK), have demonstrated an original nanospectroscopy technique that permits the study of the light–matter interaction in single subwavelength-sized nanocavities

When it comes to optical characterization of single objects in the mid-IR spectral range, optical setups and detectors traditionally lack the necessary signal-to-noise ratio. Far field measurements (such as FTIR spectroscopy) require a relatively big number of optical elements, while near field techniques (such as SNOM microscopy) yield sometimes noisy results. Clean, unambiguous spectra – especially when studying cavity resonators, where the fields are buried inside the optically active material – are a challenge when dealing with isolated structures. In this work, achieved through a joint effort between C2N and La Sapienza University of Rome, in collaboration with Rice University (USA) and University Leeds (UK), a new near-field approach to optically characterize concealed metal-insulator-metal structures at the single-resonator level has been introduced. The principle relies on the insertion of a thin layer of polyethylene, that has a large transparency window in the mid-IR spectral region, inside a metal-insulator-metal cavity resonator hosting a semiconductor quantum well in its core. Such quantum well exhibits an intersubband transition at around λ=8 µm. When light from a laser source is focused on the sample it can be absorbed by the system, due to ohmic dissipation in the metal structures and electronic transitions in the quantum well. The dissipated power is locally transformed into heat at selected frequencies. Such heat diffuses into the polymer that – in turn - thermally expands. The entire structure thus swells along the vertical direction, and an AFM tip detects the change, and therefore the resonance which is at its origin. The polymer inside the resonator behaves as a thermal transducer.

Such technique has been applied to a particularly challenging case: an intersubband transition strongly coupled to the photonic cavity mode of a single resonator. In the strong light-matter coupling regime new states appear, called intersubband polaritons in this case, that in general are studied on arrays of hundreds of resonators. The developed innovative approach has allowed the typical anticrossing characteristic of the polaritonic dispersion to be identified in the cavity loss spectra at the single nanoresonator level instead. Researchers also showed that it is possible to map the fields buried inside the cavity resonator, that are otherwise inaccessible. This technique might be even more appealing in the THz region, where detectors suffer even poorer efficiency and studying optical properties on isolated structures is even more challenging. Various Various Various tumor-

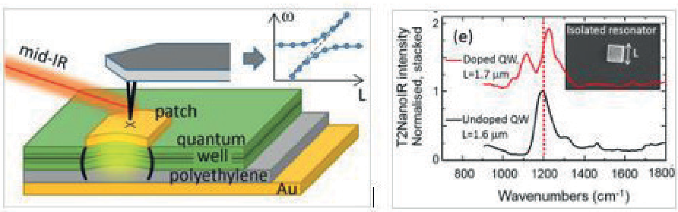

Figure 1 – Left : Sketch of the T2NanoIR experimental and illumination scheme on a single nanocavity. Laser light impinging on the system is absorbed by the active region inside the patch cavity. Dissipation leads to thermal nano-expansion of the polyethilene layer that is inserted in the cavity. Such expansion is detected with a judiciously configured atomc force microscope (AFM). Right : T2Nano-IR spectra of single nanocavities, in the case of an undoped (black curve) and doped (red curve) active region. The former reveals the bare cavity resonance, the latter reveals the two polariton branches.

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Detection of Strong Light–Matter Interaction in a Single Nanocavity with a Thermal Transducer
M. Malerba, S. Sotgiu, A. Schirato, L. Baldassarre, R. Gillibert, V. Giliberti, M. Jeannin, J-M Manceau, L. Li, A.G. Davies, E.H. Linfield, A. Alabastri, M. Ortolani, R. Colombelli

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DOI : https://doi.org/10.1021/acsnano.2c04452

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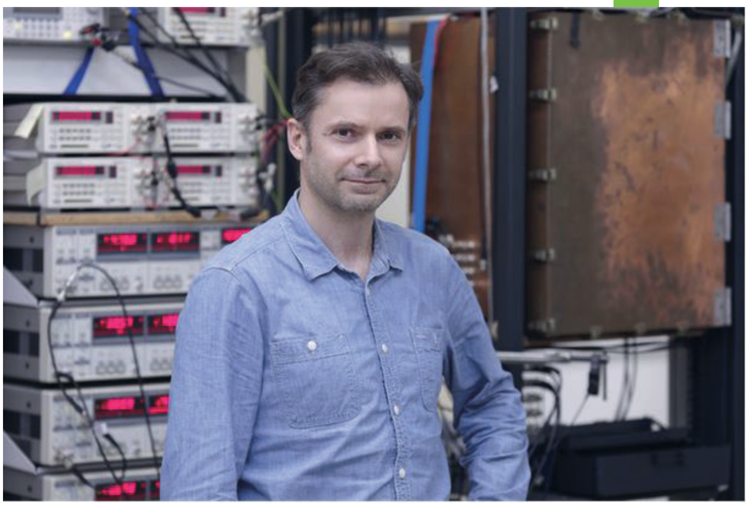
AWARDS

Pascale Senellart, Research Director at C2N, newly elected **member of the French Academy of Sciences,** intersection of science applications. She was awarded the CNRS silver medal in 2014.

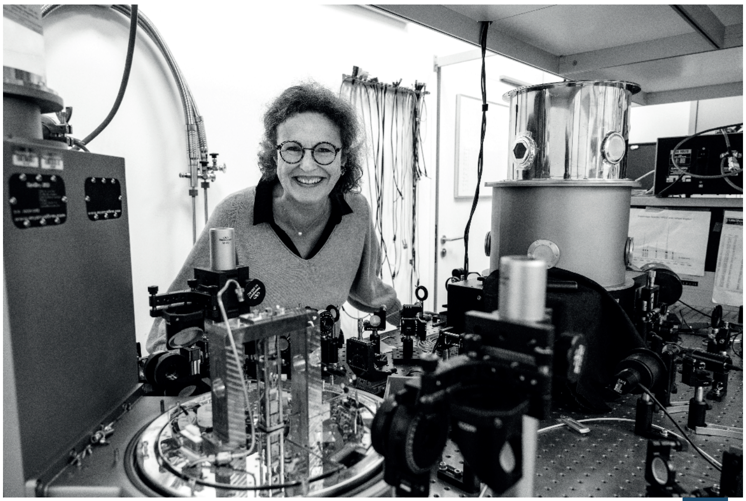
Frédéric Pierre,
CNRS Silver Medalist 2022

It is at the mesoscopic scale - intermediate between classical and quantum physics - that the first quantum behaviours of matter appear (ferromagnetism, superconductivity, etc.). It is this regime that Frédéric Pierre is exploring, and in particular the foundations of mesoscopic quantum transport. While perfectly mastering the fundamental concepts, he designs and manufactures novel electronic circuits at the nanometre scale that are state-of-the-art for very low temperature measurements of current fluctuations.



Some of these circuits are similar to quantum simulators or allow the exploration of the quantum laws of electricity, the understanding of which is fundamental for the engineering of nano devices.

Rémy BRAIVE, 2022 laureat of the Fabry – de Gramont Prize for his work around optomechanics with photonic crystals, in particular the use of mechanical modes for the generation of signals with high spectral purity and the detection of weak signals assisted by noise from phase.


@Nora Houguenade

ERC Advanced Grants 2021
Jacqueline Bloch, laureate for the project ANAPOLIS

ANAPOLIS is an interdisciplinary project aiming at using polariton arrays to explore three major problems of modern physics: the physics of non-equilibrium interfaces and their universal scaling laws, topology in the non-linear regime and quantum magnetism

ERC Advanced Grants 2022, Laurent Vivien, Laureate for the CRYPTONIT project

The project will focus on the demonstration of advanced nonlinear and optoelectronic devices on Si, operating in the near-infrared for the development of highly-efficient and broadband photonic integrated circuits and it will open new horizons for research and applications in communications, sensing, and quantum photonics.

ERC Advanced Grants 2022 , Delphine Marris-Morini, Laureate for the ELECTROPHOT project

In the ELECTROPHOT project, in collaboration with Politecnico Di Milano, we aim at addressing new routes for high resolution spectroscopic systems based on dual-comb spectroscopy by developing innovative frequency comb sources. The C2N technological facility will be heavily involved in the project (Renatech network).

ERC Consolidator Grants 2022
Konstantinos Pantzas, Laureate for the PANDORA project

The PANDORA project aims to converge two research fields with numerous applications: non-linear optics and integrated photonics. This convergence would open up new applications, whether it be producing low-power optoelectronic chips, new components for quantum computing or quantum cryptography.

ERC Consolidator Grants 2022
Carlos Alonso-Ramos, Laureate for the SPRING project

Coherent conversion between microwave and optical photons is a promising solution for transferring quantum states between remote quantum processors, enabling the development of large-scale quantum networks. The SPRING project will demonstrate quantum state transfer between superconducting qubits, monolithically integrated in a silicon chip, opening a new avenue for applications in communications, sensing and computing.

ERC Consolidator Grants 2022
Daniel Lanzilloti Kimura, Laureate for the T-RECS project

Acoustic phonons are generally considered a major source of unwanted effects in electronics, optoelectronics and quantum technologies based on solid-state platforms. The T-Recs project proposes a series of tunable nanodevices where acoustic phonons are a central resource to unveil frequency conversion phenomena, transfer information and simulate complex systems that cannot be studied with optical or electronic platforms.

ERC Starting Grant 2021
Daniele Melati, laureate for his project BEAMS

The use of laser beams is the key element of many next-generation technologies that are currently under development and that are receiving an exploding interest, such as high-speed optical communications between moving vehicles, sensing for autonomous car driving, or medical imaging. The widespread applicability of these technologies is however severely constraint by the systems that are necessary to generate, control, and detect laser beams and that today are realized with big and power hungry devices based on classical optical and mechanical elements (e.g., lenses, mirrors, and motors).

BEAMS (Multilayer photonic integration platform for free space optics) is a multidisciplinary project that aims at overcoming these limitations by exploiting silicon photonics.

Francesco Manegatti, Grand Prix I-PhD - Innovation Award for his project NCODIN developed at C2N

The explosion of data exchanges linked to the Internet and the rapid evolution of sophisticated architectures to solve complex computing problems (High Performance Computing, Artificial Intelligence/Deep Learning) requires the development of technologies that allow ever higher transmission rates and computing power while maintaining energy consumption compatible with sustainable development.

The NCODIN project aims to create nanophotonic solutions for the exchange and processing of data within integrated circuits.

David González Andrade, Marie Curie Postdoctoral Fellow at C2N for the SUNRISE project

Light technologies have revolutionized society by providing access to information, promoting sustainable development, and increasing societal health and well-being. High-performance photonic integrated circuits could enable a new revolution, underpinning the widespread deployment of light-enabled applications in sensing, 5G-6G communications, light detection and ranging, metrology and quantum. Silicon photonics holds the promise for large-scale, low-cost production of high-performance optoelectronic circuits leveraging existing complementary-metal-oxide semiconductor manufacturing infrastructure. However, addressing the needs of these emerging applications requires developing key building blocks that are not feasible in state-of-the-art silicon photonics technology.

SUNRISE (Silicon brillouin-assisted optoelectronic oscillator based on subwavelength membranes) is a multidisciplinary project that aims to overcome these constraints by exploiting Brillouin light-sound interactions.

Fabrice Raineri, nominated for the Jean Jerphagnon 2022 Prize awarded at the Société Française d'Optique Congress

Naïmul Hassan, laureate of the Chateaubriand scholarship

Naimul Hassan is a fifth year PhD student in Electrical Engineering at the Erik Jonsson School of Engineering & Computer Science at the University of Texas at Dallas (UTDallas). His research at UTDallas focuses on studying the physical properties of emerging nanoscale devices and designing circuits and systems for their applications in neuromorphic computing and non-volatile memory. Naimul has been awarded the prestigious Chateaubriand Fellowship by the French Embassy in the United States.

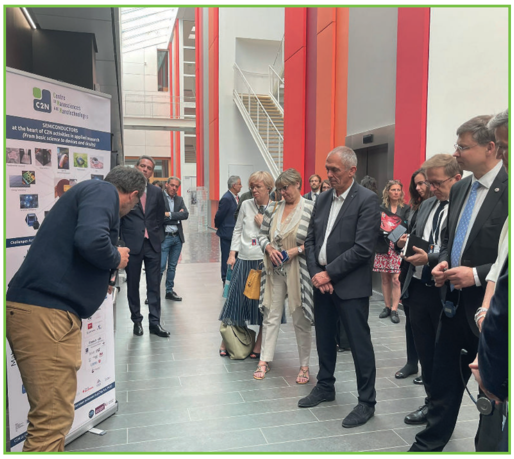
The purpose of this fellowship is to conduct collaborative research between the NeuroSpinCompute lab at UTDallas led by Dr. Joseph S. Friedman (Naimul's PhD supervisor) and the INTEGNANO research group at the Centre for Nanoscience and Nanotechnology (C2N) led by Dr. Damien Querlioz (Naimul's French supervisor).

EVENTS

C2N WELCOMED THE SECOND MEETING OF THE EU-US TRADE AND TECHNOLOGY COUNCIL (TCC)

The EU-US Trade and Technology Council (TCC) meeting took place on 16 May in Paris-Saclay. Launched in June 2021, the TCC serves as a forum for discussion between the United States and the EuropeaUnion, with the aim of coordinating trade, economic and technological issues. France **hosted this second meeting under the French Presidency of the Council of the European Union C2N has been identified as one of the French research laboratories of excellence, positioned in the European Research Area and showing a strong entrepreneurial spirit.**

The delegation, led by Giancarlo Faini, Director of C2N included European Commission Executive Vice Presidents Margrethe Vestager and Valdis Dombrovskis, the US State Department Under Secretary for Economic Growth, Energy and the Environment, Jose W. Fernandez, Director General of the CNRS, Antoine Petit, President of the University of Paris Saclay, Sylvie Retailleau



C2N's global vision for semiconductors was presented by Laurent Vivien, *Research Director, Head of the Photonics Department, Deputy Director of the Unit*, with a focus on photonics and electronics activities to meet the major challenges of communications, detection and quantum technology.

Partnership and technology transfer

During this visit, the activities of two start-ups resulting from research work carried out at C2N were also presented

Presentation of the micro energy sources that will power the next generation of lead-free pacemakers developed at C2N by Elie Lefeuvre's team (*MicroSystems and NanoBiofluidics Department)* in partnership with the company *Cairdac.*

Presentation of the startup ION-X around the new generation thruster technology developed at C2N by Jacques Gierack that will respond to the challenges of the NewSpace industry..

Presentation by Valerian Giesz of the quantum computer built by the start-up Quandela (hosted at C2N since 2017) and using the unique single-photon source technology developed for years by several C2N teams.

SECOND WOMEN IN BUSINESS BECOME A LEADER PROGRAMME

For the second year in a row, C2N welcomed the participants of the Women in Business BEcome a Leader programme of excellence designed by the Université Paris-Saclay with the support of the Women Initiative Foundation Great moments of exchange with our researchers and engineers.

september 2022

VISIT FROM THE MANAGEMENT OF AIRBUS DEFENCE AND SPACE

Visit from the management of Airbus Defence and Space (Florence Dufrasnes, VP Head of Technical Strategy, R&D, Innovation & IP Space Systems, Airbus Defence & Space and her team), C2N's long-standing partner in the development of intense and fast ion sources for micro-space propulsion. These high-quality exchanges mark a new stage in the collaboration on the design of a new generation of miniature Space Propulsion Systems with higher power.

October 2022

KICK-OFF OF THE PARIS-SACLAY INTEGRATED MATERIALS INSTITUTE

The Paris-Saclay Integrated Materials Institute (2IM) was inaugurated at CentraleSupelec on May 2nd, 2022 with an afternoon of presentations detailing the Institute's missions, structure, and topical axes. These cover Computational Materials Science, Materials Synthesis and Processing, State-of-the-Art Characterization Tools, and the Materials Life Cycle. The Integrated Materials Institute comes in aid to Paris-Saclay students, teachers, and researchers to integrate these topics and aspects in their research, training, and innovation projects. The two 2IM direction members and two managers of 2IM themes /axes illustrate the stakes held by C2N, and the investment of C2N in the Integrated Materials Institute. The inaugural event attracted some 75 attendees from all 40 laboratories participating in the Institute, and from all Paris-Saclay establishments, components, and partner organisations.

VISIT OF THE QUEBEC QUANTUM DELEGATION AS PART OF A STRATEGIC MISSION TO THE NETHERLANDS AND FRANCE

June 2022

C2N received a visit from the Délégation Québec Quantique as part of their strategic mission in France. The purpose of the visit to France was to establish research and innovation collaborations with European scientists developing activities in the quantum sector. In January 2021, the French Presidency announced the national strategy on quantum technologies at C2N, thus confirming the positioning of our laboratory as one of the major players in the field.

FIRST LIVE SCIENTIFIC STREAM FROM A CLEAN ROOM

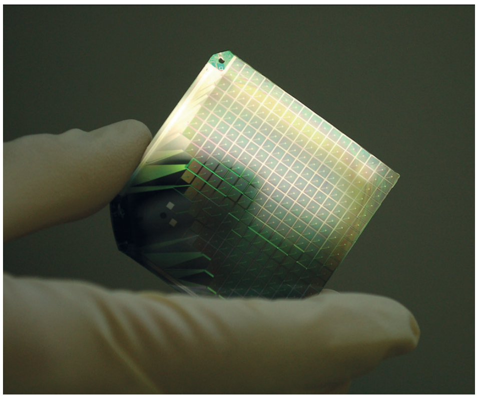
ARTE's Scope programme (in partnership with the CNRS) was live from C2N and broadcast on Twitch. We are honoured to have shared this live broadcast with **Alain Aspect, laureat of the 2022 Nobel Prize in Physics**, and also delighted to have opened the doors of our clean room exclusively for this high-quality scientific stream. An exciting immersion into the heart of quantum physics.

December 2022

INAUGURATION OF THE QUBIC TELESCOPE

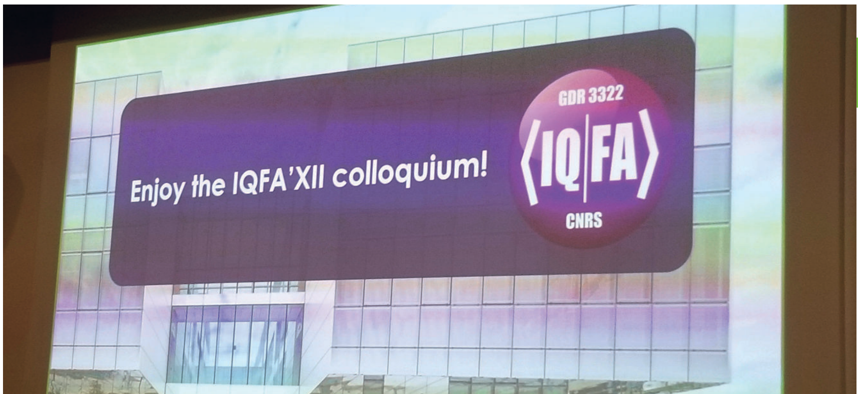
C2N, represented by Giancarlo Faini, Director of the Unit, and Cynthia Vallerand, Secretary General, accompanied by Benoît Bélier, Technical Director of the Platform for Innovation in Micro and Nanotechnologies (PIMENT), attended the inauguration of the QUBIC Observatory in Argentina. This project is supported by an international collaboration of 19 laboratories in France, Italy, Ireland, UK, USA and Argentina. Among them, C2N has been a long-standing partner of the APC and the IJCLab since 2004. The detector arrays that equip the QUBIC telescope are the result of 18 years of research and technological development in the C2N facility.

October 2022



QUBIC bolometric detector array (256 NbSi thermometers suspended on individual silicon nitride grids) realized in the C2N technology center

C2N ORGANISED THE 13TH (AND LAST) COLLOQUIUM OF THE GDR IQFA



November 2022

The conference covered the latest developments in quantum engineering, structured according to the key themes of the IQFA: Fundamental Quantum Aspects,, Quantum communication and cryptography, Quantum Detection and Metrology, Quantum Simulation Quantum processing, algorithms and computing, Cross-disciplinary engineering and methods

MICRO AND NANOPHOTONICS DAYS

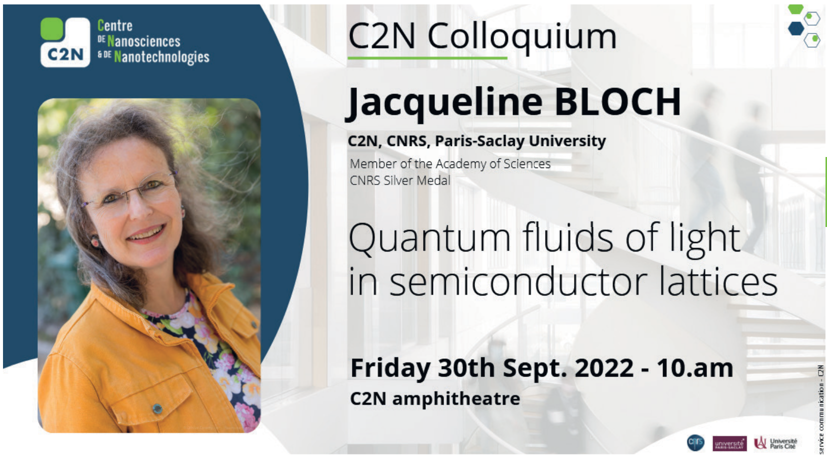
This 2-day scientific workshop covered a wide range of topics in photonics and aimed to establish an international synergy around C2N, which hosts one of the largest European research departments in photonics, and to bring together the most prominent researchers in the field.

The event also aimed to promote knowledge transfer between the different branches of photonics. It was designed to provide an international forum where leading researchers from around the world presented and discussed their latest results and future challenges.

During the conference, we were delighted to welcome **Alain Aspect, Nobel Prize in Physics 2022**

March 2022

THE C2N COLLOQUIA WERE BACK



The C2N colloquia were back ! Great first C2N colloquium by Jacqueline Bloch (CNRS Senior researcher at C2N, CNRS Silver Medal 2017, Academie des Sciences Member 2020) "Quantum fluids of light in semiconductor lattices"

September 2022

THE C2N TECHNOLOGICAL FACILITIES

The C2N Technological Facilities are hosted in a **clean room of 2 900 sqm**, dedicated to micro and nanofabrication processes, epitaxy and characterization of materials. Some areas are also devoted to education and continuous training in micro-nanotechnologies, and **250sqm are dedicated to start-up or SME activities**. More than **50 M€ are invested in state-of-the-art equipments for micro-nanotechnologies** and **40 engineers and technicians work in 3 platforms : PIMENT, POEM and PANAM**.

The C2N cleanroom is an essential tool for research carried out in the laboratory. It is also part of the French network (RENATECH) coordinated by the CNRS to support research and innovation in the field of micro-nanotechnologies at the national level. Today, more than two hundred academic and industrial projects are supported by our facilities. Among these projects, 25% are from external laboratories.

To access our facilities

- To send a request via the RENATECH website (https://projets.renatech.org)

- Contact directly the Technological Facility staff by e-mail : renatech@c2n.upsaclay.fr

Micro and Nano-Technologies Innovation Platform - PIMENT

The Platform PIMENT has more than 150 pieces of equipment for the development, shaping and characterisation of materials, the manufacture and assembly of components. It meets the to the needs of micro and nano manufacturing of the unit's study objects and, more broadly to the demand of the scientific and industrial community.

Expertises

- Optical and alternative lithography lithography, nanolithography
- Metal deposition, dielectric deposition and heat treatments
- Dry and chemical etching, Electrochemistry
- Characterisation by scanning electron microscopy microscopy and physico-chemical physico-chemical
- Back-end

One of the key features

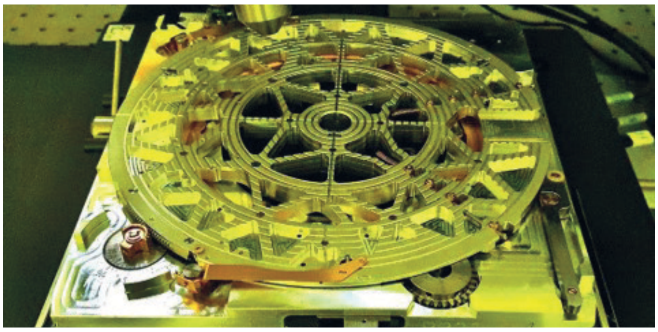
Latest generation electronic masker
Raith Ebpg 5200

Main features

100 kV acceleration voltage (FET source)
1mm x 1mm writing field
Lithography on a full 200mm wafer
Ultimate resolution of 10nm or less
125 MHz write speed
Writing on non-planar samples with height variations of up to 10mm
BEAMER third-party software :
Fracturing and proximity effect correction
Simulation of spatial impulse response (psf) of the ebeam

Key figures

Number of users : 26
Utilization rate : 70% and 2000 hours per year (3950 including maintenance)
Number of training courses per year : 8
Number of projects per year : 42



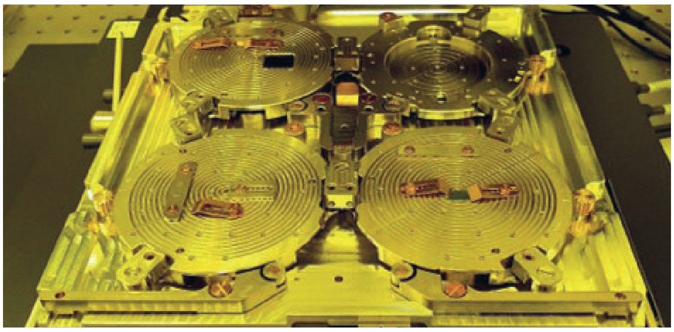


Figure 1: (a) Photograph of the Raith EBPG5200 masker installed in an ISO4 clean room, (b) Holder for 100mm to 200mm wafers, (c) Holder for samples from a few mm² to 3» wafer.

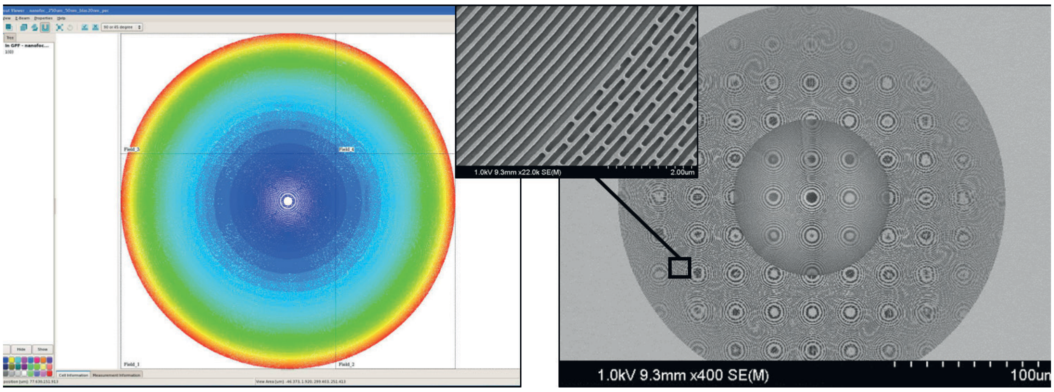


Figure 2: BEAMER software (Genisys GmBh) for fracturing and proximity effect correction (PEC): example of a Fresnel lens implementation

Material Growth Facilities - POEM

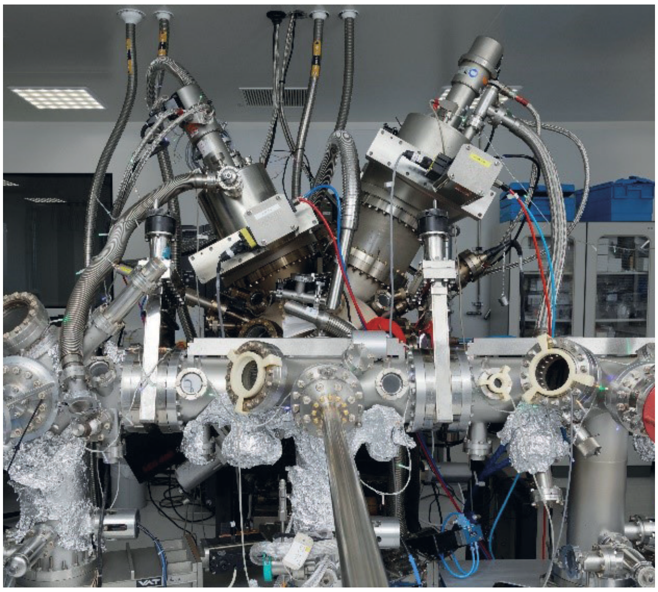
The Material Growth Facilities develop advanced materials for the scientific and industrial community such as crystalline thin films or semiconductor nanostructures IV and III-V, two-dimensional (2D) materials and functional oxides.

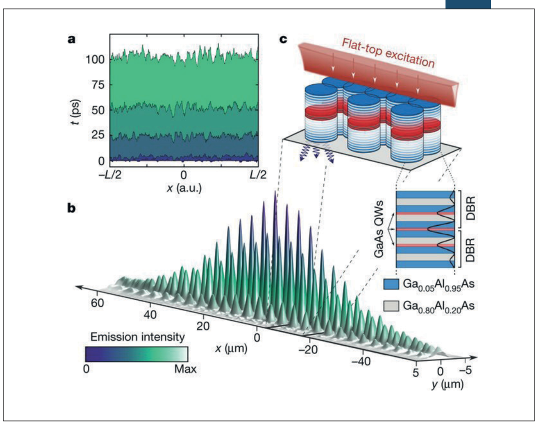
Expertises

- Thin and crystalline materials, 2D, functional and hybridization
- Epitaxy (MBE, MOCVD, CVD, PLD, UHV-CBE)
- Heterostructures and nanostructures of III-V on GaAs, InP, GaP and IV elements on Si
- Nanowires III-V, GaN, SiGe
- Integration of III-V materials on silicon
- Thin magnetic films and functionalized oxides
- Two-dimensional materials (graphene, TMDs, hBN, etc.)
- Topological materials

Epitaxial growth of III-V heterostructures for quantum photonics, phononics and opto-mechanics

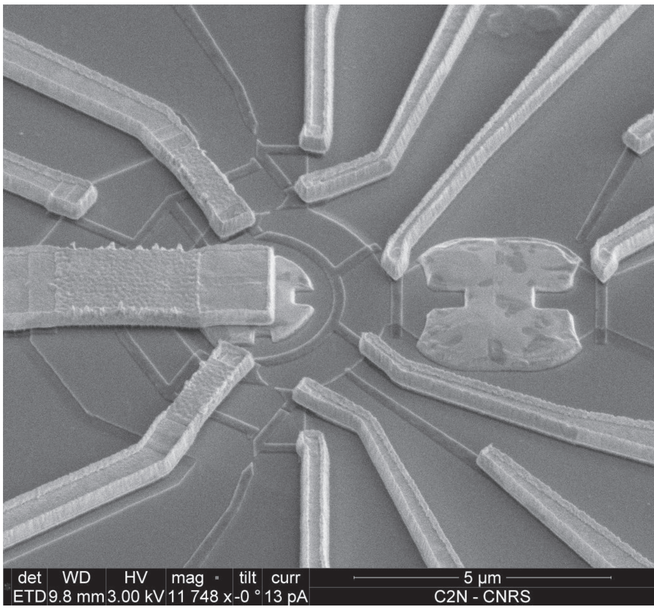
Legend : Epitaxial growth of GaAlAs two-dimensional electron gases used for electronic transport such as the realisation of Zehnder devices





Kardar–Parisi–Zhang universality in a one-dimensional polariton condensate
Fontaine, Q., Squizzato, D., Baboux, F. et al.,

Nature, Vol. 608, 687-691 (2022
DOI : 10.1038/s41586-022-05001-8



Transmitting the quantum state of electrons across a metallic island with Coulomb interaction
H. Duprez, E. Sivre, A. Anthore, A. Aassime, A. Cavanna, U. Gennser, F. Pierre

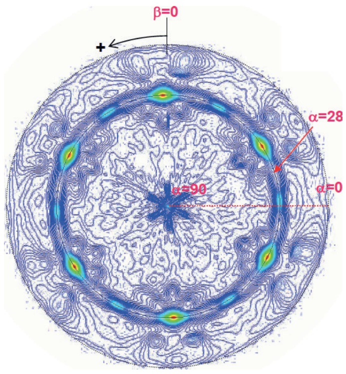
Science, Vol 366, Issue 6470
DOI : 10.1126/science.aaw785

Material ANAlysis Platform - PANAM

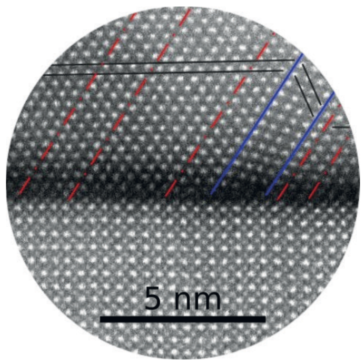
The members of the platform have an exstensive expertise in structural, optical and chemical material analysis down to the atomic scale.

Expertises

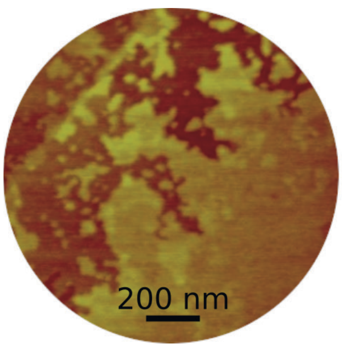
- Analysis of thin film and nanostructures of semiconductors, 2D materials, oxides
- Study of growth modes, strain, plastic and elastic relaxation channels
- Structural/chemical analysis of surfaces and interfaces
- Surface magnetic, electrical and optical properties
- Opto-electronic properties of semiconductors at both nanometer and picosecond scales (band structure, carrier dynamics, crystal phases, defects)
- Imaging of optical modes



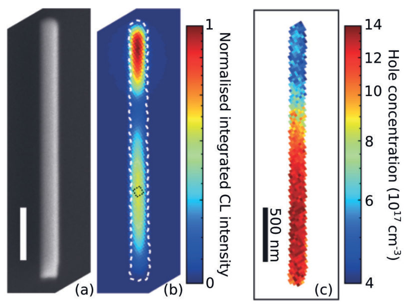
X-rays diffraction and reflectometry
GaN 10-10 pole figure: crystallographic orientantion of GaN nanowires on Si(001)



Transmission Electron Microscopy
STEM-HAADF image of partial dislocations and twinning in a MBE-grown InP layer on SrTiO3 substrate



Atomic Force Microscopy
Epitaxial graphene layer formed by SiC substrate sublimation



Cathodoluminescence (CW and pulsed modes)
(a) GaAs:Be NanoWires (NWs) SEM image.
(b) Normalised integrated CL intensity map.
(c) Hole concentration map extracted from CL map.
Phys. Rev. Applied, 15, 024007 (2021)

INSTRUMENTATION AND ION SOURCES PLATFORM, POEM, PANAM, PIMENT

Selective Growth of graphene films on gallium-focused ion beam irradiated domains

Graphene, a single layer of carbon atoms tightly bound in a hexagonal honeycomb lattice to form a two-dimensional lattice, is a very interesting material with promising electronic, optical, chemical, and mechanical applicative potential [Geim and Novoselov, Nat. Mater. 6, 183 (2007)]. The properties of graphene make it suitable for a wide range of applications; however, its applicative future still depends on large scale technologies capable to robustly and reproducibly transfer its outstanding intrinsic properties into devices or complex structures. It must be recognized that a crucial technological problem, that still inhibits the applicability of high quality graphene material properties, is related to the patterning of this material using traditional top down instruments and lithographical methods. In this work, we will detail our investigations on applying a precise 30 keV Ga+ ion irradiation to selectively shape and modify a copper precursor surface for promoting the local growth of graphene surface domains. The morphology of these domains is investigated using scanning tunneling microscopy and spectroscopy to probe simultaneously the structural and the electronic properties at the atomic scale of the graphene films. In this work we have demonstrated that single graphene domains can be fabricated, localized and organized directly via a specific Ga+ FIB patterning process. We have demonstrated that high FIB irradiation doses (106 ions/pixel) can resist the rearrangement process that occurs during the high temperature CVD preparation process, a temperature required in our experimental growth chamber to achieve high quality graphene films. The copper substrate annealing and copper native oxide removal performed around 1060°C induce a significant rearrangement of the copper precursor surface. Below the 105 ions/pixel threshold, the thin (around ten nm thick) FIB modified surface are erased by the annealing process. The line spacing, orientation or zigzag irradiation were found to provide identical results in the form of high quality localized 2D graphene films having sizes in coherence with the FIB irradiation pattern dimensions. The procedure we have presented relying on specific FIB irradiation can be carried as a batch process and hundreds of devices could be fabricated within a single patterning run. Finally the investigated separation distances between two adjacent scanned lines ranging from 50 to 300nm representing a factor around 10 to 75 with respect to the calculated lateral projected ranges of 35 keV gallium ions (40nm), suggest that the sputtered and redeposited copper atoms (sputtering yield around 10) during the FIB irradiation process plays a central role in our approach. This FIB assisted bottom-up growth technique we have presented would represent a major step towards a better control in the fabrication of structurally well-defined and well positioned 2D graphene flakes. Further work aiming at investigating the lower threshold ion dose required to initiate the growth of graphene is currently under investigation.

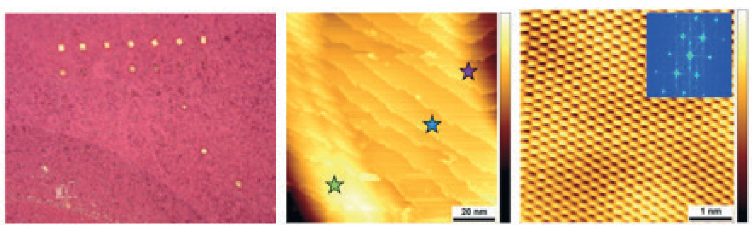


FIG. 1. (a) Optical microcopy image of the patterned structures after CVD growth of graphene. (b) Constant current STM topographic image (500nm x 500nm) obtained on a high dose FIB irradiation (106 ions/pixel) of the Cu(100). The Z colored scale varying from 0 to 20 nm is found to be identical to initial bare copper surface. (c) Higher resolution STM image (5nm x 5nm) performed on the same zone showing atomically resolved STM image of the surface graphene layer and its Fourier pattern in the inset. On this image the Z colored scale is varying from 0 to 130pm. The recorded shape of the individual carbon atoms is attributed to the anisotropic electronic structure of the tip apex atoms.

Selective growth of graphene films on gallium-focused ion beam irradiated domains Editor's Pick
Jacques Gierak, Gilles Raynaud, Caroline Guiziou, Jean René Coudevylle, Ali Madouri, Lars Bruchhaus, Achim Nadzeyka, Björn Whittman, Ralf Jede, Christophe David, Jean Christophe Girard

Journal of Vacuum Science & Technology B 40, 052602 (2022)
DOI : https://doi.org/10.1116/6.0002104

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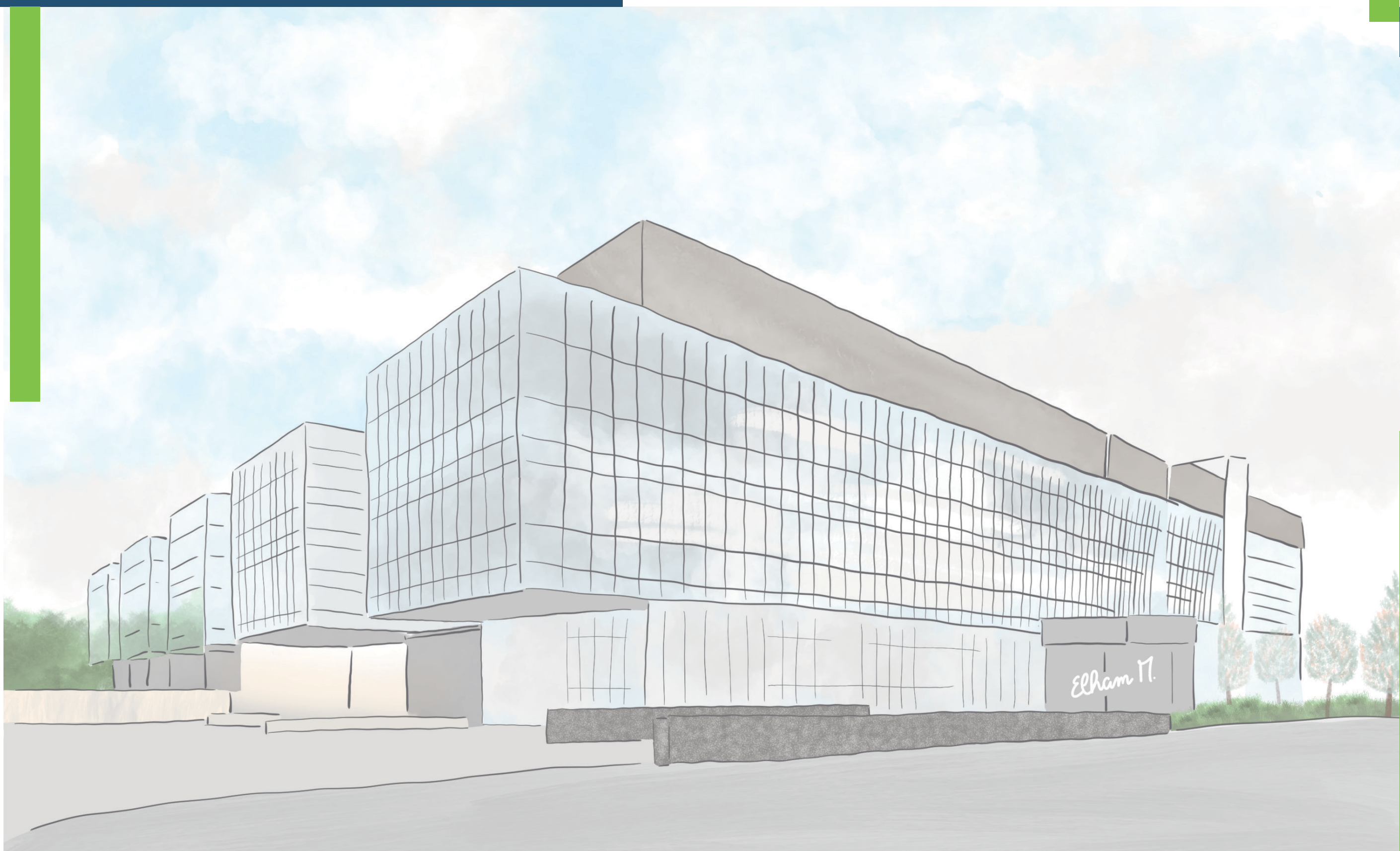

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