Highlights 2024

C2N

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Highlights 2024

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Welcome

C2N

Presentation

C2N, located on the Saclay plateau in the Paris region, embodies an ambitious vision by establishing itself as a major research hub in Nanosciences and Nanotechnologies. It benefits from a strategic location that fosters collaborations with academic laboratories and regional industrial R&D.

The C2N pursues two complementary objectives: to be a leading laboratory for research in nanosciences and nanotechnologies, and to provide local, national, and international stakeholders with access to an open and accessible academic nanotechnology facility, promoting innovation and collaboration between the academic and industrial worlds.

Foreword

In 2024, C2N continued its commitment to pursuing excellence in both fundamental and applied research, driven by a spirit of responsible innovation. Our work, at the intersection of multiple disciplines, addresses the major scientific, technological, and societal challenges of our time.

This report illustrates the breadth of our contributions, marked by recognized scientific and technological advances within strategic projects, notably through the Priority Research Programs and Equipment (PEPR). By actively contributing to the strengthening of national sovereignty in key areas — electronics, photonics, quantum technologies, energy, artificial intelligence, health, and new materials — C2N positions itself as a key player in tackling today's major challenges: the energy and environmental transition, medical advances, and the digital revolution.

This report also highlights our dynamic approach to innovation and technology transfer, through the creation of groundbreaking start-ups and the strengthening of industrial collaborations.

Aware of our responsibility to society and the environment, we are committed to building sustainable research, by fully integrating ecological transition goals into our infrastructures and practices.

The recognition expressed this year by the HCERES Committee reinforces this trajectory. During its visit, the Committee praised the excellence of the scientific, technological, and organizational activities carried out by the laboratory's teams. It highlighted their strong involvement in local, national, and international ecosystems, as well as their contributions to societal challenges and strategic thinking within the research landscape.

Beyond this institutional recognition, the laboratory reaffirms its commitment to fostering a deeper dialogue between science and society. Convinced that the dissemination and transmission of knowledge are essential for a cohesive society, we are actively working to strengthen the connection between science and citizens.

This 2024 report is a testament to the vitality, excellence, and dedication of all C2N personnel. This dynamic would not exist without the commitment and enthusiasm of our entire staff — researchers, faculty members, technical and administrative personnel, PhD students, and postdocs — whom I wish to warmly thank. Thanks to everyone's dedication and to the support of the Management Board, C2N is a recognized player at local, national, European, and international levels.

I would also like to express my sincere gratitude to all those who contributed to this edition of the "2024 Highlights" and to our communications team for their invaluable support.

Giancarlo Faini
Director – C2N

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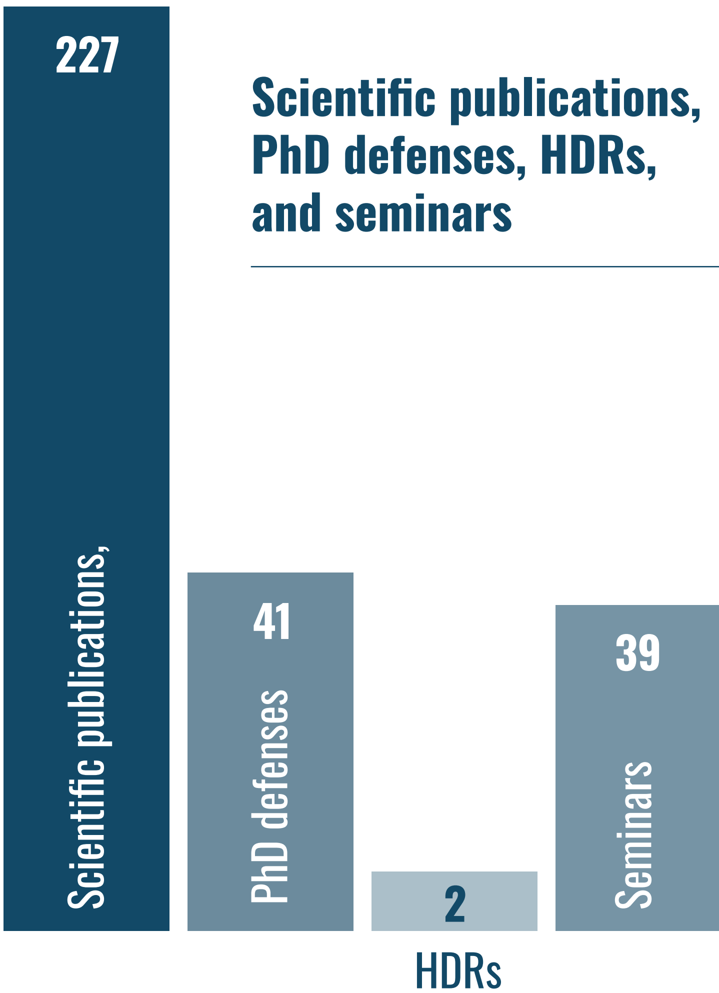
Scientific publications, PhD defenses, HDRs, and seminars



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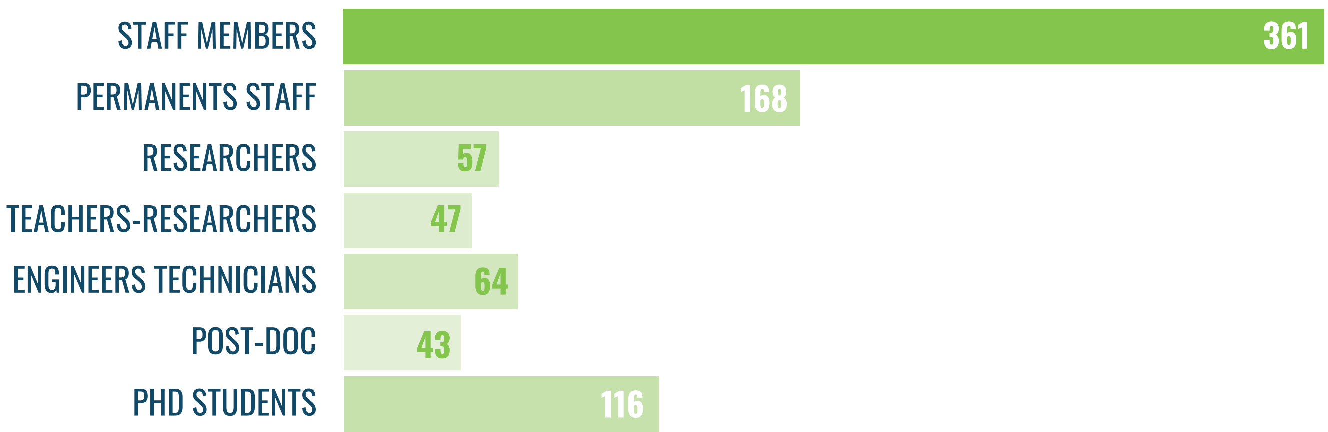

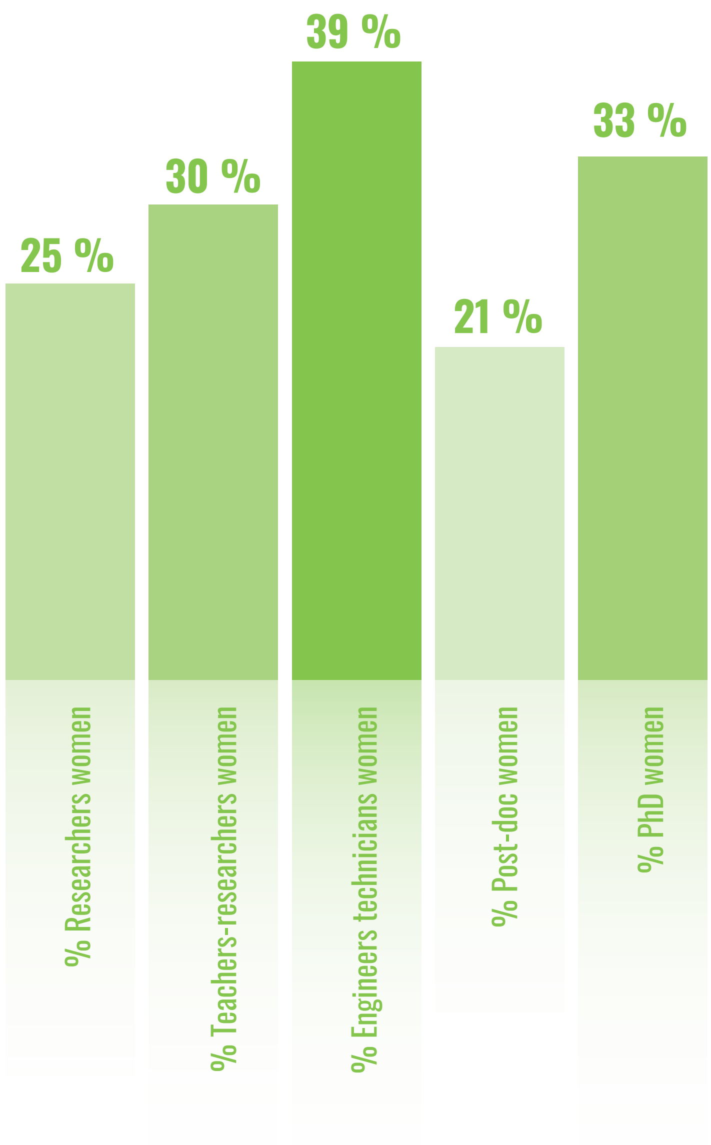

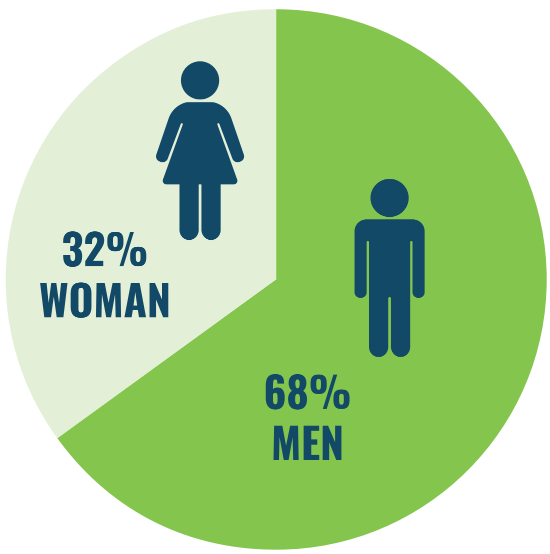

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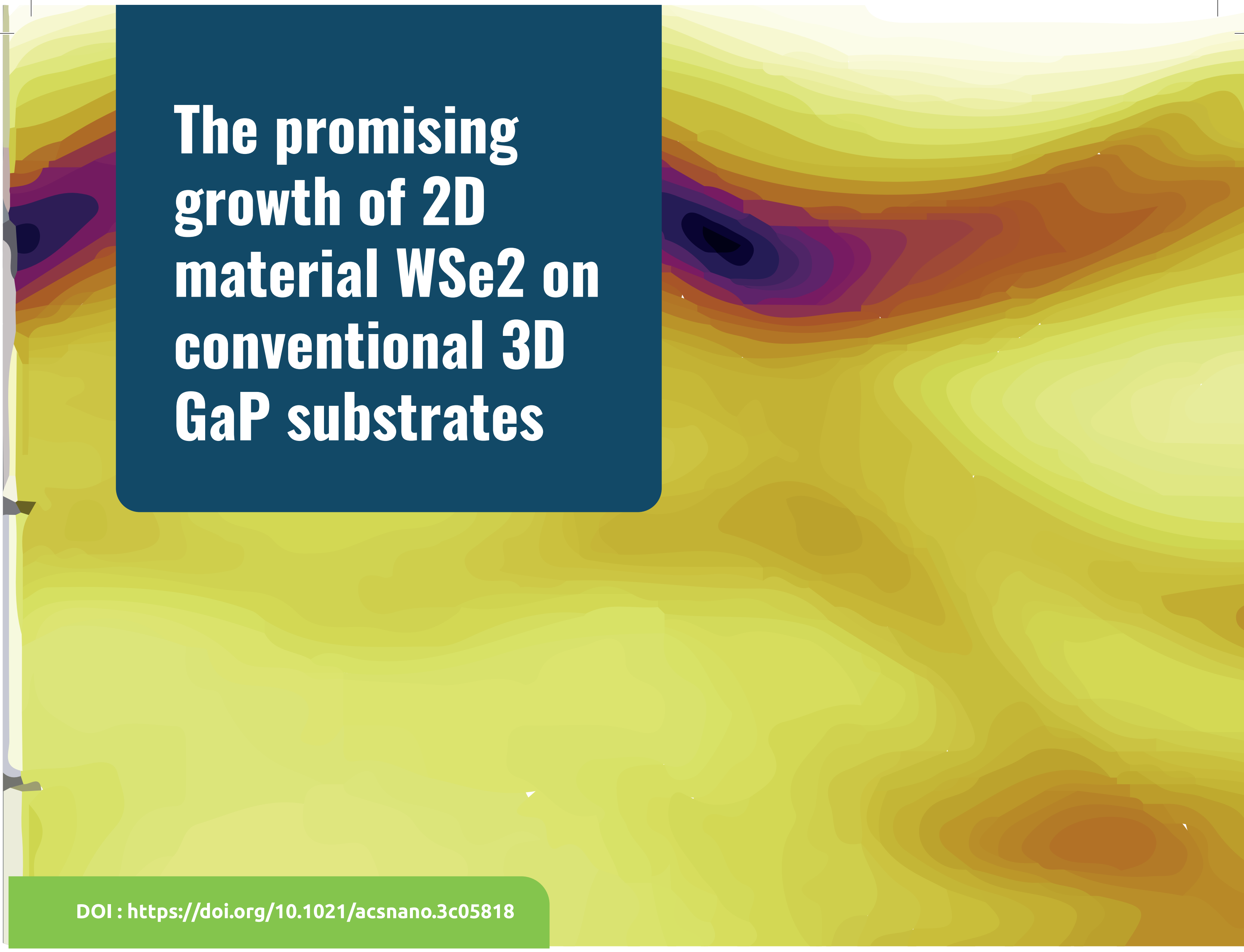
Scientific Publications

- ▶ The promising growth of 2D material WSe2 on conventional 3D GaP substrates
- ▶ Biomechanical MEMS Electrostatic Energy Harvester for Pacemaker Application : a study of optimal interface circuit
- ▶ C2N and Partners Unveil Groundbreaking Memristor-Based Neural Network for Enhanced Medical Diagnostics
- ▶ Electrically injected metamaterial grating DFB laser for telecom applications exploiting an ultra-high Q Electromagnetic Induced Transparency resonance
- ▶ On-Chip Electro-Optic Frequency-Comb Generation at 8 µm wavelength
- ▶ Towards future quantum networks using interactions between spins and photons
- ▶ Coherent interferometric control of strongly-coupled nano-electromechanical resonators
- ▶ Indentation of a ternary 2D material membrane coupled with local optical measurement
- ▶ Towards the first reference standard for resistance and current measurements in C-AFM



The promising growth of 2D material WSe2 on conventional 3D GaP substrates

DOI : https://doi.org/10.1021/acsnano.3c05818

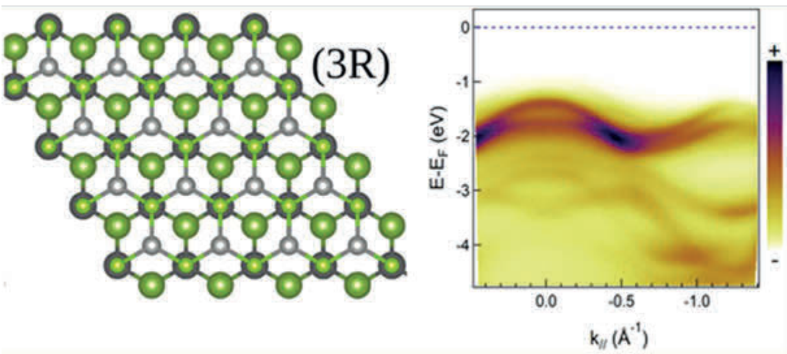
With the perspective of enhancing the physical properties of two-dimensional materials, the MAT2D team at C2N is studying the optical and electronic properties of 3R stacking tungsten diselenide (WSe_2) grown on III-V semiconductor gallium phosphide (GaP). The used growth technique is molecular beam epitaxy, using a particular selenium passivation step of GaP substrate before the actual growth of WSe_2. The research team and collaborators have clarified how the electronic properties of the 2D material are impacted by the underlying GaP substrate.

KEYWORDS

2D materials • MBE • 2D on 3D heterostructure • electronic band structure • bilayer WSe2 • DFT

The growth of two-dimensional (2D) materials on conventional 3D semiconductors results in 2D/3D hybrid heterostructures, which offer a large variety of electronic properties depending on chemical composition, number of layers, and stacking order. Our team at C2N is studying the promising ferroelectric 3R phase of bilayer WSe_2. After studying the electronic band structure of such 2D material in other form (Phys. Rev. B 108, 045417), we demonstrate that such rhombohedral-stacked bilayer of tungsten diselenide can be obtained by molecular beam epitaxy at the surface of a selenium-treated gallium phosphide substrate. We confirm the presence of a 3R-stacking bilayer using scanning transmission electron microscopy (STEM), micro-Raman spectroscopy, and high-resolution angle-resolved photoemission spectroscopy (ARPES). Our findings confirm the absence of chemical bonds at the interface, which confirms the quasi-van der Waals epitaxy of the 2D material on the III-V substrate. Our ARPES measurements reveal the expected valence band of WSe_2 with the band maximum located at the Γ point of the Brillouin zone. The comparison with DFT calculations on free-standing bilayer WSe_2 confirms the rhombohedral nature and the weak quasi-van der Waals interaction between the 2D material and the (selenium-treated) 3D substrate.

FIGURE
Schematic representation of the top view of 3R bilayer WSe2 stacking sequences and ARPES measurement of the valence band along the ΓK high-symmetry direction



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Quasi van der Waals Epitaxy of Rhombohedral-Stacked Bilayer WSe_2 on GaP(111) Heterostructure

ACS Nano 2023, 17, 21, 21307–21316

Aymen Mahmoudi[1],
Meryem Bouaziz[1],
Niels Chapuis[2],
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Biomechanical MEMS Electrostatic Energy Harvester for Pacemaker Application : a study of optimal interface circuit

The leadless pacemaker is the most recent pacemaker concept, developed to overcome conventional pacemakers' limitations. This technology offers better comfort to the patients, lower risk from implantation, and higher reliability. However, these devices suffer from limited battery lifetime due to the extreme miniaturization required for implantation inside the heart cavities. This work proposes extending the battery lifetime by converting biomechanical heartbeat energy into electricity using an innovative electrostatic MEMS energy harvesting device. Based on theoretical models and experiments, we propose a general approach to choosing the

FIGURE
Left : leadless pacemaker ; center : biomechanical energy harvesting MEMS ; right: SEM picture with details of the silicon combs performing electrostatic transduction

DOI : 10.1109/TBME.2023.3327957

optimal interface circuit which considers the parasitic capacitance of the circuit, as it is an imperfection that significantly affects the power performance. According to the energy consumed by the last generation commercial leadless pacemakers, the proposed MEMS solution with optimal interface circuit experimentally showed the possibility of extending the pacemaker battery lifetime by up to 44%.

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Biomechanical mems electrostatic energy harvester for pacemaker application : a study of optimal interface circuit

IEEE Transactions on Biomedical Engineering (2023)

Francisco Ambia
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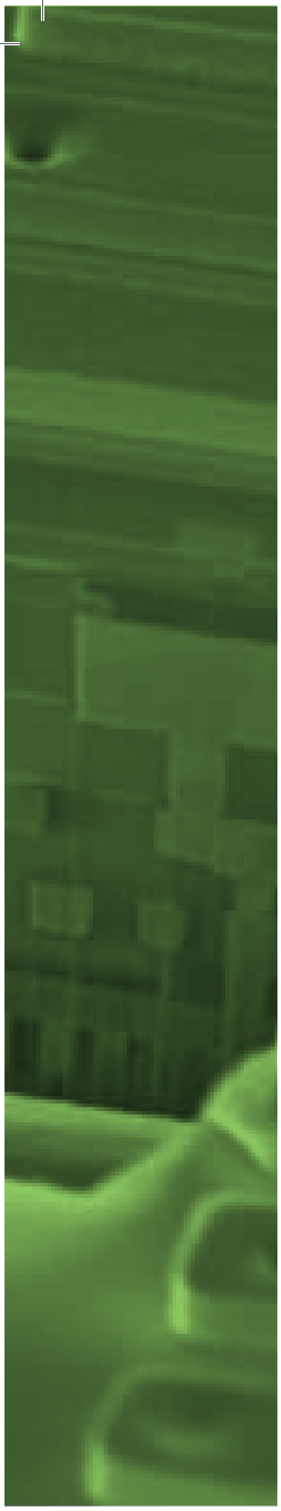
C2N and Partners Unveil Groundbreaking Memristor-Based Neural Network for Enhanced Medical Diagnostics

DOI : https://doi.org/10.1038/s41467-023-43317-9

A groundbreaking study published in Nature Communications on December 7, 2023, showcases a major advancement in neural network technology, with significant implications for medical diagnostics. A collaborative team, including researchers from the Centre for Nanoscience and Nanotechnology (C2N) at CNRS, CEA-Leti, CEA-List, and IM2NP, has successfully implemented the first complete memristor-based Bayesian neural network tailored for a real-world application. This innovative technology offers enhanced capabilities in classifying different types of arrhythmia recordings, integrating a sophisticated approach to managing uncertainty. This feature is particularly valuable in medical diagnosis and other safety-critical tasks that require accurate decision-making based on limited, often noisy data. Bayesian neural networks are uniquely suited to these tasks due to their ability to assess predictive uncertainty. However, these networks traditionally demand high energy and computational resources due to their probabilistic nature, which necessitates storing probability distributions – or synaptic weights – often using a random number generator.



The research team, including Damien Querlioz from C2N, has innovatively used the intrinsic variability of memristors to store these probability distributions, bypassing the need for separate random number generators. This approach not only reduces energy consumption but also streamlines the overall process.

A significant challenge in implementing this system was the need for extensive parallel multiply-and-accumulate (MAC) operations, which are typically resource-intensive when performed on CMOS-based systems. The team's solution involves using memristor crossbars, which naturally facilitate these operations through Ohm's law and Kirchhoff's current law, leading to a marked reduction in power consumption.

An additional aspect of this research was the integration of memristors with Bayesian neural networks. Memristors, governed by the laws of device physics, often display statistical effects that can be challenging to reconcile with the more arbitrary nature of effects in Bayesian neural networks. The team developed a novel training algorithm incorporating a 'technological loss' that adapts to the idiosyncrasies of the memristors during the learning phase, ensuring compatibility between the network and the memristor's imperfections.

A key advantage of this Bayesian neural network is its uncertainty quantification capability. Unlike traditional neural networks, which might misclassify unfamiliar inputs with false confidence, a Bayesian neural network can recognize and acknowledge unknown or out-of-distribution situations. This feature is critical in environments where erroneous predictions can have severe consequences, such as in medical diagnostics.

The network's unique approach to synaptic values – treating them as probability distributions rather than precise values – results in outputs that are also probabilistic, offering insights into the network's level of certainty. This represents a significant step forward in the field of neural network technology, promising substantial improvements in medical diagnostics and other critical applications.

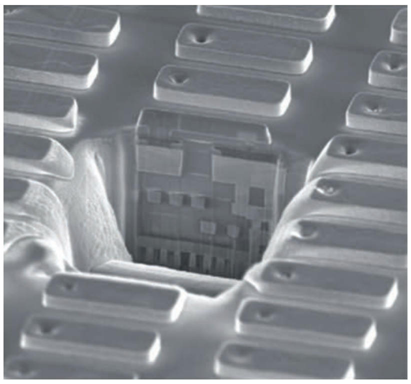


FIGURE
Scanning Electron Microscopy image of a filamentary memristor in the back end of line of our hybrid memristor/CMOS process

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Bringing uncertainty quantification to the extreme-edge with memristor-based Bayesian neural networks

Nature Communications
volume 14, Article number: 7530 (2023)

Djohan Bonnet[1,2], Tifenn Hirtzlin[1], Atreya Majumdar[2], Thomas Dalgaty[1], Eduardo Esmanhotto[1], Valentina Meli[1], Niccolo Castellani[1], Simon Martin[1], Jean-François Nodin[1], Guillaume Bourgeois[1], Jean-Michel Portal[3], Damien Querlioz[2], Elisa Vianello[1]

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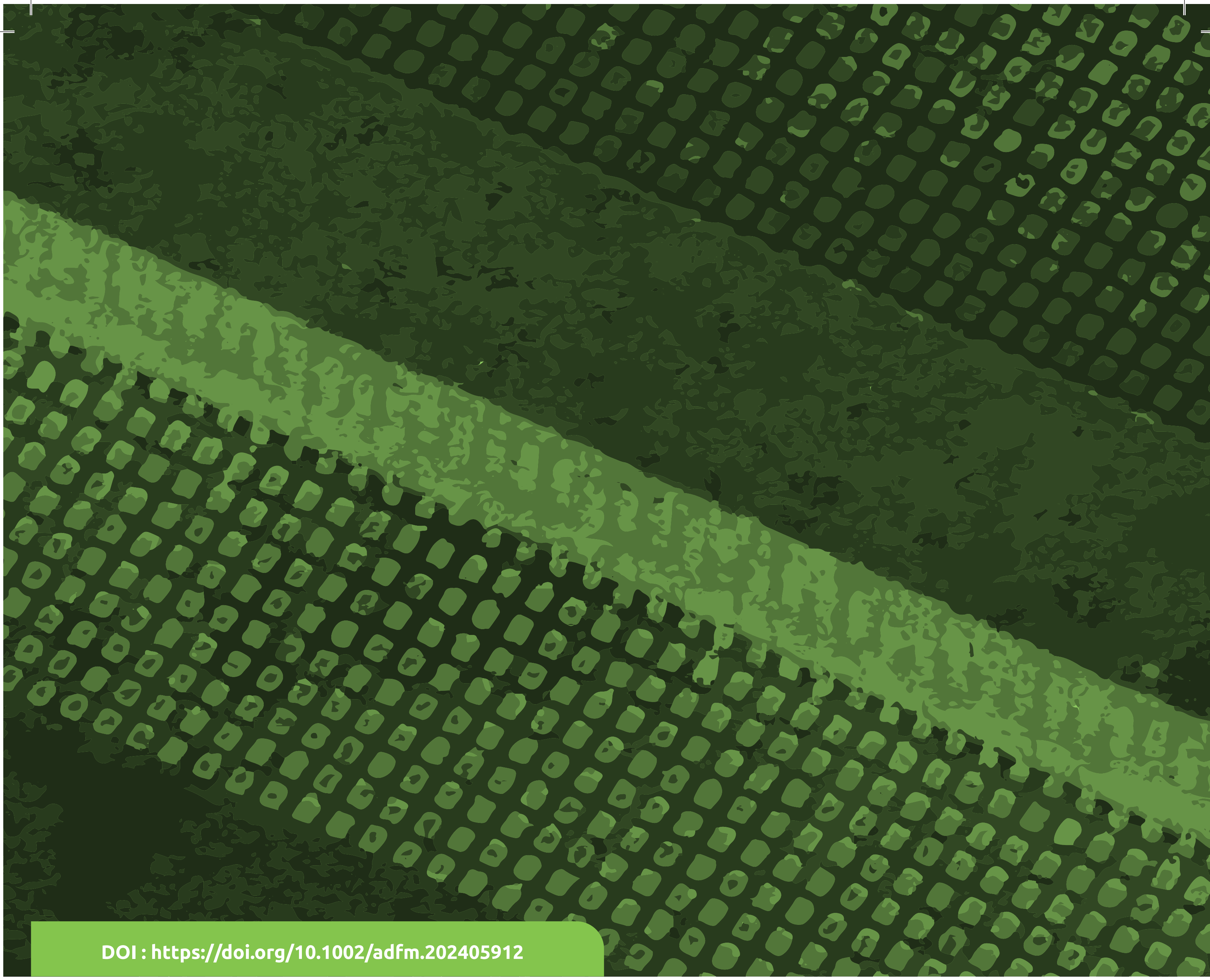
Electrically injected metamaterial grating DFB laser for telecom applications exploiting an ultra-high Q Electromagnetic Induced Transparency resonance

Researchers at the Centre de Nanosciences et de Nanotechnologies (C2N), in collaboration with Laboratoire Charles Fabry (LCF) and Telecom SudParis proposed to use a 2D metamaterial Bragg grating assisted waveguide to achieve Electromagnetically-Induced-Transparency (EIT) resonance with an ultra-high Q~5000 and contrast >20dB. This concept was further applied to the demonstration of single frequency emission electrically injected distributed feedback (DFB) lasers in the NIR telecom domain. The ability of metamaterials to shape lasing properties with EIT - based low losses light propagation opens promising perspectives that such types of lasers may present increased robustness with respect to parasitic optical return which constitutes one of the major impairments of DFB lasers in telecommunications applications.



DOI : https://doi.org/10.1002/adfm.202405912

Metamaterials (MMs) exploit the emerging properties of an array of individual elements displaying some kind of resonance, with the scope of producing artificial photonic responses absent from normal materials. The form of a 2D array commonly designated as "metasurfaces" has often been considered for obvious feasibility reasons, with basic features such as near-normal incidence transmission/reflection exhibiting a host of new effects. The popular word of "metasurfaces" commonly refers to the most of such 2D arrays. Waveguides (WGs), which are a privileged vehicle of functional photonics, have also been considered with MMs. However, since metallic/plasmonic structures often constitute the elementary MM resonators, the incurred losses, to which guided modes are quite sensitive, have been a substantial hurdle to the achievement of convincing and broad-reaching demonstrations.

In a work published in May 2024 in Advanced Functional Materials journal, a team of researchers at the Photonics Department of the Centre de Nanosciences et de Nanotechnologies – C2N (CNRS/Univ. Paris-Saclay) in collaboration with the Laboratoire Charles Fabry– LCF (CNRS/Univ. Paris-Saclay), and Telecom SudParis reported the observation of a marked Fano type EIT effect with record high quality factor

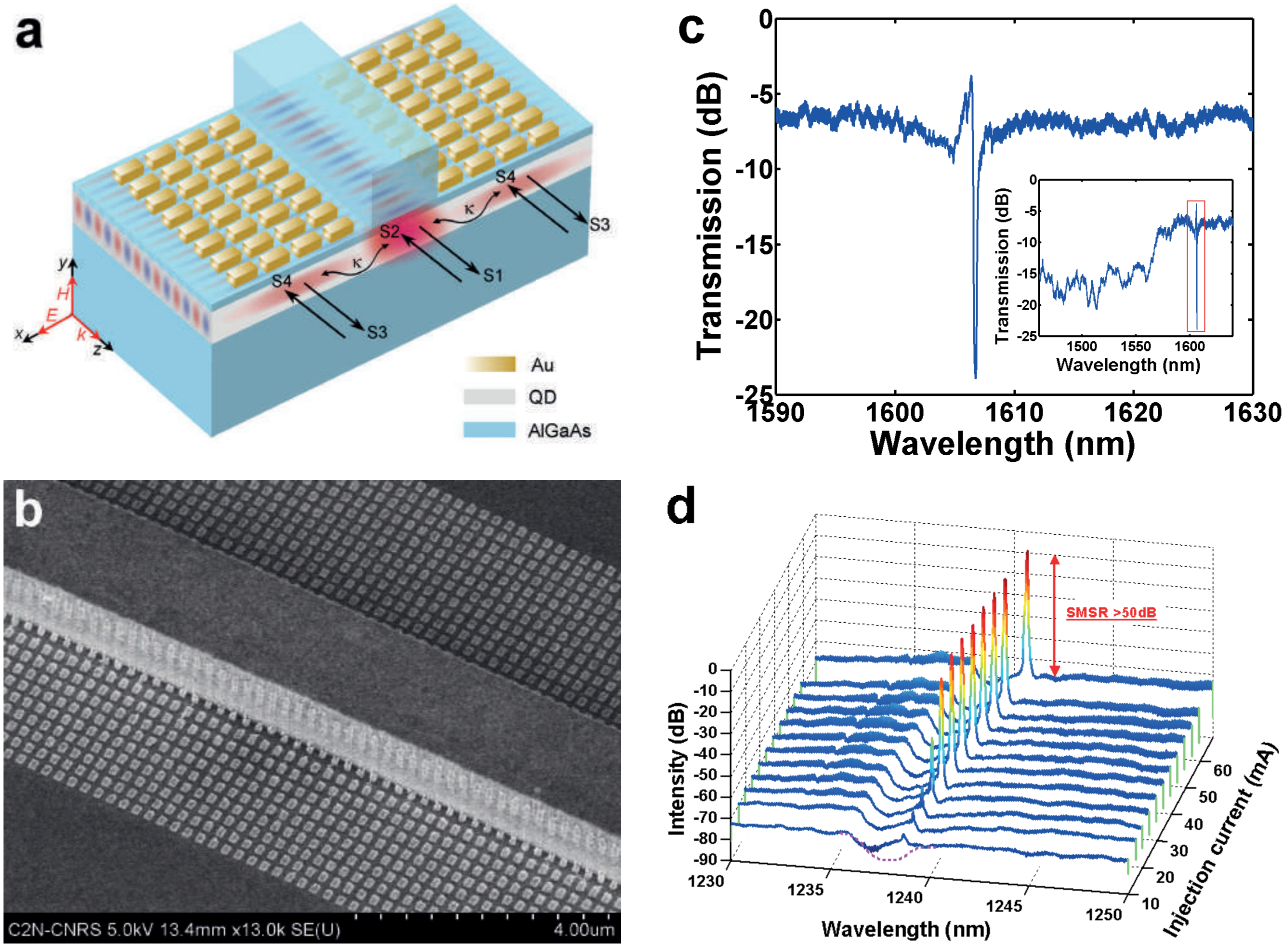


FIGURE
(a) Sketch of the dielectric ridge waveguide assisted by MM Bragg grating. The arrows S1 and S2 represent the two counter-propagating modes of the ridge waveguide. The arrows S3 and S4 represent the fundamental plasmonic supermode of the MM grating. Their profiles (blue/red/brown) are visible on the different cuts., (b) SEM view of gold cut-wires MMG and III-V passive semiconductor waveguide. (c)Transmission spectrum of a 2 µm wide and 3.2 mm long MMG ridge waveguide in the EIT region. The inset shows the spectral response at extended wavelength range. The red box indicates the EIT region. (d) Emission spectra of 1.68 mm long laser waveguide structures at dufferent injection currents.

* In the C2N Technology Facility (cleanroom), member of the French network of large high-end facilities (RENATECH CNRS).

of resonance: Q~5000 and contrast >20dB in metamaterial Bragg grating (MMBG) assisted passive WGs. This supports the idea that MMs, as functional photonic building blocks, can lead to low losses in many standard devices if properly designed. Unlike any standard metal grating, MMBG assisted WGs exhibit both strong grating coupling strength and low-loss properties simultaneously. This concept is further applied to the demonstration of single frequency emission electrically injected DFB lasers in the NIR telecom domain. The key point is that laser emission occurs at the peak of EIT, i.e. the maximum in transmission.

It addresses in this way one of the main critical issues of DFB lasers related the single frequency yield. The laser performances are at the state-of-the art (Ith<20mA, Pmax->23mW at I=200mA, side mode suppression ratio >50dB, enhanced polarization selectivity > 10dB, tolerance to optical feedback > -21dB compliant with IEEE 802.3 standard without an isolator). The presented approach is compatible with existing industrial technologies and promising for large scale real-life telecom applications. Such highly coherent laser sources are indeed required in diverse applications as coherent communications, sensing, programmable photonic circuits.

Figure 1a represents the principle of MMBG with EIT arising from physically separated resonant contributions, nevertheless sensed as a whole by the waveguide mode. The fabrication and characterization of the experimental structure (see Figure 1b), were performed at C2N*, charecterization by C2N and Telecom SudParis, while design and modeling were carried out by C2N* and LCF partners.

The experimental transmission spectral response represented in Figure 1c for a 3.2 mm long MMG ridge waveguide shows the presence of a marked EIT at 1607 nm. As can be seen, the peak value of transmission is more than 2 dB higher with respect to the WG transmission level outside the EIT resonance. The high-contrast narrow transmission band may provide an advantage toward more robust single-frequency operation of DFB lasers. To prove the validity of the present flavor of EIT concept, the same heterostructure that served for the passive MMBG WG study was also used for the fabrication of an “EIT laser” with an emission wavelength around 1.24 µm.

The emission spectra for a MMBG laser at different injection currents are shown in Figure 1d. They display a clearly visible EIT feature, especially when the injection current is below the threshold, which is around Ith =21 mA. The laser emission line grows exactly at the sub-threshold local emission maximum, emerging within a few nm wide dip attributed to the MMBG. The laser emission is single frequency with a side mode suppression ratio greater than 50 dB up to the largest current (I ~ 3Ith).

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Electrically injected metamaterial grating DFB laser exploiting an ultra-high Q electromagnetic Induced Transparency resonance for spectral selection.

Advanced Functional Materials, 2024, 34 (45), 2405912.

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V. Brac de la Perrière[1]
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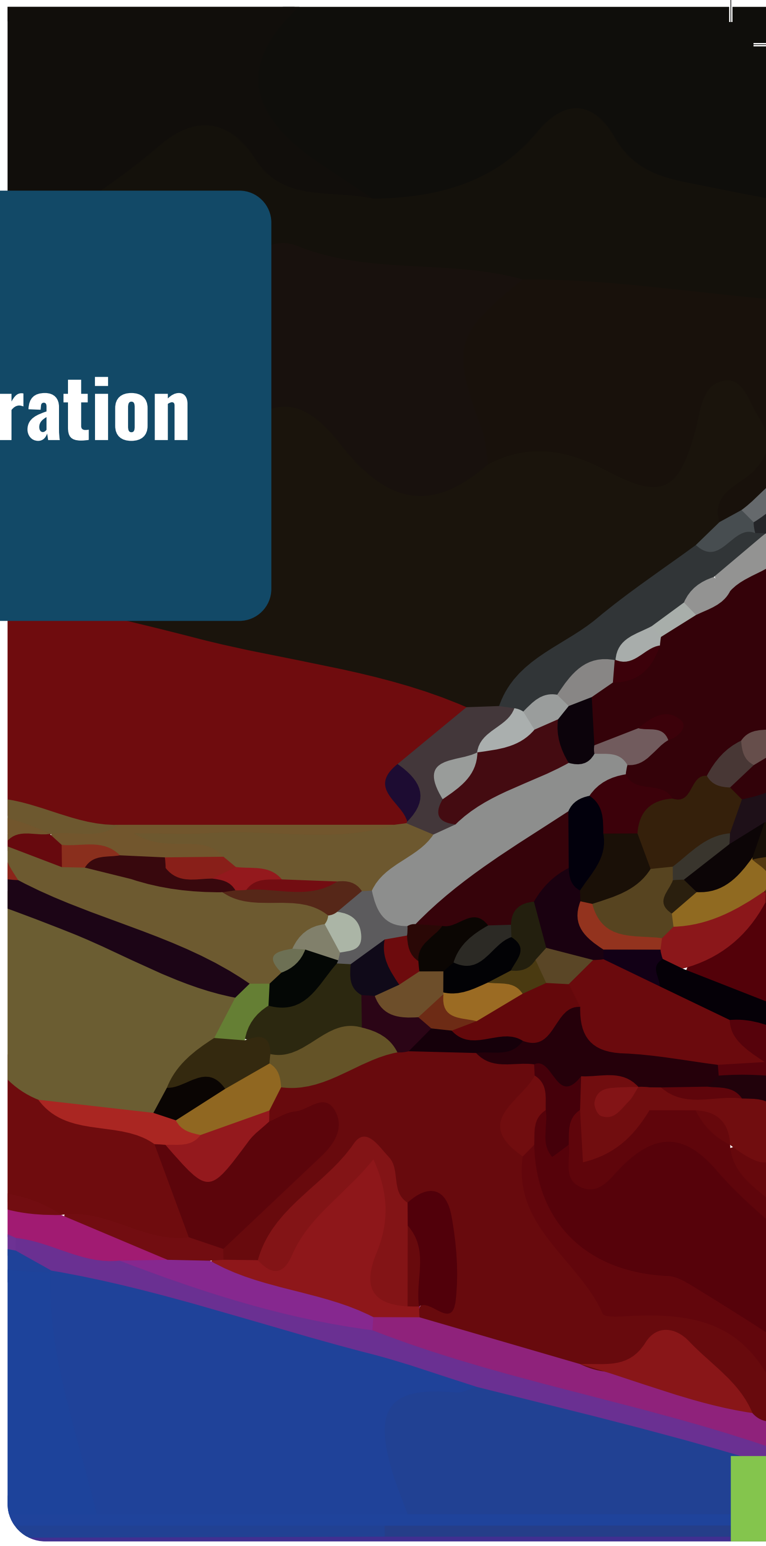
On-Chip Electro-Optic Frequency-Comb Generation at 8 µm wavelength



The development of compact systems operating in the long-wave infrared wavelength range is of high interest for spectroscopic and sensing applications. There is currently a wide interest toward the development of optical frequency-combs to enhance the performances of these systems.

Amongst the different techniques to obtain optical frequency-combs, electro-optic frequency-comb generation presents major advantages thanks to the tunable repetition rate only limited by the bandwidth of the used electro-optical modulator.

In this context, researchers from C2N in collaboration with Politecnico Di Milano have experimentally demonstrated for the first time electro-optic comb generation in the deep mid-IR wavelength range.

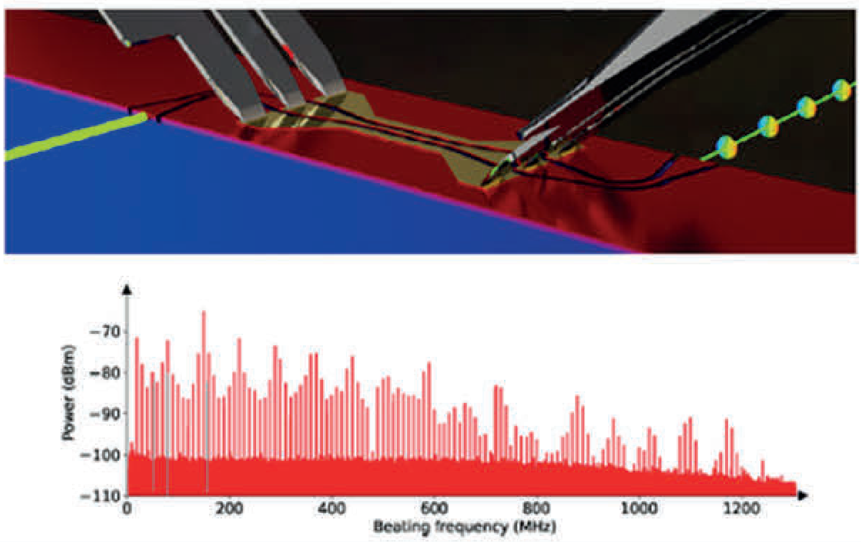
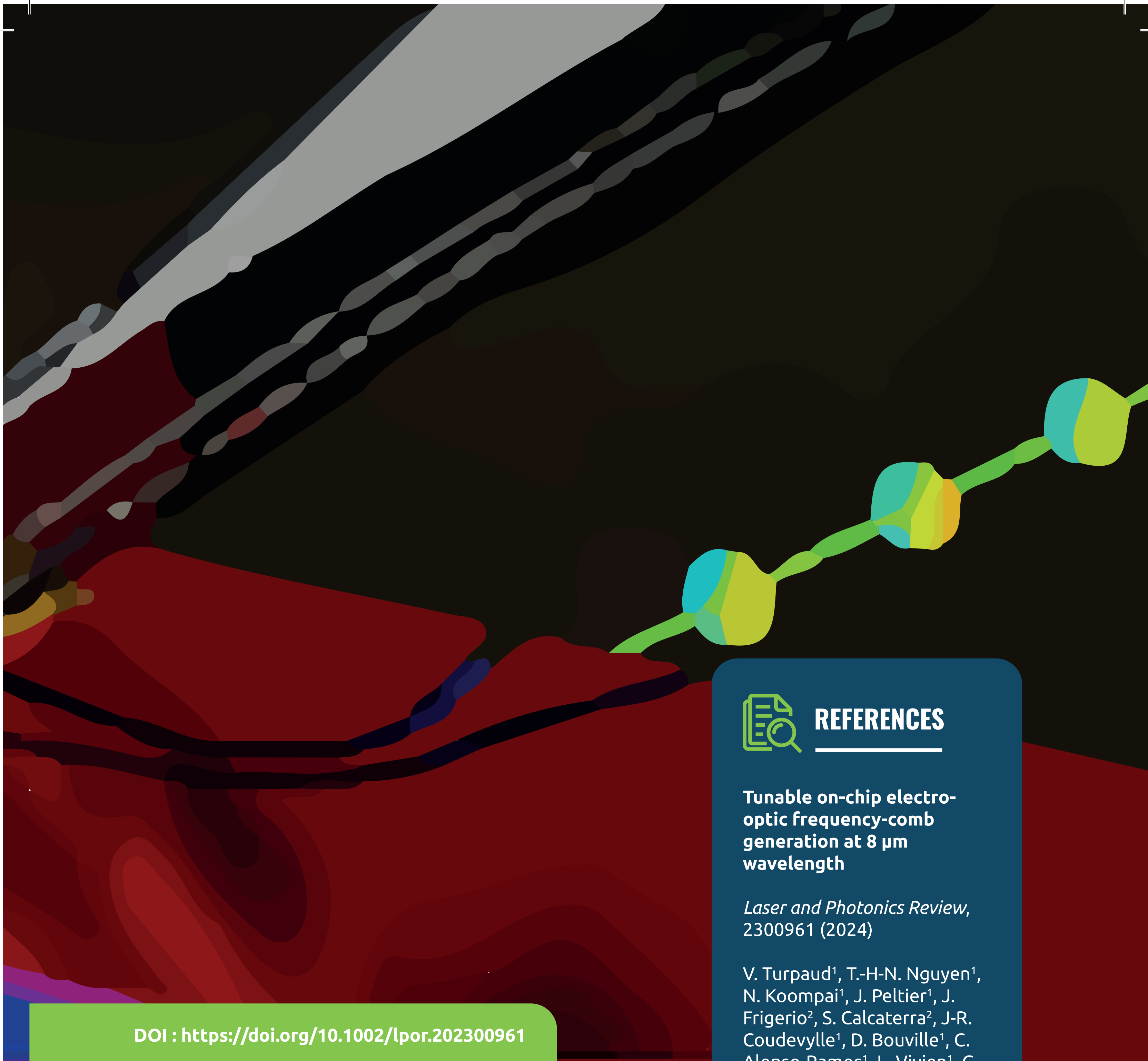


FIGURE
Top : Electro-optical frequency comb generation principle. A CW laser source is sent to the modulator, driven by a periodic electrical signal, which modifies both the light amplitude and instantaneous phase and frequency, leading to optical pulses at the output corresponding to frequency comb in the spectral domain. bottom : Example of measured beatnote signal showing frequency comb operation.



DOI : https://doi.org/10.1002/lpor.202300961

In this work, a Schottky-based modulator embedded in a Ge-rich graded SiGe waveguide is used for electro-optic frequency-comb generation. Considering the limited efficiency of the modulator, harmonically-rich RF signals are used to enhance the generation of comb lines around the optical carrier. Interestingly, this allows to demonstrate the generation of electro-optical combs spanning over 2.4 GHz around 8 µm wavelength.

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Tunable on-chip electro-optic frequency-comb generation at 8 µm wavelength

Laser and Photonics Review, 2300961 (2024)

V. Turpaud[1], T.-H-N. Nguyen[1], N. Koompai[1], J. Peltier[1], J. Frigerio[2], S. Calcaterra[2], J-R. Coudevylle[1], D. Bouville[1], C. Alonso-Ramos[1], L. Vivien[1], G. Isella[2], D. Marris-Morini

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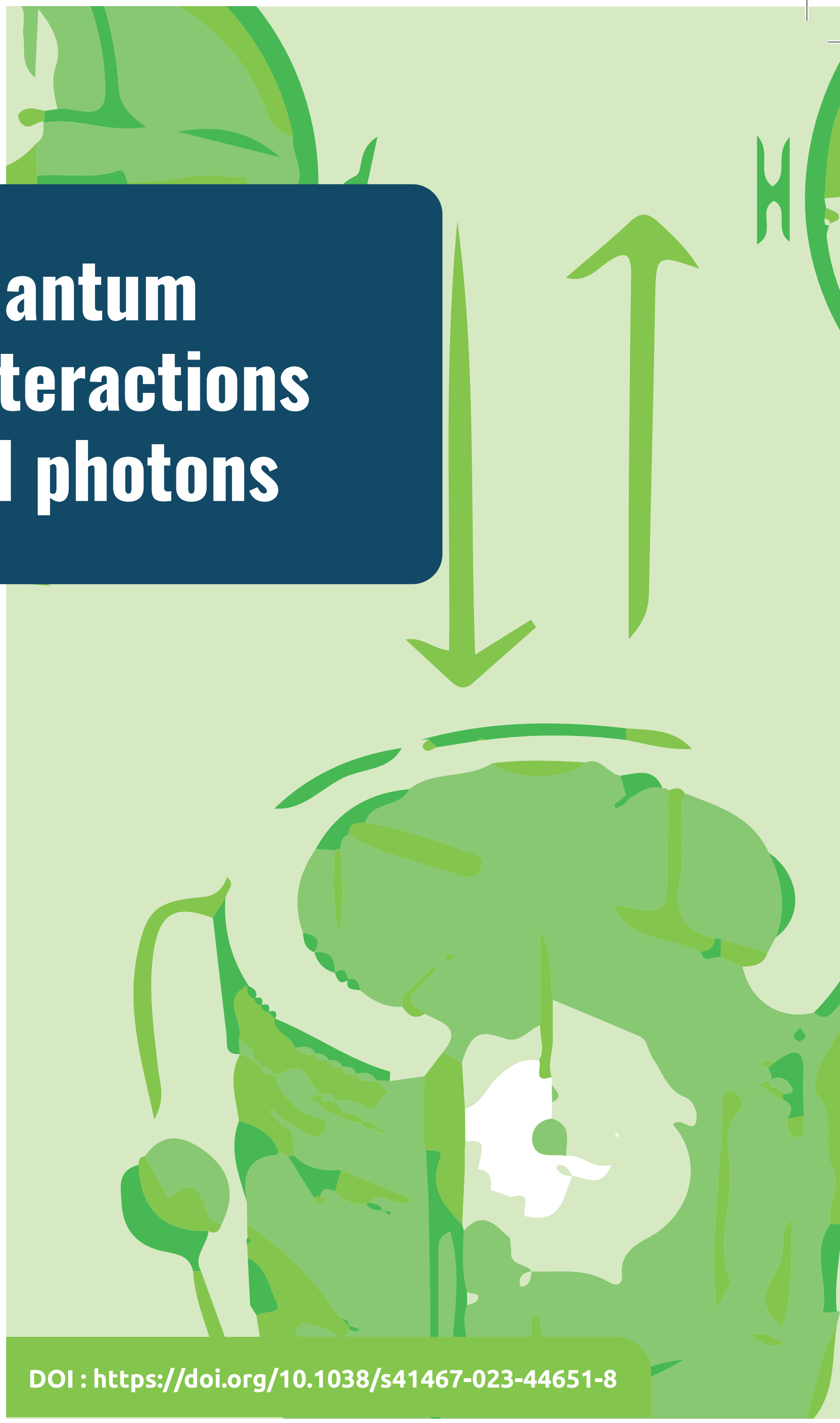
Towards future quantum networks using interactions between spins and photons



DOI : https://doi.org/10.1038/s41467-023-44651-8

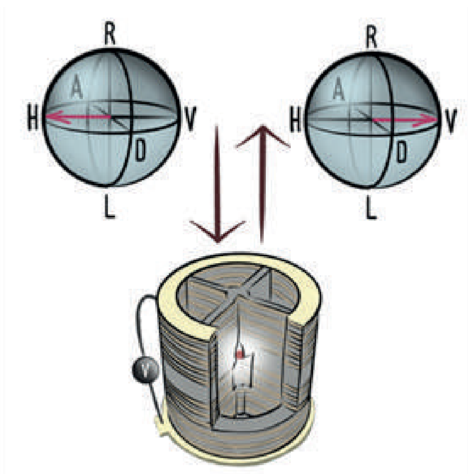
In the framework of optical quantum computing and communications, a major objective consists in building receiving nodes implementing conditional operations on incoming photons, using a single stationary qubit. In particular, the quest for scalable nodes motivated the development of cavity-enhanced spin-photon interfaces with solid-state emitters. An important challenge remains, however, to produce a stable, controllable, spin-dependent photon state, in a deterministic way. Here we use an electrically-contacted pillar-based cavity, embedding a single InGaAs quantum dot, to demonstrate giant polarisation rotations induced on reflected photons by a single electron spin. A complete tomography approach is introduced to extrapolate the output polarisation Stokes vector, conditioned by a specific spin state, in presence of spin and charge fluctuations. We experimentally approach polarisation states conditionally rotated by , π and , in the Poincaré sphere with extrapolated fidelities of (97 ± 1) %, (84 ± 7) %, and (90 ± 8) %, respectively. We find that an enhanced light-matter coupling, together with limited cavity birefringence and reduced spectral fluctuations, allow targeting most conditional rotations in the Poincaré sphere, with a control both in longitude and latitude. Such polarisation control may prove crucial to adapt spin-photon interfaces to various configurations and protocols for quantum information.

For the development of quantum communications and optical quantum computing, a major concern is to control light-matter interaction at the most fundamental level: the qubits (quantum bits) associated with single particles. Spin-photon interfaces are one of the most interesting platforms from this point of view, as they allow to couple a spin qubit (potentially serving as a computational node) with messenger qubits: photons. A major challenge is to effectively use such interfaces as receiving devices for incoming photons – capable of modifying the state of the received photons via interaction with the spin qubit.

A research team led by Dr. Loïc Lanco at C2N, the Centre for Nanoscience and Nanotechnology (CNRS - Université Paris Saclay - Université Paris Cité), has studied a spin-photon interface consisting of an artificial atom – an InGaAs semiconductor quantum dot – embedded in a photonic structure – an electrically-contacted micropillar cavity. The goal of such an interface is to establish a perfect mapping between the spin state of an electron, confined in the quantum dot, and the polarisation state of a photon reflected by the device.

In these experiments, carried out under a magnetic field and at liquid helium temperature, the C2N team demonstrated a giant optical polarisation rotation induced by the spin of a single electron. Despite very fast fluctuations of the spin orientation, they were able to extrapolate the conditional polarisation state of reflected photons, when the spin points upwards.

Contrary to all previous works, the C2N scientists were able to carry out polarisation tomography - i.e. to determine the complete state of the polarisation qubit, represented in the Poincaré sphere describing all possible states. Thanks to spin-photon interfaces that have been greatly optimized compared to previous achievements, the team was able to demonstrate a complete rotation (180° in the Poincaré sphere) of the polarisation state, and analyse the residual depolarisation induced by environmental fluctuations.



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Giant optical polarisation rotations induced by a single quantum dot spin

Nature Communications volume 15, Article number: 598 (2024)

E. Mehdi[1], M. Gundín[1], C. Millet[1], N. Somaschi[2], A. Lemaître[1], I. Sagnes[1], L. Le Gratiet[1], D. A. Fioretto[1], N. Belabas[1], O. Krebs[1], P. Senellart[1] & L. Lanco[1]

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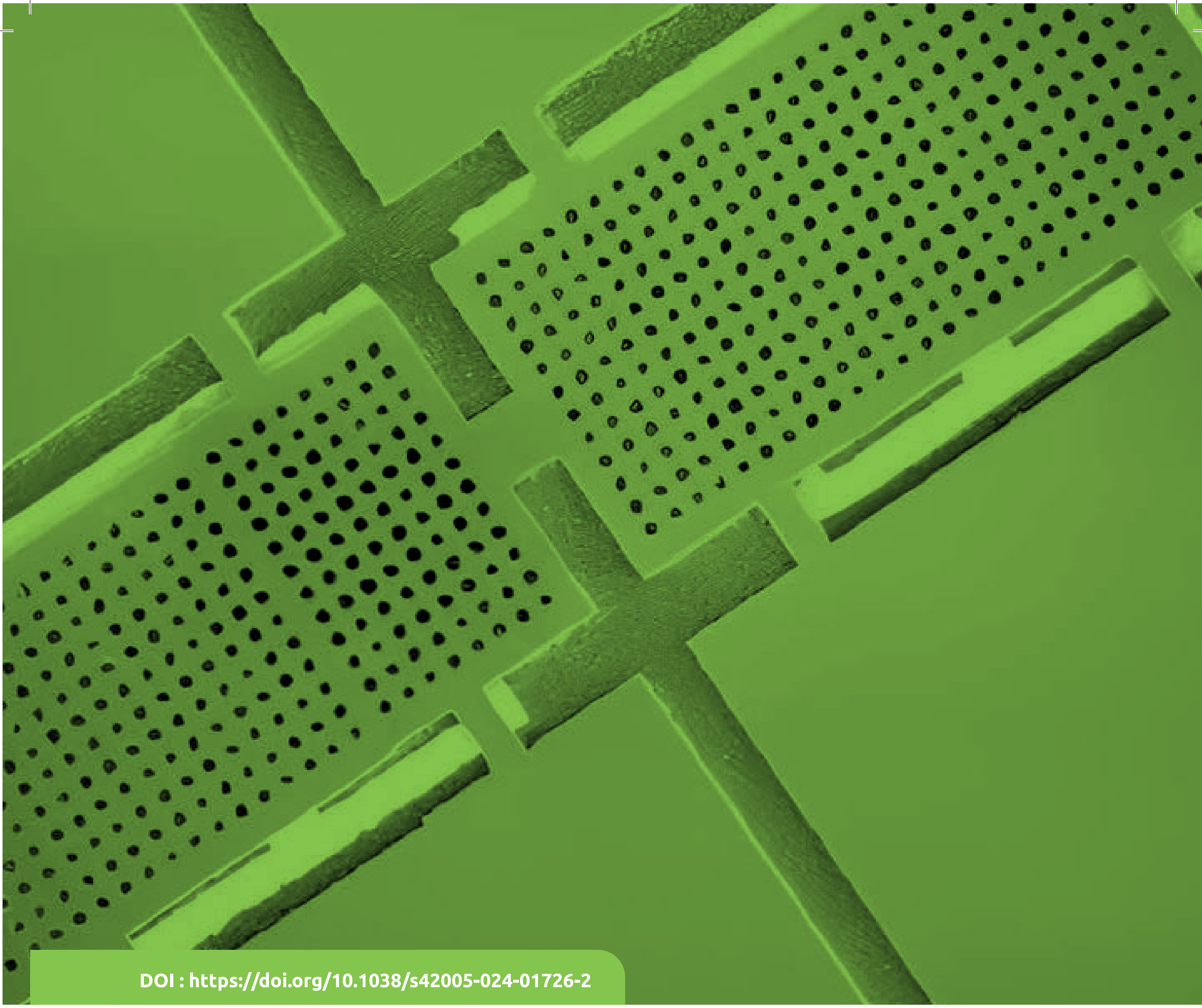
“Our tomography approach, to measure the polarisation rotation at the output of our system, gives access to the complete characteristics of the polarisation state: its longitude and latitude in the Poincaré sphere, but also the polarisation purity,” said Dr. L. Lanco, a teacher-researcher at Université Paris Cité. “As we expected, the spins of the nuclei constituting the quantum dot induce spectral fluctuations, which limit the polarisation purity of the reflected photons, but do not limit the rotation angles that can be reached, in latitude or longitude.”

This work is one of the first steps towards the development of more efficient spin-photon and photon-photon logic gates, which could serve as building blocks for a future quantum network performing quantum computation with photons.

Coherent interferometric control of strongly-coupled nano-electromechanical resonators

The interferometric control of dissipation in a two-port system is a fruitful concept enabling the enhancement or cancellation of the input amplitudes as a function of their relative phases. Here, beyond the canonical configuration of Coherent Perfect Absorption (CPA), we apply this concept to two simultaneously excited strongly-coupled nanoscale electromechanical resonators submitted to independently controlled phase-shifted excitations. Both subsystems are read simultaneously by optical means allowing us to completely reconstruct the signature of coherent annihilation or amplification on both quadrature. We evidence that the mechanical modes amplitude can be enhanced or inhibited with respect to the case of single port excitation while phase experiences strong variations with the excitation imbalance and phase difference. Meanwhile, phase singularities with opposite topological charges are observed for mechanical normal modes. Close to the phase singularity, we demonstrate that the input of a weak phase modulation induces a large, pure phase modulation of the normal mode. These experimental demonstrations are fully modelled via the mechanical dynamical equations of our system. The interferometric control may open avenues for novel low-power amplitude controlled phase modulation schemes and vice-versa for potential switches and logical gates.



DOI : https://doi.org/10.1038/s42005-024-01726-2

Coherent Perfect Absorption (CPA), the coherent interferometric control of two-port systems, has attracted lots of interest as "Time reversed laser". It has been mainly investigated within the canonical geometry of two counter-propagating fields and almost exclusively in optics. Recently, other approaches using two strongly coupled non-identical sub-systems have been developed, still in the field of optics. These ones allow to address only partially the behaviour of the overall system: the amplitude signature is recovered but no information about the phase behaviour is extracted. Thus, a complete understanding and investigation of the physics in such studies is lacking.

In this article, we present for the first time to our knowledge an experimental investigation of coherent interferometric control in nano-mechanical resonators. Our system consists of two identical nano-electromechanical resonators which are mechanically coupled and whose displacements are both and simultaneously read by optical means. We establish and evidence the strong coupling regime between the two resonators. This mandatory condition allows us to reconstruct the signature of coherent amplification or annihilation with respect to the single port excitation for a specific phase mismatch and driving ratio between the drives of the two ports. Within this framework, we reconstruct the phase evolution of the mechanical modes and evidence phase singularities whose topological charge change with the mode considered. Finally, we take advantage of this peculiar feature to demonstrate high contrast, pure phase modulation of an input signal using a priori arbitrary low input drives.

Though demonstrated on nano-electromechanical resonators, This approach is quite general and applies to a broad range of physical systems. We therefore think it should appeal a broad audience ranging from physicists, biologists to chemists. At the same time, it constitutes a model system enabling the investigation of various coherent phenomena involving amplitude and/or phase modulation, a domain of active fundamental research with potential applications down the line. Beyond its fundamental vivid prospects, such general mechanism indeed opens interesting prospects for phase switches and photonic modulators or for phase shaping dedicated to sensing or laser spectroscopy at the nanoscale.

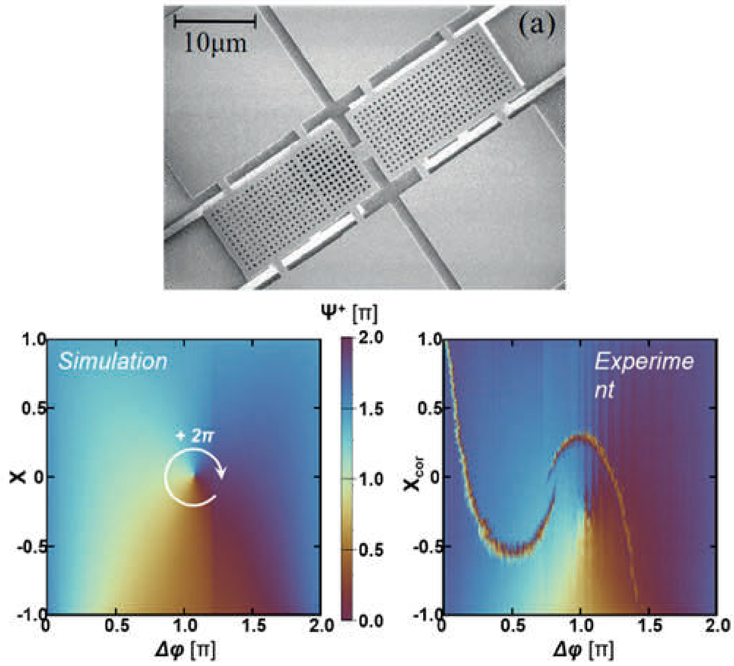


FIGURE
SEM image showing photonic crystal membranes connected by a mechanical bridge; Numerical and experimentale evolution of the phase of anti-symmetric mechanical mode (Ψ+) as function of the phase mismatch and driving ratio between the drives of the two ports (Δφ,X)

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Coherent interferometric control of strongly-coupled nano-electromechanical resonators

Communications Physics volume 7

Article number: 233 (2024)Franck Correia[1], Gladys Jara-Schulz[1], Guilhem Madiot[1], Sylvain Barbay[1] & Remy Braive[1,2,3]

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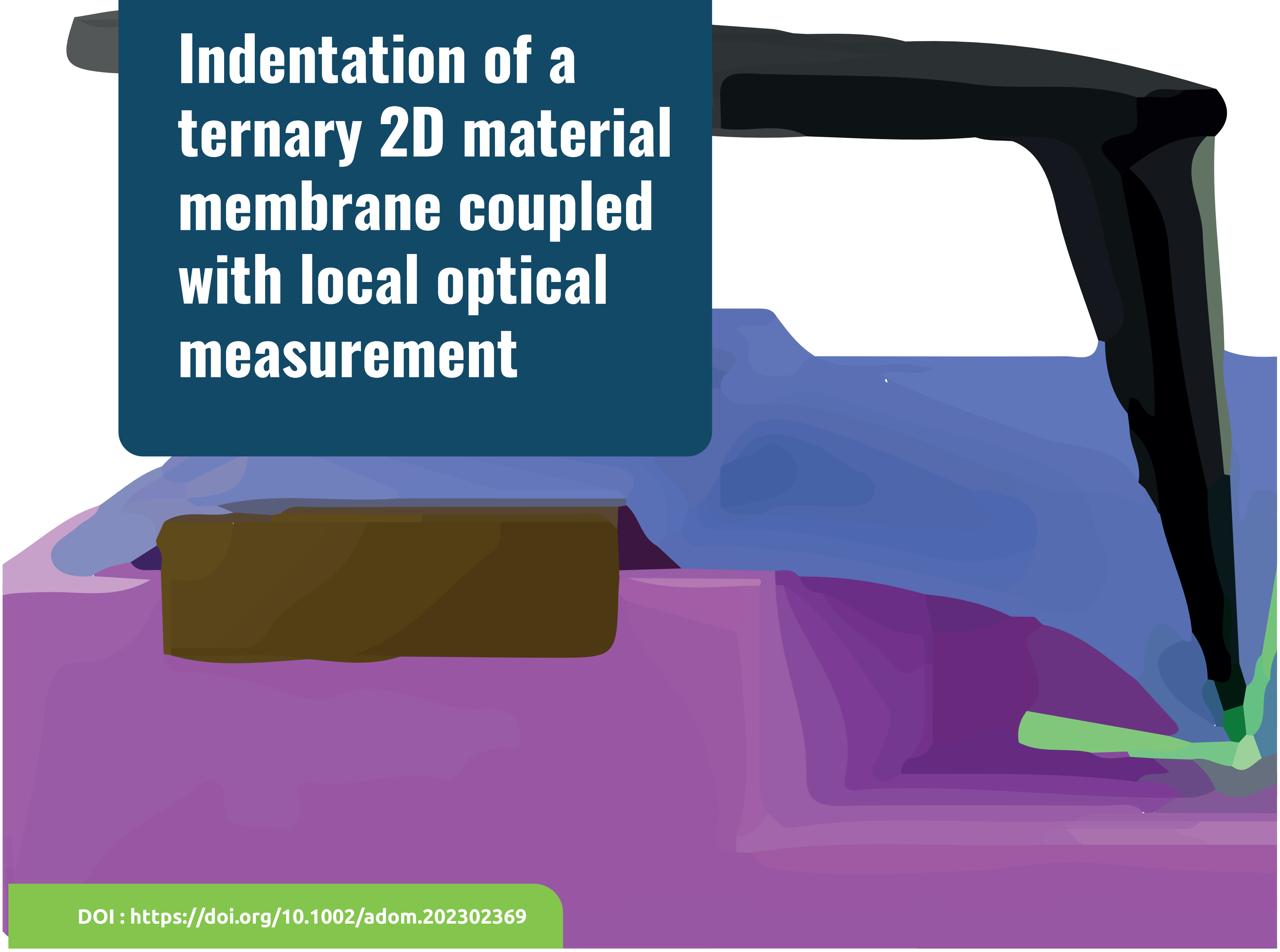
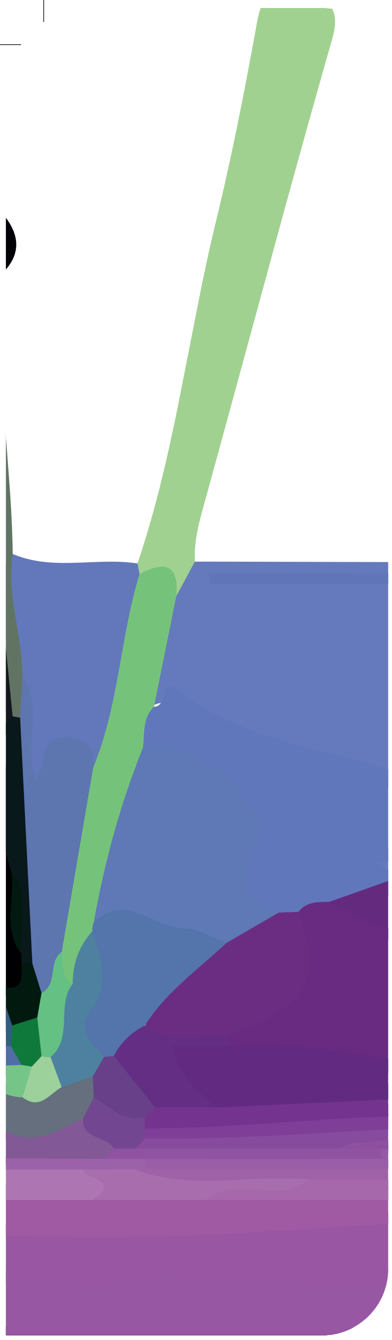
LASSYS

Indentation of a ternary 2D material membrane coupled with local optical measurement



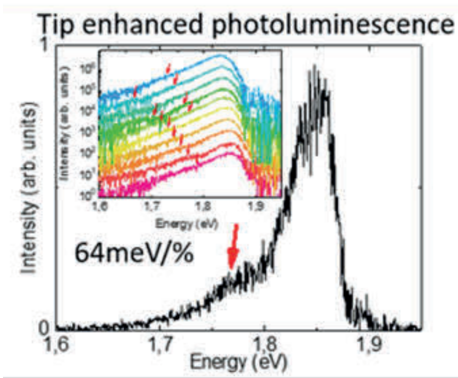
DOI : https://doi.org/10.1002/adom.202302369

Straintronics involves the manipulation and regulation of the electronic characteristics of 2D materials through the use of macro- and nano-scale strain engineering. In this study, an atomic force microscope (AFM) coupled with an optical system is used to perform indentation measurements and tip-enhanced photoluminescence (TEPL), allowing to extract the local optical response of a suspended monolayer membrane of ternary WSSe at various levels of deformation, up to strains of 10%. The photoluminescence signal is modeled considering the deformation, stress distribution, and strain dependence of the WSSe band structure. An additional TEPL signal is observed that exhibits significant variation under strain, with 64 meV per percent of elongation. This peak is linked to the highly strained 2D material lying right underneath the tip. The amplification of the signal and its relation to the excitonic funneling effect are discussed in a more comprehensive model. The diffusion caused by Auger recombination against the radiative excitonic decay will also be compared. TEPL is used to examine and comprehend the local physics of 2D semi-conducting materials subject-



ed to extreme mechanical strain. Chemical vapor deposition-fabricated 2D ternaries possess high strain resistance, comparable to the benchmark MoS_2, and a high Young's modulus of 273 GPa.

C2N's mat2D group is an expert in the electronic properties of 2D materials (Graphene, MX and MX_2). Our activities focus on the design, fabrication and electronic properties of new hybrid heterostructures based on two-dimensional materials, with a view to realizing a new generation of nanoelectronic devices. This publication is made in collaboration with Hunan University, Polytechnique and Horiba.



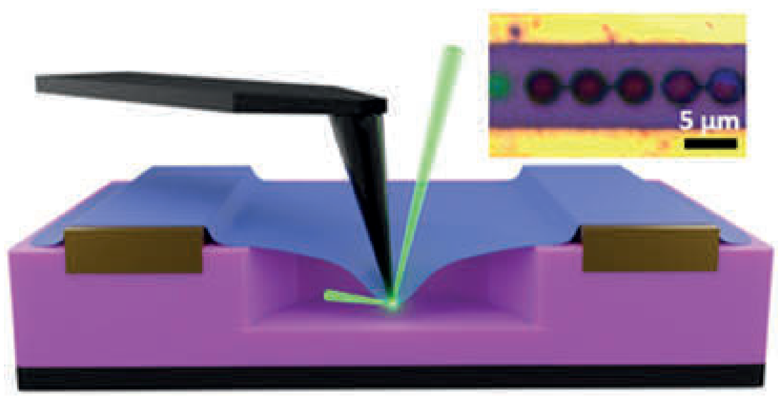


FIGURE
Indentation of a ternary 2D membrane, a WSSe monolayer, coupled with optical measurement. (Left) a schematic of the experimental set-up (insert) a photo of the sample seen from above. (Right) TEPL signal measurements. The shoulder visible at lower energies comes from the area at the tip of the tip, which is highly mechanically stressed, with deformations of up to 10%. This signal varies strongly with strain, according to 64meV/% strain.

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High Strain Engineering of a Suspended WSSe Monolayer Membrane by Indentation and Measured by Tip-enhanced Photoluminescence

Advanced optical materials, April 2024

Anis Chiout [1]
Agnès Tempez[2]
Thomas Carlier[2]
Marc Chaigneau[2]
Fabian Cadiz[3]
Alistair Rowe[3]
Biyuan Zheng[4]
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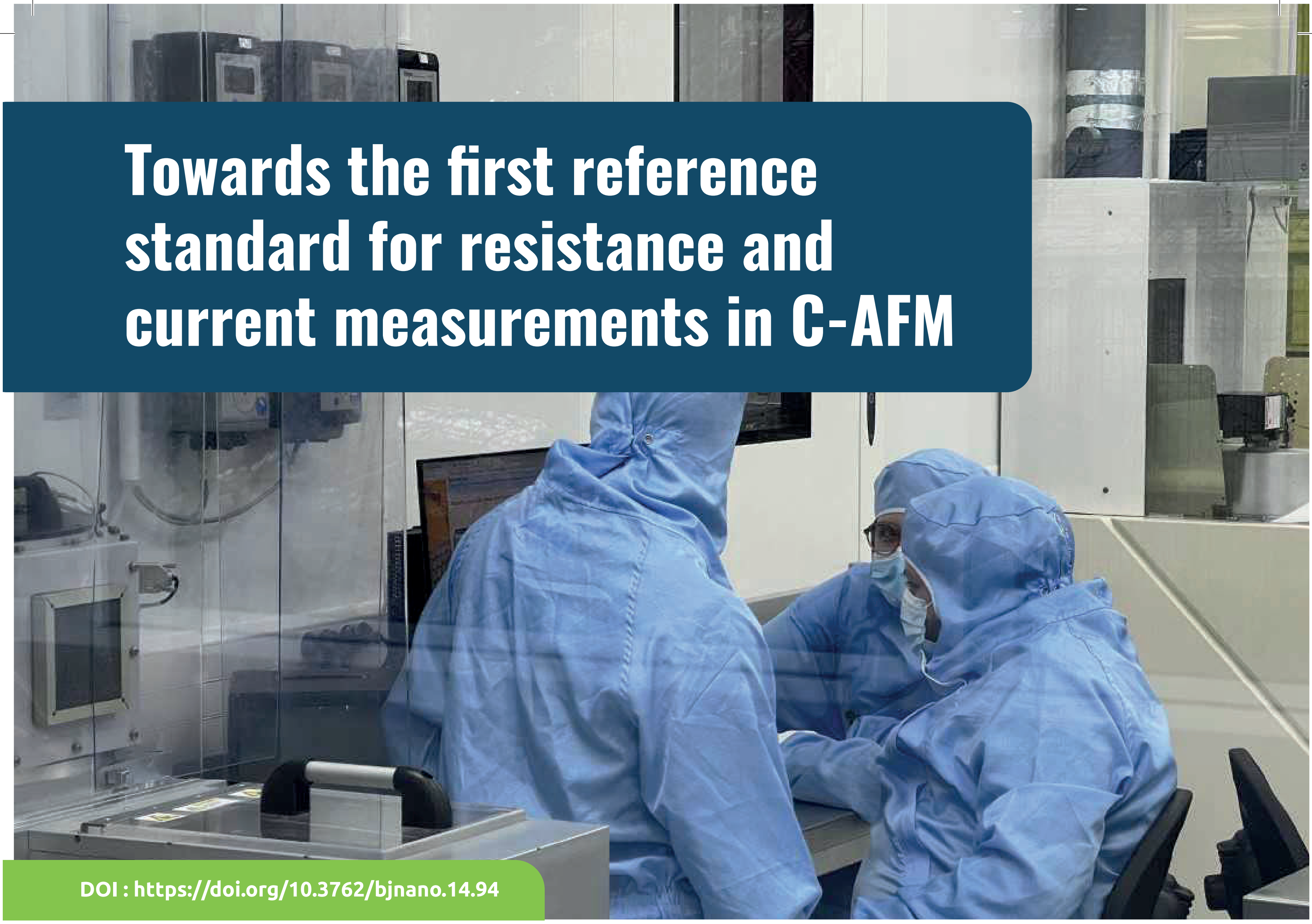


Towards the first reference standard for resistance and current measurements in C-AFM

DOI : https://doi.org/10.3762/bjnano.14.94

A C2N team, in collaboration with the LNE and the Geeps has developed a multiple resistance wide range calibration sample compatible with any commercially available AFM system.

Measuring resistances at the nanoscale has attracted recent attention for developing microelectronic components, memory devices, molecular electronics, and two-dimensional materials. Despite the decisive contribution of scanning probe microscopy in imaging resistance and current variations, measurements have remained restricted to qualitative comparisons. Reference resistance calibration samples are key to advancing the research-to-manufacturing process of nanoscale devices and materials through calibrated, reliable, and comparable measurements. No such calibration reference samples have been proposed so far.

In this work, we demonstrate the development of a multi-resistance reference sample for calibrating resistance measurements in conductive probe atomic force microscopy (C-AFM) covering the range from 100 Ω to 100 GΩ. We present a comprehensive pro-

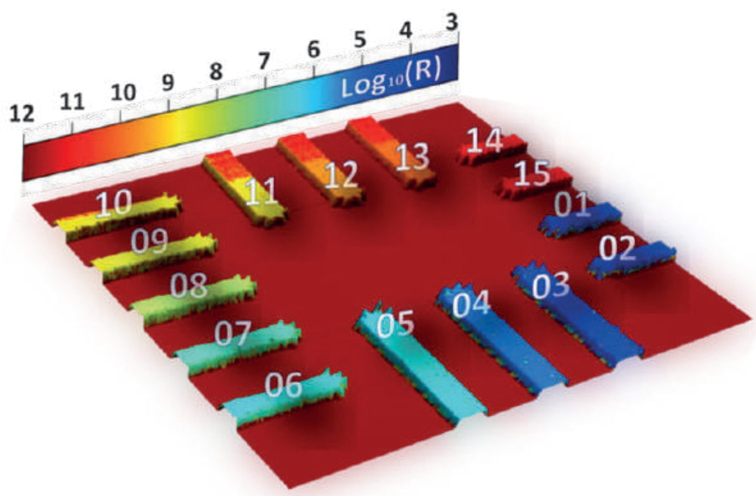
KEYWORDS

Resistance standard; Conductive probe Atomic Force Microscopy; Calibration; nanoscale; Measurement protocol

tocol for in situ calibration of the whole measurement circuit encompassing the tip, the current sensing device, and the system controller. Furthermore, we show that our developed resistance reference enables the calibration of C-AFM with a combined relative uncertainty (given at one standard deviation) lower than 2.5% over an extended range from 10 kΩ to 100 GΩ and lower than 1% for a reduced range from 1 MΩ to 50 GΩ. Our findings break through the long-standing bottleneck in C-AFM measurements, providing a universal means for adopting calibrated resistance measurements at the nanoscale in the industrial and academic research and development sectors.

We are continuing the development of these calibration samples and are currently working on another version that offers easier access to C-AFM measurements of lower resistances (from 100 Ω to 10 kΩ) and an expanded resistance range up to 1 TΩ. This research work was carried out in the framework of the ELENA project (EMPIR 20IND12), which is supported by the European Metrology Programme for Innovation and Research (EMPIR).

FIGURE
Resistance map of the sample's central zone (60 µm × 60 µm) imaged by C-AFM. Numbers refer to the i index of the resistance arms. Colors rendering refers to measured resistance values given in decimal logarithm scale.



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Multi-Resistance Wide-Range Calibration sample for Conductive probe Atomic Force Microscopy Measurements

Beilstein J. Nanotechnol, 2023, 14, 1141–1148

François Piquemal[1], Khaled Kaja[1], Pascal Chrétien[2,3], José Morán-Meza[1], Frédéric Houzé[2,3], Christian Ulysse[4] and Abdelmounaim Harouri[4]

Projet ELENA

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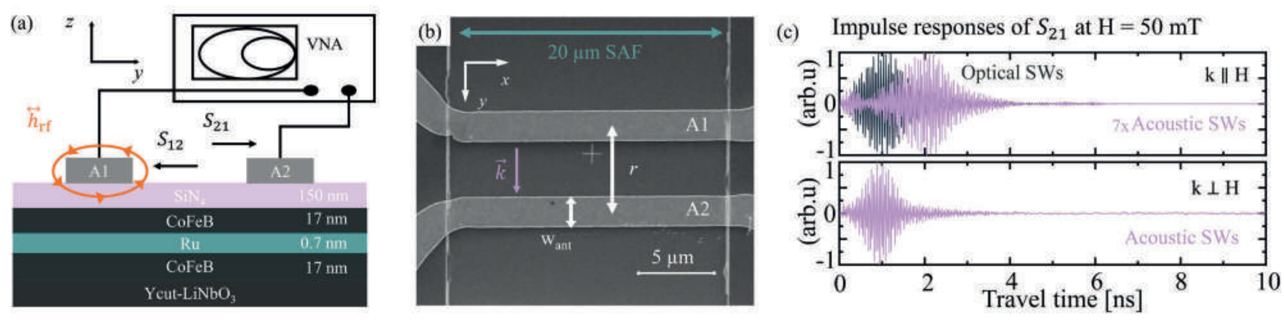
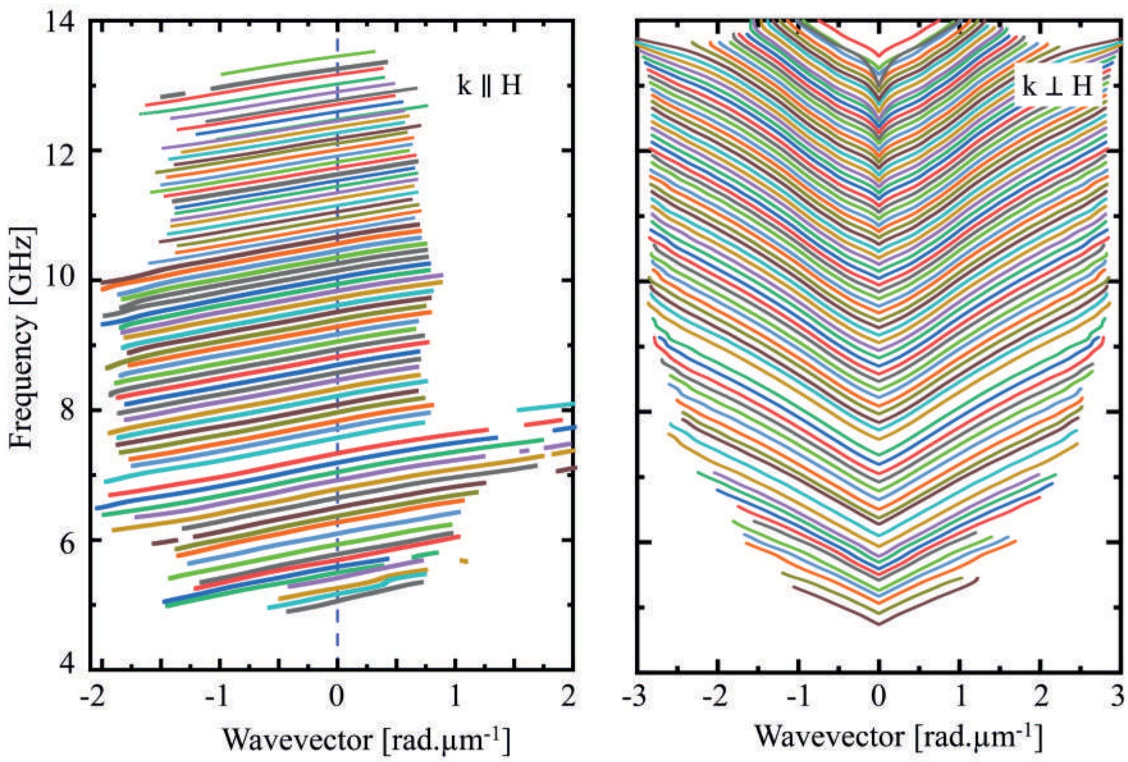
Device-based spectroscopy of the spin waves in synthetic antiferromagnets

Magnonics –the art of manipulating spin waves– has been attracting increasing interest in the recent years, essentially because spin waves exhibit unique features such as strong non-linearity and absolute non-reciprocity. A deep understanding of their dynamics is crucial for the better implementation of spin waves in signal processing devices. At C2N, we have developed a method harnessing Vector Network Analyzer techniques and dedicated microfabricated samples to measure the magnonic band structure in magnetic nanostructures (Fig. 1a).

The samples (Fig. 1b) are spin wave conduits covered by nanofabricated microwave antennas. A first antenna transceiver launches spin waves which propagate into the conduit, and are finally collected by a second antenna transceiver. The analysis of the frequency dependence of the spin wave transmission forms the *propagating spin wave spectroscopy* (PSWS). The analysis requires first a velocity-selective sorting of the different spin wave modes that are launched. This is implemented by a time-of-flight technique, able to separate for instance the "acoustic" spin waves and the "optical" spin waves (Fig. 1c). In a second step, the phase of the transmission signal can be unwrapped to reconstruct the dispersion relation of each band within the magnonic band structure. We have implemented this method on a Synthetic antiferromagnets, and have successfully shown that depending on the direction of the spin wave wavevectors, the spin waves can either behave as standard quasiparticles, i.e.

FIGURE 1
(a) Setup used for propagating spin wave spectroscopy. (b) Example of device with its microwave antenna (light gray), its spin wave conduit (medium gray, 20 micron wide) made from a Synthetic antiferromagnet (SAF). (c) Time-domain analysis of the successive arrival of several spinwave wavepackets.





DOI : https://doi.org/10.1103/PhysRevApplied.22.034040

FIGURE2
Experimental dispersion relations for wavevector orientations leading to reciprocal (a) and non-reciprocal (b) spin wave dispersion relations.

with a V-shaped dispersion relation (Fig. 2b) like photons or phonons. For the other orientation, they possess a line-shaped dispersion relation (Fig. 2a) that has no analog with other wave systems. This leads to a “diode” behavior, where the energy carried by a spin wave wavepacket of zero total moment flows in a unidirectional manner [1, 2].

[1] G.Y. Thiancourt, S.M. Ngom, N. Bardou, and T. Devolder. Unidirectional spin waves measured using propagating-spinwave spectroscopy. Phys. Rev. Appl. 22, 034040 (3 2024).
[2] G. Y. Thiancourt, S. M. Ngom, N. Bardou, and T. Devolder. Spectroscopy of the spin waves of a synthetic antiferromagnet grown on a piezoelectric substrate. 2024. arXiv: 2411.18202 [cond-mat.mtrl-sci].

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Device-based spectroscopy of the spin waves in synthetic antiferromagnets
Phys. Rev. Applied 22, 034040

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2

Research Priority Readiness Program

PEPR

The C2N, dedicated to strategic and technological research

C2N is a key player in the Priority Research Programs and Equipment (PEPR) of France 2030. Involved in 26 ongoing projects as both a coordinator and partner within strategic consortia, it is strengthening French scientific leadership particularly in the development of high-performance electronics, advances in health technologies, the exploration of quantum technologies' potential, and the acceleration of innovations in artificial intelligence.

- National research programme Spintronics (PEPR SPIN)
- National research programme Quantum (PEPR Quantique)
- The 'Electronics' acceleration PEPR
- The 'Decarbonated Hydrogen' acceleration PEPR
- The 'Advanced Energy Systems Technologies' (TASE) acceleration PEPR

National research programme Spintronics (PEPR SPIN)

››› SPINCOM Project (Spintronics for Communication)

ROLE OF C2N

Partner, Leader of Work Package 4 (Time series processing with complex states)

PUBLICATIONS AND RESULTS

Development of a simulation code to model the dynamics of spin-transfer-torque-coupled oscillators (as part of doctoral research conducted at C2N)

MAIN AMBITIONS

The primary goal of the SPINCOM project is to explore radiofrequency spintronics for smart sensors, enabling low-power, secure communication and high-speed data processing. By leveraging the multifunctional and nonlinear dynamic properties of nanoscale spin-torque nano-oscillators (STNOs) based on magnetic tunnel junctions, the project aims to address key challenges in microwave wireless communication systems, which are critical for sensor networks, edge computing, and IoT applications.

TARGET SECTORS

▶ RF computing and telecommunications components

SCIENTIFIC AND TECHNOLOGICAL CHALLENGES ADDRESSED

▶ Reducing energy consumption of RF components to improve autonomy.
▶ RF energy harvesting.
▶ Securing data and its transmission.
▶ Real-time pattern and signal classification

IMPLEMENTED SOLUTIONS

▶ Mastering and controlling the complex, multifunctional dynamics of RF spintronic devices.
▶ Developing new quantitative models for complex, stochastic, and nonlinear dynamics.
▶ Designing novel materials and defining innovative device architectures.

››› SWING Project (Spin Waves for Advanced Signal Processing)

PUBLICATIONS AND RESULTS

«Symmetry of the coupling between surface acoustic waves and spin waves in synthetic antiferromagnets» *Physical Review B*, 2024, 109 (10), pp.104416.

DOI: 10.1103/ PhysRevB.109.104416

The SWING project falls within the field of magnonics, which aims to leverage the unique physical properties of spin waves (magnons) to develop novel information technologies. These waves encode data through their phase or amplitude, enabling innovative signal processing approaches.

MAIN AMBITIONS

- ▶ Improve energy efficiency
- ▶ Develop new methods to control spin wave properties
- ▶ Enhance the integration level of existing magnonic components

SCIENTIFIC AND TECHNOLOGICAL CHALLENGES ADDRESSED

- ▶ Engineering new materials
- ▶ Improving spin wave interconversion
- ▶ (Re)generating spin waves via acoustic methods
- ▶ Developing non-reciprocal devices

››› SPINCHARAC Project (SPINtronics CHARACterization)

PUBLICATIONS AND RESULTS

«Symmetry of the coupling between surface acoustic waves and spin waves in synthetic antiferromagnets», Rafael Lopes Seeger, Léa La Spina, Vincent Laude, Florian Millo, Ausrine Bartasyte, Samuel Margueron, Anne Solignac, Grégoire de Loubens, Laura Thevenard, Catherine Gourdon, Claude Chappert, Thibaut Devolder, *Physical Review B*, 2024, 109(10), 104416 (13).

DOI: 10.1103/ PhysRevB.109.104416

MAIN AMBITIONS

The transversal SPINCHARAC project aims to provide cutting-edge infrastructure and tailored instrumentation for advanced characterization capabilities, including physical and magnetic characterization. This initiative was developed in close coordination with the spintronics community to address their specific research needs.

SCIENTIFIC AND TECHNOLOGICAL CHALLENGES

- ▶ Development of innovative equipment enabling novel research capabilities (e.g., spin wave imaging techniques and specialized terahertz measurement systems)
- ▶ Acquisition of state-of-the-art commercial equipment to expand experimental capacities (e.g., magneto-electric measurement platforms extending RF spectrum analysis capabilities with automated systems for statistical performance evaluation of large device arrays)
- ▶ Establishment of an open-access instrument network

National research programme Quantum (PEPR Quantique)

››› OQULUS Project - National research programme Quantum (PEPR Quantique)

MAIN AMBITIONS

The objective of the project is to develop the fundamental building blocks required for constructing a photonic quantum computer: efficient sources of quantum light, integrated photonic chips enabling logic gates, photon detectors, rapid modulation and reconfiguration, etc. The technological and experimental developments are guided and supported by specific theoretical studies.

The consortium aims to build two prototypes of moderate-sized, noisy intermediate-scale quantum (NISQ) computers:

One prototype will manipulate photonic qubits using single and entangled photon sources based on semiconductor quantum dots. The photons will be processed on silicon nitride circuits and detected using superconducting detectors integrated into the chips.

Another prototype will leverage squeezed light generated through frequency conversion, creating cluster states of 10 to 10,000 nodes and implementing non-Gaussian operations.

In parallel, the project will develop a theoretical roadmap to guide the advancement of NISQ machines up to the software level.

TARGET SECTORS

▶ Quantum computing, Scientific computing and simulation

ROLE OF C2N

Coordinator

C2N oversees the entire OQULUS project and plays a key role in developing the single and entangled photon sources at the core of one of the quantum computing demonstrators. Additionally, it is responsible for assembling one of the quantum computer prototypes by integrating various components developed by the partners. The flexibility of the light sources developed at C2N also allows exploration of multiple approaches for encoding information (polarization, photon number, path).

KEY SCIENTIFIC AND TECHNOLOGICAL CHALLENGES

Generate single and entangled photons from quantum dots and couple these photons to reconfigurable silicon nitride computing circuits.

Extend the spin coherence time of quantum dots to enable the generation of larger clusters and improve the stability of quantum processors.

Create deterministic photon-photon gates.

Build and operate the quantum computing prototype based on single photons and perform elementary calculations using the resources developed with partners, in close collaboration with theorists proposing adapted algorithms.

PUBLICATIONS AND RESULTS

Publications

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II. Gundín M., Hilaire P., Millet C., Mehdi E., Antón C., Harouri A., Lemaître A., Sagnes I., Somaschi N., Krebs O., Senellart P., and Lanco L. (2025). Spin Noise Spectroscopy of a Single Spin Using Single Detected Photons. Physical Review Letters, 134(3), 036902. DOI: 10.1103/PhysRevLett.134.036902.

III. H Huet, PR Ramesh, SC Wein, N Coste, P Hilaire, N Somaschi, M Morassi, A Lemaître, Isabelle Sagnes, MF Doty, Olivier Krebs, L Lanco, DA Fioretto, P Senellart. Deterministic and reconfigurable graph state generation with a single solid-state quantum emitter, arXiv:2410.23518 — in press at Nature Communications

The ‘Electronics’ acceleration PEPR

››› OFCOC Project (Optical Frequency Combs On a Chip)

PUBLICATIONS AND RESULTS

Orientation-patterned gallium phosphide for integrated nonlinear photonicsKonstantinos Pantzas, Sylvain Combrié, Yoan Léger, Grégoire Beaudoin, Luc Le Gratiet, Abdelmounaim Harouri, Bruno Gerard, Gilles Patriarche, Isabelle Sagnes and Arnaud Grisard **Orientation-patterned gallium phosphide for integrated nonlinear photonics. Photoniques, 2023, 122, pp.64-69. (10.1051/photon/202312264). (hal-04314963)**

MAIN PROJECT AMBITIONS

Develop integrated, broadband, robust, reliable, and miniaturized frequency combs on a fully semiconductor-based platform. These devices target applications in autonomous sensors capable of, for example, monitoring air quality or detecting viruses.

TARGET SECTORS

- Healthcare
- Environment
- Security
- Telecommunications

SCIENTIFIC AND TECHNOLOGICAL CHALLENGES ADDRESSED

Frequency combs are currently limited to niche applications due to their complex implementation. The OFCOC project aims to overcome this limitation by creating an integrated microcomb source that is broadband, robust, and reliable on an all-semiconductor platform.

To achieve this, the project leverages the co-integration of two leading French technologies:

- Antimony-based interband cascade lasers (ICLs), providing integrated optical pumping for frequency combs.
- Nonlinear GaP platform, enabling ultra-broadband frequency conversion.

››› Projet BEP (BioElectronPhoton)

PUBLICATIONS AND RESULTS

Demonstration of a self-powered AI with memristors operating on solar energy.
Powering AI at the edge: A robust, memristor-based binarized neural network with near-memory computing and miniaturized solar cell, Fadi Jebali, Atreya Majumdar, Clément Turck, Kamel-Eddine Harabi, Mathieu-Coumba Faye, Eloi Muhr, Jean-Pierre Walder, Oleksandr Bilousov, Amadéo Michaud, Elisa Vianello, Tifenn Hirtzlin, François Andrieu, Marc Bocquet, Stéphane Collin, Damien Querlioz, Jean-Michel Portal, Nature Communications, Jan .2024

Doi : 10.1038/s41467-024-44766-6

MAIN AMBITIONS

- Develop bio-inspired processor architectures combining ultra-dense and reconfigurable electrons and photons to enable energy-efficient AI.

TARGET SECTORS

- Edge embedded computing

SCIENTIFIC AND TECHNOLOGICAL CHALLENGES

- Combining electricity and light to mimic the brain's energy-efficient three-dimensional architecture.
- Developing memory technologies that imitate synapses to enable efficient learning in circuits.
- Creating interconnected nano-neurons capable of performing complex computations with low energy consumption.

RESULTS

Design of a neuromorphic chip embedding a Bayesian AI capable of detecting and classifying cardiac anomalies.

pepr-electronique.fr

››› EMCOM Project (Emerging Memories for Computing)

MAIN AMBITIONS

The EMCOM project aims to develop new magnetic memory (MRAM) architectures, particularly benefiting embedded AI and low-power embedded computing.

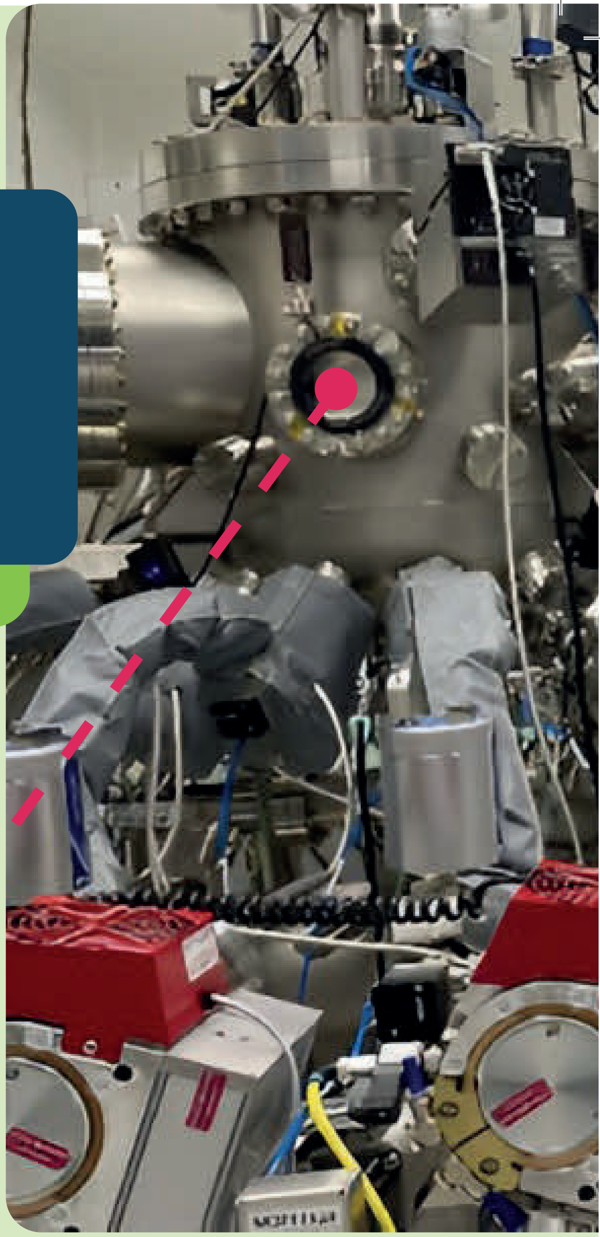
TARGET SECTORS

- Embedded computing
- Embedded artificial intelligence

SCIENTIFIC AND TECHNOLOGICAL CHALLENGES

The project explores several innovative MRAM technology solutions to overcome the limitations of existing technologies. Amongthe approaches being investigated are architectures that enhance the decoupling of writing and reading processes.

NEW MO-MBE SYSTEM: GROWTH WINDOW FOR OXIDE EPITAXY



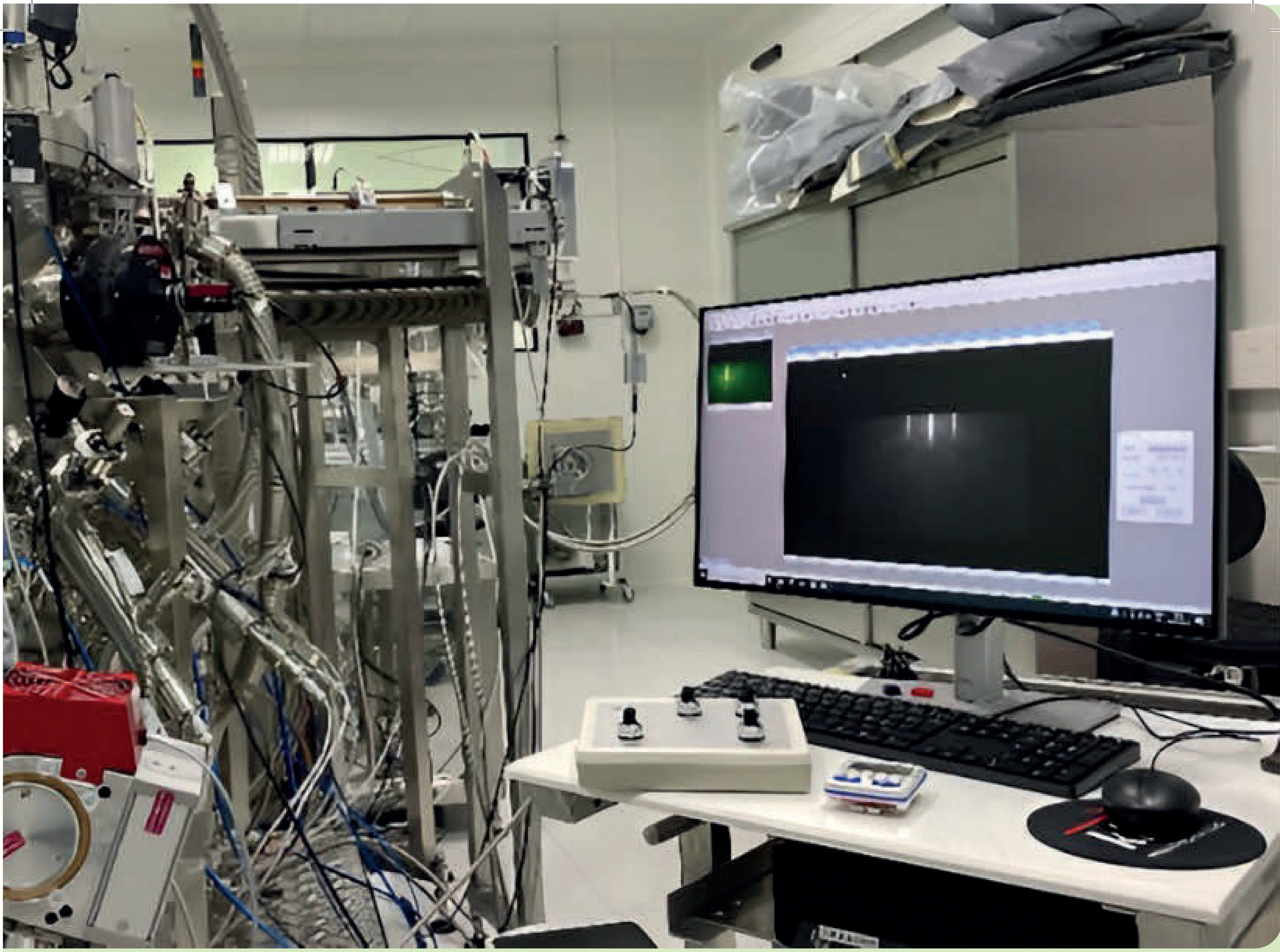
A metalorganic (MO)-MBE system (DCA Instruments, Finland) for epitaxial growth of complex oxides has arrived in C2N cleanroom in March 2024. Designed for substrates up to 2” in diameter, it is fully operational since October 2024 with the installation of a pure ozone generator (Meidensha, Japan) as additional oxygen source next to the RF plasma one.

The most distinctive feature of this system is the presence of 3 injectors for metalorganic precursors of metals such as Ti, Zr and Hf. Used in conjunction with conventional effusion cells, they enable a self-regulated desorption growth window, greatly simplifying the obtention of stoichiometric oxide films compared to conventional oxide MBE. The system also comprises an electron beam source in the growth chamber. All solid sources feature differential pumping in order to limit their exposure to the highly oxidizing ambient during growth.

FUNDINGS

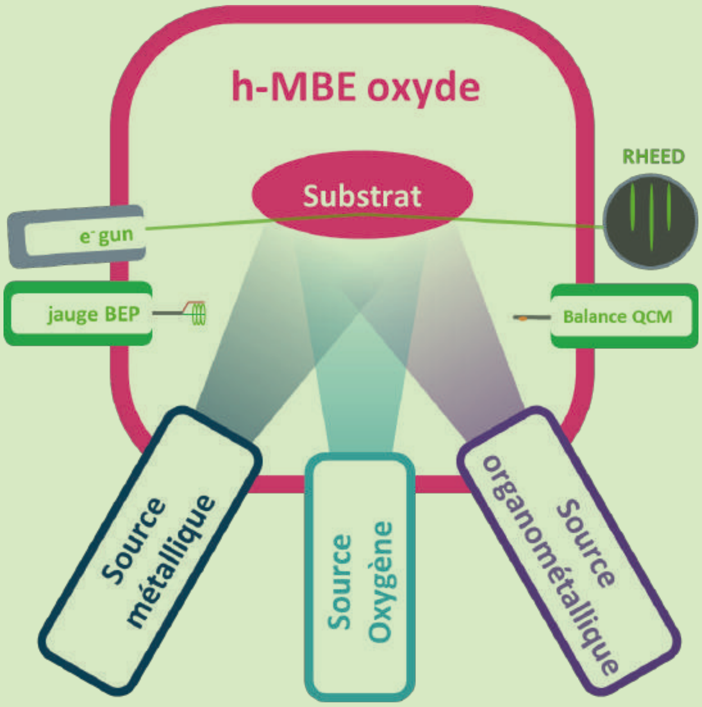
- EQUIPEX+ NANOFUTUR
- CPER PANORAMA
- PEPR Electronique
- RENATECH

cnrs
FRANCE 2030
RENATECH
NanoFutur - PIA3 - ESR/EquipEx



Crédits photos : © C2N.

Materials developments on the system aim at capitalizing on the ultrahigh vacuum environment, versatile oxygen sources, and stoichiometry control offered by MO sources to tackle issues such as oxygen vacancies in perovskite oxides or polarization control in ferroelectrics. Thin films of $SrTiO3$ (dielectric), $SrRuO3$ (ferromagnetic metal) and $ZrO2$ are currently grown in the system, with $BaTiO3$ (ferroelectric) as next material on the list.



The ‘Decarbonated Hydrogen’ acceleration PEPR

››› NAUTILUS Project

MAIN AMBITIONS OF THE PROJECT

The NAUTILUS project proposes a solution to develop photoelectrochemical cell (PEC) technology that combines the low cost and technological maturity of silicon with the high efficiencies achievable using III-V semiconductors. This technology could be implemented within the national industrial framework for solar hydrogen production applications.

In the context of global warming, the direct conversion of solar energy into storable, transportable, and on-demand reusable hydrogen fuel through water splitting appears to be an ideal environmental solution.

NAUTILUS aims to develop a renewable hydrogen production solution at reduced cost compared to current state-of-the-art technologies, paving the way for large-scale deployment.

SCIENTIFIC AND TECHNOLOGICAL CHALLENGES ADDRESSED

AddressedThe NAUTILUS project, led by a French consortium, has three main objectives:

▶ Develop new material assemblies/stacks for III-V-on-silicon photoelectrodes enabling better electrode protection and catalytic properties superior to current state-of-the-art

▶ Clarify the electrochemical and catalytic processes involved in III-V-on-silicon photoelectrodes coated with protective oxide layers

▶ Demonstrate the feasibility of a dual-photoelectrode PEC cell composed of a co-catalyst/protective layer/III-V-on-Si stack, showing:

1. Solar-to-hydrogen (STH) efficiency >10%
2. Extrapolated lifetime >1,000 hours

NEXT STEPS

▶ As a next step, C2N will publish results on the atomic structure of antiphase boundaries in epitaxial III-V/Si(100) semiconductors analyzed via plan-view STEM-HAADF.

The ‘Advanced Energy Systems Technologies’ (TASE) acceleration PEPR

››› Projet IOTA

ROLE OF C2N

C2N is responsible for the scientific coordination of the project. It is also involved in the development of new low-cost processes (nanometric-scale structuring, bonding) and optical management.

MAIN AMBITIONS

▶ Develop the next generation of high-efficiency (>30%) and low-cost solar cells
▶ Propose innovative tandem architectures based on thin layers on silicon
▶ Develop breakthrough technological solutions
▶ Use materials and processes compatible with rapid industrial transfer

SCIENTIFIC AND TECHNOLOGICAL CHALLENGES ADDRESSED

▶ Development of interface materials to improve the connection between absorbing layers
▶ Optimization of material deposition processes, such as perovskite on rough surfaces
▶ Development of new nano-structuring and localized deposition processes
▶ Development of advanced numerical simulation tools for studying tandem cells in real-world conditions

TARGET SECTORS

▶ The energy and photovoltaic sector
▶ The semiconductor and nanotechnology industry

NEXT STEPS

▶ The fabrication of the first tandem solar cells of the IOTA project is expected in 2025Prochaines étapes :

3

Sustainable Commitment of C2N

► **Reducing the Carbon Footprint of Cleanrooms : C2N in Action**

Reducing the Carbon Footprint of Cleanrooms : C2N in Action

Photo Credits: @Laurent Ardhuin for C2N

The December 2024 CNRS Letter and CNRS.fr highlight the efforts of C2N and LAAS-CNRS to reduce the environmental footprint of their cleanrooms while maintaining cutting-edge research.

At **C2N**, these efforts resulted in the **greenhouse gas emissions** of the building being **halved between 2021 and 2024**. This achievement was made possible through the **collective mobilization** of researchers, engineers, and technicians who identified and implemented solutions tailored to the specific constraints of their research infrastructure.

A COLLECTIVE APPROACH

Under the leadership of **Sophie Bouchoule** and **Aristide Lemaitre**, the laboratory's sustainable development representatives, several **working groups** contributed to im-proving energy efficiency :

- The **CVC and Sorbonnes groups** collaborated closely with the company **AXIMA**, which constructed and commissioned the **«Reduced» mode** of the cleanroom's air conditioning system in 2022, leading to a **reduction in annual electricity consumption of over 1 GWh**.
- The **Logistics and Infrastructure Service** played a key role in adapting the facilities to the laboratory's daily needs.
- The **IT Service** oversaw upgrades to the databases and supervision servers, enabling the performance analysis.
- The **Réglage_CVC_Labos group** supported the extension of the "Re-

-duced" air conditioning mode to the experimental rooms as part of the **CNRS Low Carbon 2023 project**.

The upcoming projects set to start at **C2N in 2025**, as part of the **Environmental Transition initiative**, build on these results. Scaling up would not have been possible without the support of the **technical and real estate services** of the regional delegation **DR04-CNRS**.

Towards a Controlled Carbon Footprint for Research Infrastructures

C2N will continue its efforts to minimize the environmental impact of its building, guided by the principles of **energy efficiency**, **energy recovery**, and **decarbonization**.

This success is the result of **collective commitment** and the support of numerous stakeholders.

Congratulations to all for this exemplary display of environmental responsibility :

Sophie Bouchoule, Aristide Lemaitre, Alain Clement, Laoges Thao, Antoine Caselles, Alain Péan, Sébastien Sauvage, Stéphane Collin, Abdelmounaim Harouri, Jean-Christophe Harmand, Guillemin Rodary, Nicolas Zerounian, Hervé Aubin, Olivier Krebs, Stefano Pirotta, Ali Madouri, Alan Durnez, Teo Baptiste, Laurent Travers, Fabrice Oehler, Martina Morassi, Jean-René Coudevylle, Jean-Pierre Marchesseau, Denis Bole, Cynthia Vallerand, Giancarlo Faini.

4

Valorisation and Technology Transfer

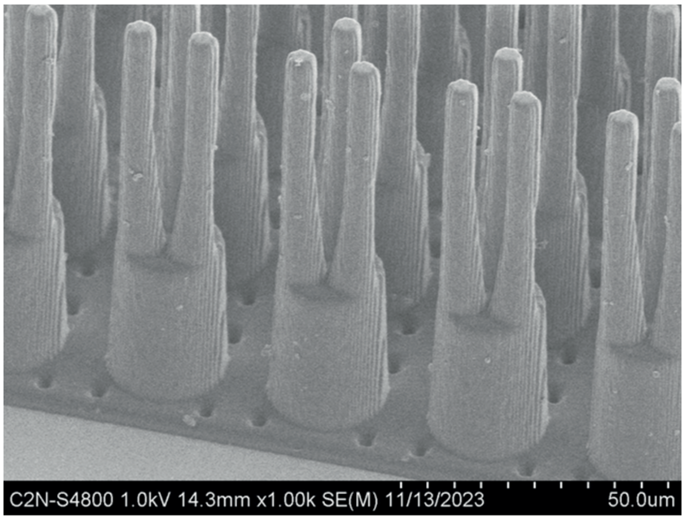
Innovate today for the technologies of tomorrow our commitments

C2N plays a key role in bridging the long timescale of fundamental research, which lays the groundwork for tomorrow's technologies, and the short timescale of applied research, which transforms these discoveries into concrete solutions for society.

- ► Next-generation retinal implant via bioengineering (Eretina project)
- ► LumiSync : data synchronization at the speed of light
- ► E-miRgency : the new spin-off from C2N's research work
- ► The C2N and the start-up Quandela : Partners in the QDlight Joint Laboratory Dedicated to Quantum Photonics

Next-generation retinal implant via bioengineering (eRETINA project)

Retinal degenerative diseases, such as age-related macular degeneration (AMD) and retinitis pigmentosa (RP), affect approximately 200 million and 1.5 million people worldwide, respectively. These conditions lead to the progressive loss of retinal cells, ultimately resulting in irreversible vision impairment. Currently, no effective therapeutic solution exists for the majority of patients.



Regenerative medicine, which aims to replace damaged retinal cells with laboratory-grown cells, represents a promising avenue of research. It is within this context that the eRETINA project was launched, stemming from a collaboration initiated in 2016 between the Center for the Study of Stem Cells (CESC/I-Stem) and the Center for Nanoscience and Nanotechnology (C2N) at the Université Paris-Saclay.

The goal of eRETINA is to develop a next-generation retinal tissue using bioengineering techniques. These implantable tissues are composed of flexible, biocompatible polymer membranes with microstructured surfaces, forming a three-dimensional (scaffold) structure developed in C2N's technology facility.

In parallel, biocompatibility tests have been conducted in the cell culture laboratory (L2) of C2N's Biotech platform using retinal pigment epithelium (RPE) cells. These scaffolds are designed to host and promote the maturation of specific retinal cells, particularly photoreceptors (PRs) and RPE cells, which are derived from pluripotent stem cells at CESC/I-Stem.

The first in vivo studies of these implants are scheduled to take place between late 2024 and early 2025 at CESC/I-Stem.

LumiSync : data synchronization at the speed of light

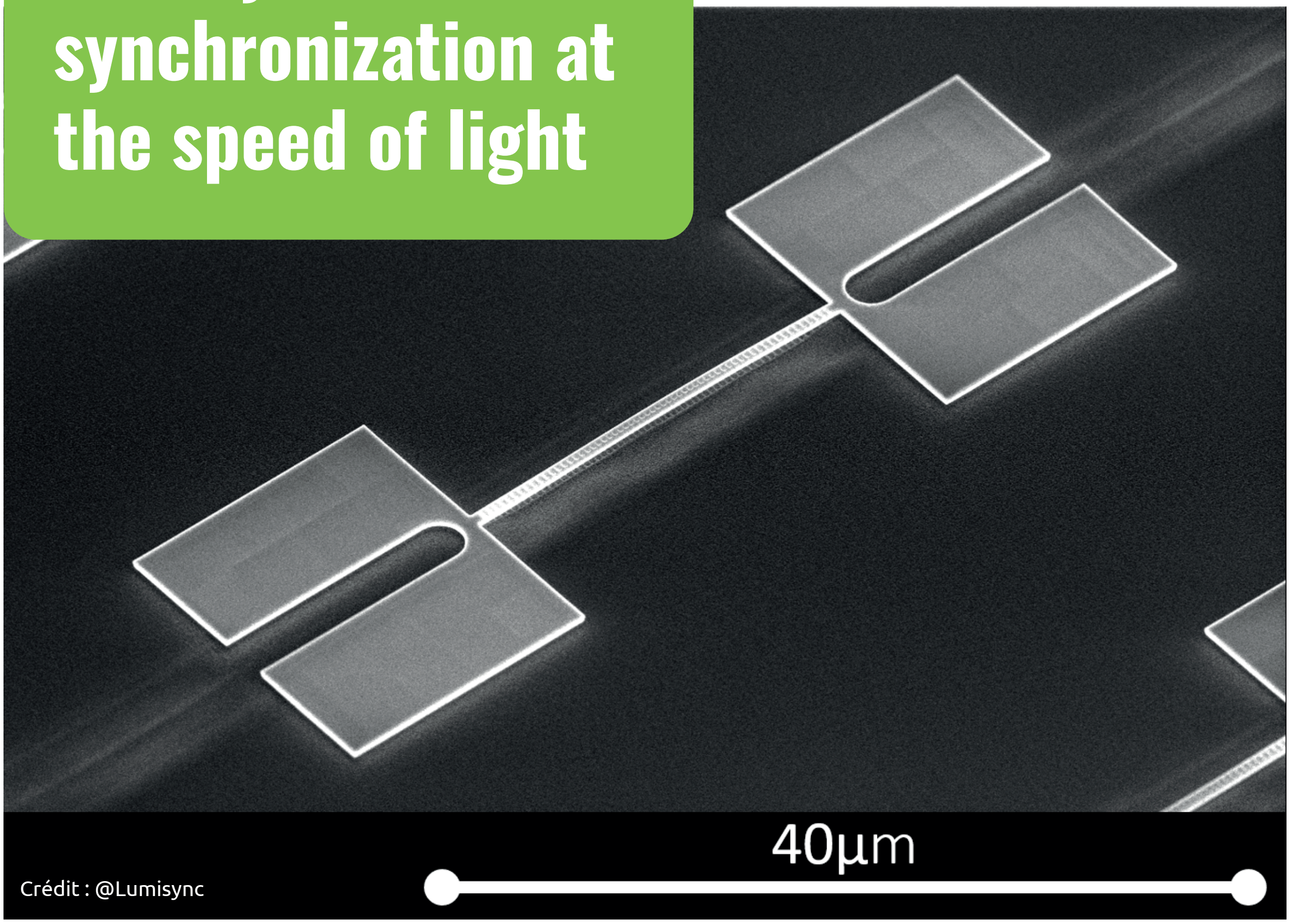


FIGURE
Nano-oscillator

The start-up LumiSync is developing the world's first on-chip 100% photonic oscillator based on a unique technological and instrumental savoir-faire developed for several years at C2N with the strong support of its state-of-the-art cleanroom facilities. The ultra-stable microwave oscillations produced by this nano-component enable data synchronization at the speed of light, unlocking the full potential **of next-gen AI, HPC and optical computing, as well as new telecom and aerospace use-cases**.

Founded in December 2024 by Giuseppe Modica (CTO) and Rémy Braive (CSO), researchers at C2N, along with Alexis Jonville (CEO), entrepreneur, LumiSync has benefited from CNRS 'pré-maturation' funding and CNRS INNOVATION support. The first prototype is now ready for industrial testing. In 2025, LumiSync will seek funding to scale up, aiming for on-field demonstration by 2027.

LumiSync is the 7th start-up to emerge from the research conducted at C2N.

E-miRgency : the new spin-off from C2N's research work

Founded in January 2024 and housed at C2N, this start-up aims to exploit a patented technology based on microfluidics and electrochemistry to detect nucleic acids in short sequences quickly, sensitively and without error compared with RT-qPCR. This technology is the result of 8 years of academic research (ANR, labex Nanosaclay) and CNRS prematuration. Thanks to this technology, the e-miRgency start-up aims to revolutionise cancer diagnosis and monitoring by correlating the signature of panels of microRNAs from development through to mapping the evolution of the cancer in order to provide better monitoring.

Searching for and finding representative panels of microRNAs to predict and control the evolution of cancers

The ability to diagnose cancer even before the first symptoms appear and to establish the most appropriate treatment to cure it are the two main challenges of the next decade in terms of medical diagnosis. 1,2 Magnetic resonance imaging (MRI) is a routine test used to diagnose cancer, providing 3D images of the organ in question[1,2.] However, MRI provides information about lesions that are already advanced and not visible on X-rays (ultrasound, CT scan, etc.). Imaging the molecular activity of an organ using a PET scan (or PET stands for Positron Emission Tomography) is the latest cutting-edge device in the search for early cancerous tumours, and is proving far more effective than MRI. However, a PET scan costs an average of €2.5 million, with an installation cost of around €800,000 and an annual operating budget of €2 million.

In France, 121 PET scans are currently available. 2 As a result, this test is mainly used at the end of cancer treatment to monitor the eradication of cancer cells rather than for early diagnosis. This is one of the reasons why blood analysis (a form of liquid biopsy) remains the most cost-effective method of establishing an early, rapid and less costly diagnosis. Since their involvement in early-stage cancer pathologies was discovered some twenty years ago, intracellular microRNAs (miRNAs) have become highly promising biomarkers for medical diagnosis.[3] MiRNAs, which consist of around twenty nucleotides, are heavily involved in post-transcriptional regulatory mechanisms capable of inducing the silencing or activation of certain genes. The presence of these RNAs in body fluids (plasma, cerebrospinal fluid, urine, saliva, etc.), known as «circulating RNAs», is a sign of major disruption or deregulation of their expression.

There is therefore a need, on the one hand, for a personalised assay to establish a profile of changes in circulating miRNA concentration before the cancer develops, and on the other hand, for personalised monitoring of these changes to adapt the treatment protocol. This strategy would represent an economic gain in terms of considerable healthcare costs during patient management, but above all, the information provided by these personalised assays would enable more effective use of innovative and very costly anti-cancer treatments. We have developed a miRNA detection process based on the combination of magnetic hyperthermia (capture and release) and electrochemical detection (capture and detection) of the hybridisation of nucleic acid sequences, without using the well-known technique known to the general public by its acronym RT-PCR (reverse transcription - polymerase chain reaction). This major advance makes it possible to resolve two complex steps in RT-PCR: (i) the reverse transcription (RT) step to convert RNA into DNA (PCR cannot process RNA as such), (ii) the chemical amplification of the copy number step (the target sought cannot be detected at its initial concentration). Our technology, developed at C2N, therefore makes it possible to use a clever method to directly capture (without transcribing or amplifying) the targets we are looking for in a complex biological sample and to release them in a localised manner into a fluidic microchannel containing electrochemical sensors. Over the past 8 years, this work has been the subject of two CNRS pre-maturation programmes, two projects co-funded by Labex Nanosaclay and the ANR, and has led to the recent publication of patents and know-how by the CNRS and Université Paris-saclay.[4]

NOTES

1. e-cancer national cancer information website.
2. Cour des Comptes report, Communication to the Senate Social Affairs Committee, Report on medical imaging in France, page 5-163, May 2016.
3. Swarup V, Rajeswari MR. Circulating (cell-free) nucleic acids. A promising, non-invasive tool for early detection of several human diseases. FEBS Lett. 2007, 581, 795-9.
4. Patent 1: FR application 3072097 (2017-10-05) then EU PCT application, and USA application: Method for detecting nucleic acid molecules by magnetic hyperthermia and kit therefor, Protected in France and the USA (managed by CNRS Innovation), (ii) Patent 2: FR application 2112764 (2021-11-30) then EU PCT application: Binding of nucleic acids on platinum electrodes, PCT procedure in progress (since 2022-11-30) (managed by Université Paris-Saclay), and (iii) the production of laboratory prototypes giving rise to a declaration of know-how (DSF): filing DI. 10633-02 (2021-11-21) «Instrument and assembly for the multi-detection of circulating nucleic acids in 1, 2 and 8 microfluidic channels», CNRS Innovation procedure (France).

e-miRgency
Seek and Find

CONTACT
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The C2N and the start-up Quandela : Partners in the QDlight Joint Laboratory Dedicated to Quantum Photonics

The C2N, supported by its supervisory institutions (CNRS, Université Paris-Saclay, and Université Paris Cité), is proud to collaborate in the QDlight joint laboratory dedicated to quantum photonics. This six-year partnership aims to address major challenges:

- Designing innovative quantum light emitters,
- Developing advanced protocols in quantum photonics,
- Optimizing devices based on semiconductor quantum dots,
- Creating networks and graphs of entangled photons.

With the expertise of its teams and its cutting-edge infrastructure, the C2N will play a key role in this initiative, pushing the boundaries of quantum computing and shaping its future.

The QDlight joint laboratory was inaugurated on November 13 at the C2N in the presence of the key participants : Thierry Dauxois (Director of the CNRS Institute of Physics and Scientific Director for CNRS at Paris-Saclay), Giancarlo Faini (Director of the Center for Nanoscience and Nanotechnology), Camille Galap (President of Université Paris-Saclay), Valérian Giesz (Co-founder and COO of Quandela), Antoine Kouchner (Vice-President for Strategic International Relations at Université Paris Cité), Pascale Senellart-Mardon (CNRS Research Director and Co-founder of Quandela), and Niccolo Somaschi (Co-founder and CEO of Quandela).

- Press Release
- Quandela, le CNRS, l'Université Paris-Saclay et l'université Paris Cité ensemble pour accélérer la recherche et l'innovation en photonique quantique

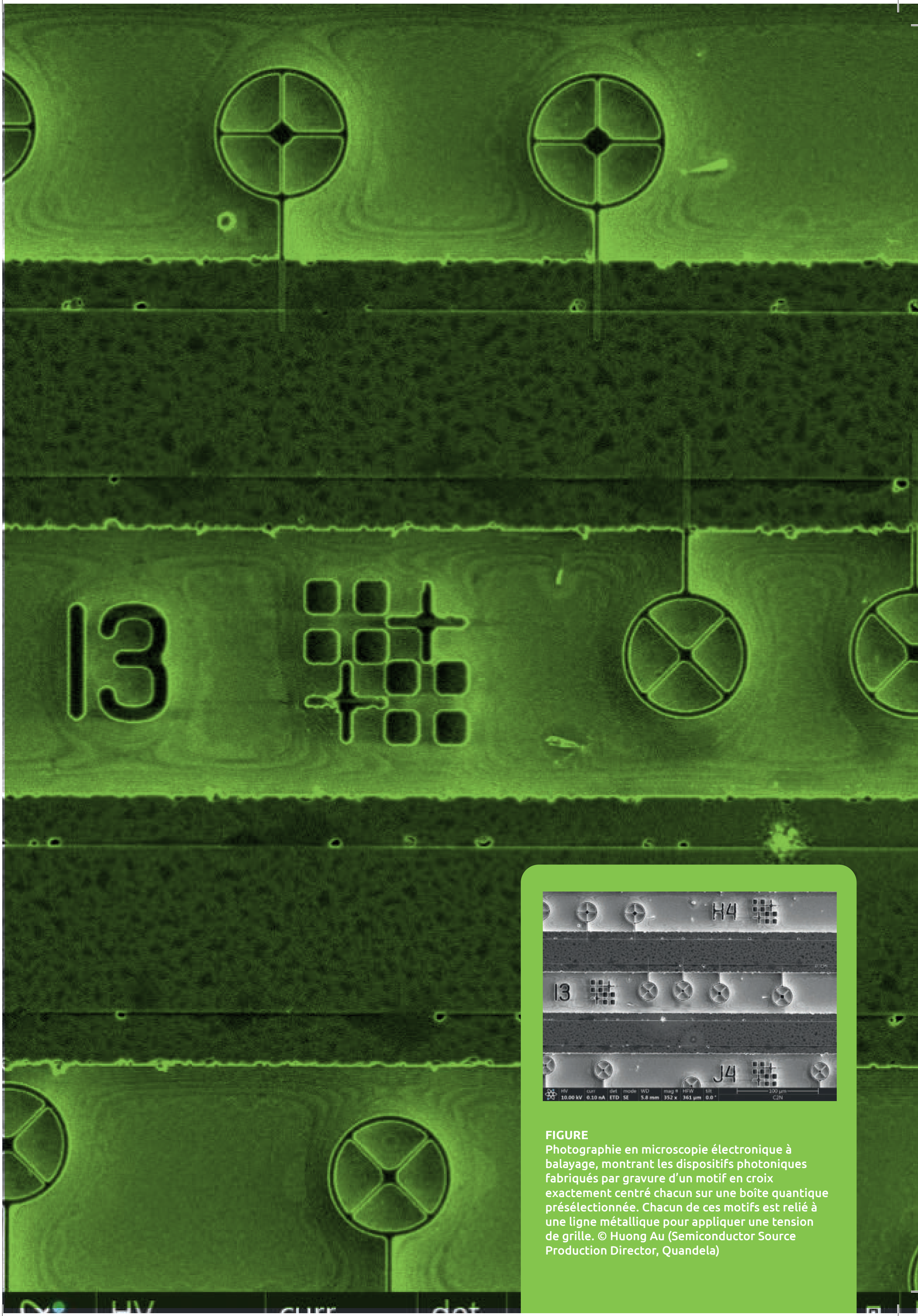


FIGURE
Photographie en microscopie électronique à balayage, montrant les dispositifs photoniques fabriqués par gravure d’un motif en croix exactement centré chacun sur une boîte quantique présélectionnée. Chacun de ces motifs est relié à une ligne métallique pour appliquer une tension de grille. © Huong Au (Semiconductor Source Production Director, Quandela)

5

First Scientific Days of the C2N

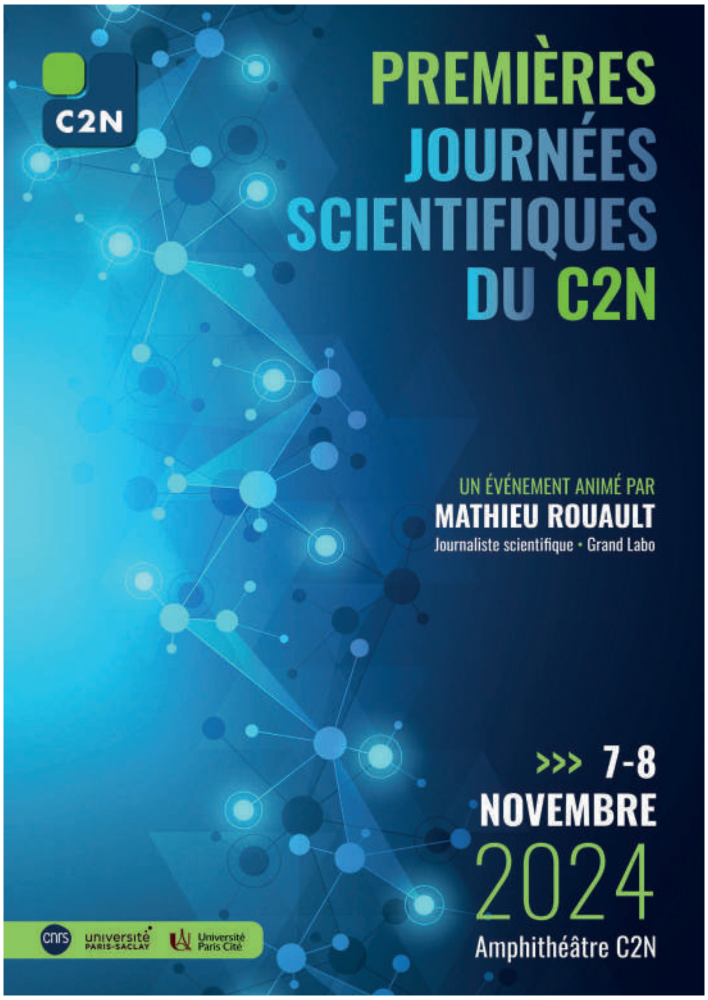
First Scientific Days of C2N : A unique event to celebrate innovation and the excellence of our teams

Last November, C2N organized its first Scientific Days, an exceptional event aimed at highlighting the expertise of its teams and the significant advances made in its various research fields.

It also provided an opportunity to emphasize interdisciplinary collaboration between the various research departments, teams, and the clean room, underscoring the crucial importance of collaborative approaches in C2N's successes. This event highlighted the essential link between fundamental and applied research, while affirming C2N's position as a leading laboratory in the field of nanosciences and nanotechnologies.

Hosted by Mathieu Rouault, a science journalist at Grand Labo, this meeting provided an opportunity to present some of the major projects of the past two years. Participants were able to engage in interactive and captivating formats such as round tables and open discussions, offering a great opportunity to discover C2N's successes and discuss the challenges ahead.

First Scientific Days of C2N



Crédits photos : © C2N.

06

Science and Society

SCIENCE OUTREACH: A YEAR OF COMMITMENT AND SHARING

In 2024, C2N strengthened its commitment to science outreach, particularly through the Year of Physics. Our initiatives reached a wide audience, from high school students to PhD candidates, while also engaging the general public. These actions reflect our dedication to shaping the future of science. Our mission is essential: making science accessible, sharing knowledge, and inspiring future vocations. Through these efforts, C2N asserts itself as a key player in science communication, sparking curiosity and inspiring the scientists of tomorrow.

- ► **Déclic Collège. Project labeled «Year of Physics 2024» by CNRS Physique**
- ► **La Physique autrement with Julien Bobroff**
- ► **Fête de la Science**
- ► **Biomim'expo**

LA PHYSIQUE AUTREMENT *WITH* JULIEN BOBROFF

Julien Bobroff, physicist and science communicator, invites you to explore physics in a fun and accessible way through his channel "La Physique autrement". His innovative approach makes complex concepts simple and captivating. C2N has also participated in several videos, showcasing its research and facilities within its technology center.

DÉCLIC COLLÈGE

March - June 2024

Project labeled "Year of Physics 2024" by CNRS Physique

A unique opportunity for exchange and discovery

The Déclic Collège project aims to facilitate direct and interactive encounters between middle school students and researchers. This format encourages free expression and discussions on a variety of topics:

- ▶ Science and research
- ▶ Educational pathways and scientific careers
- ▶ Higher education and professional opportunities

It is also a unique opportunity for students to benefit from the shared experiences and advice of scientists, broadening their horizons and future perspectives.

C2N'S INVOLVEMENT

C2N is participating in this project through four thematic workshops:

- ▶ "*Team 25, The Leaky Pipe Effect*"
- ▶ "*Nanos Under the Microscope*"
- ▶ "*Nanoscience and Nanotechnologies: Addressing the Challenges of Tomorrow's Communication Systems*"
- ▶ "*Challenges in Energy Storage and Recovery*"

conducted in middle schools across Île-de-France:

5 schools | 23 classes | 720 students

BIOMIM' EXPO

Biomim'expo is the major annual event bringing together actors in biomimicry and nature-inspired approaches to innovate and promote environmentally sustainable development. In 2024, the exhibition attracted 3,000 visitors, offering a unique platform to discover bio-inspired solutions.

The BIOSYS team from the Micro Nano-Biofluidics Department of C2N presented its latest technological innovations. The BIOSYS group's research focuses on understanding biophysical phenomena within microfluidic devices and promoting new nanofabrication technologies for the life sciences. The team has been developing innovative micro/nanofluidic systems for biological applications. This multidisciplinary field encompasses six key research topics, including:

- On-chip Separation and Identification
- On-chip Electrochemistry
- On-chip Magnetic Actuation and Detection
- On-chip Nanophotonics
- On-chip Micronano Robotics
- On-chip Cell Culture

FÊTE DE LA SCIENCE

C2N once again opened its doors for the Fête de la Science, taking visitors on a fascinating journey into the mysteries of the infinitely small.

From solar panels to quantum computers, and electronic chips… Nanoscience and nanotechnology are all around us, yet they remain largely unknown.

Exhibitions, science cafés, live demonstrations, and exclusive explorations… Throughout this exceptional day, numerous activities were offered alongside our experts, providing a unique opportunity to discover how today's science is shaping the world of tomorrow.

7

Awards and Distinctions

- Aristide Lemaitre awarded the CNRS 2024 silver medal
- The Jean Ricard Prize 2023 was awarded to Pascale Senellart
- Hana Boukharouba awarded at 18th edition of the IEEE

The Jean Ricard Prize 2023 was awarded to Pascale Senellart by the French Physical Society (SFP), in recognition of her exceptional contributions to quantum photonics

© Laurent Ardhuin

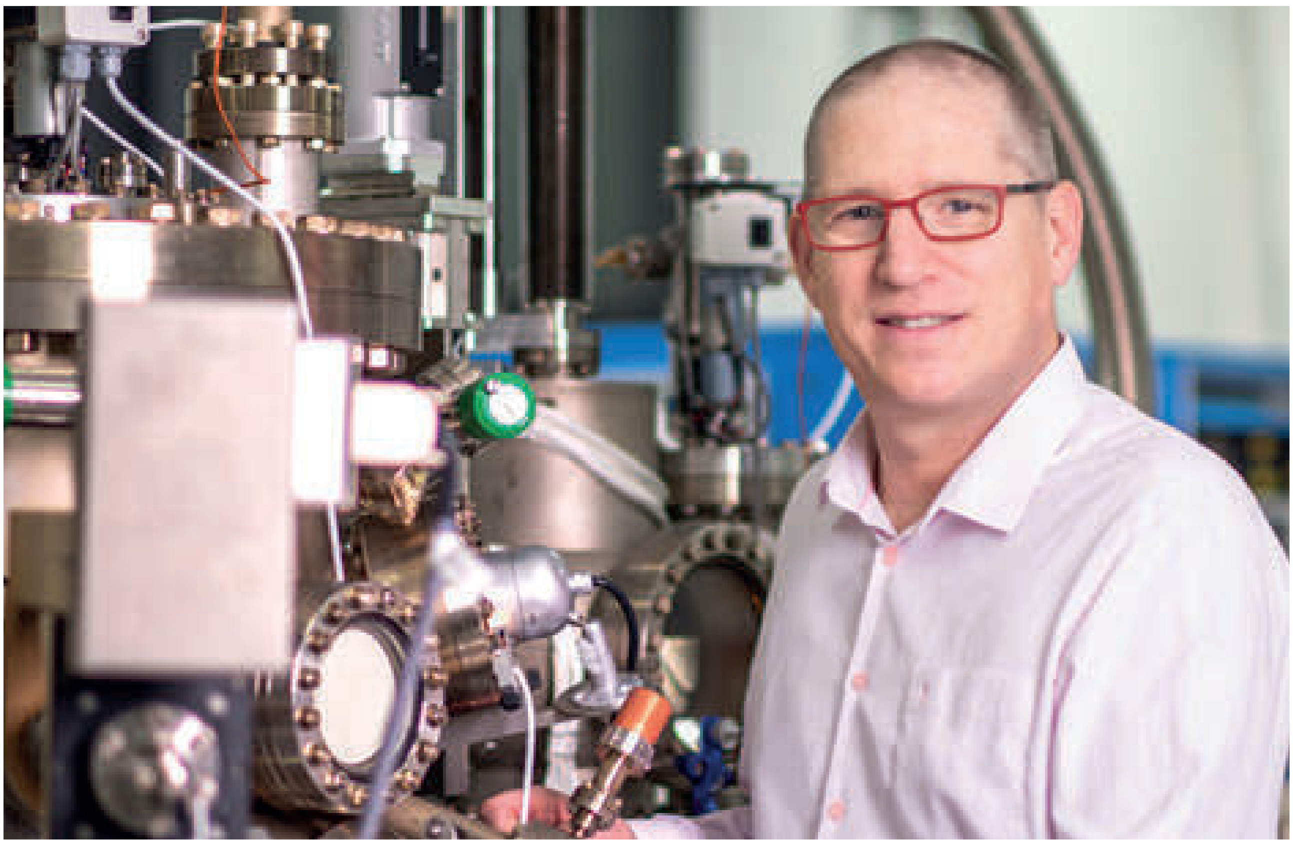
Pascale Senellart was honored with the 2023 Jean Ricard Prize by the French Physical Society (SFP) for her major contributions to quantum photonics, which are essential advancements for the future of quantum communications and computers. This prestigious award was presented to her during the anniversary events held at C2N, marking the 40th anniversary of epitaxial quantum dots and paying tribute to Jean-Yves Marzin, a pioneer of quantum dots and Pascale's PhD supervisor. Her research focuses on optical components for quantum information processing, at the intersection of solid-state physics, quantum optics, and nanotechnology. In addition, Pascale Senellart is a co-founder and scientific advisor of the start-up Quandela, which stands out in the field of quantum photonics innovation.

The Jean Ricard Prize is among the most prestigious distinctions in physics, having been awarded to illustrious laureates such as Claude Cohen-Tannoudji, Serge Haroche, and Albert Fert, all of whom were Nobel Prize winners.

Aristide Lemaitre awarded the CNRS 2024 silver medal

Aristide Lemaître, CNRS Research Director at C2N, is developing new III-V semiconductor-based materials to meet the needs of numerous natio-nal and international teams. He is a lea-ding expert in the most advanced epitaxy techniques. His many contributions have earned him the CNRS Silver Medal 2024*.

* CNRS Physique : Epitaxie de semi-conducteurs : Aristide Lemaître reçoit la médaille d'argent du CNRS 2024
@Gwendoline Chopineau



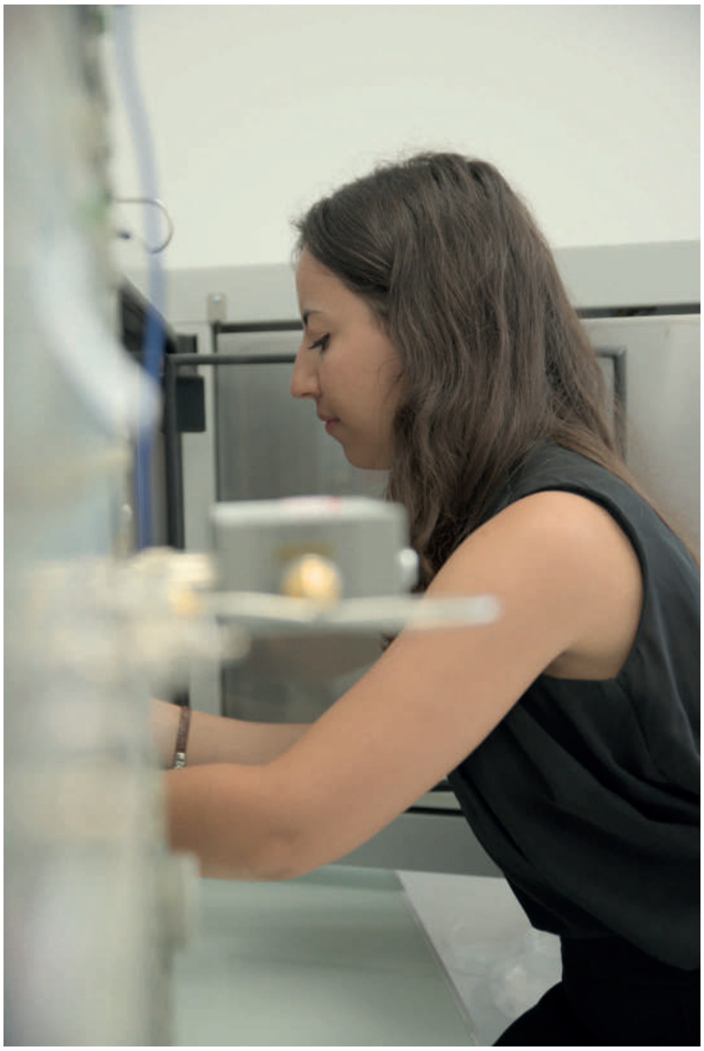
Hana Boukharouba awarded at 18th IEEE International Symposium on Medical Measurements and Applications

© C2N

Hana Boukharouba, a third-year PhD student in the Microsystems and Nano Biofluidics Department at C2N awarded at 18th edition of the IEEE International Symposium on Medical Measurements and Applications held in the Netherlands.

Hana BOUKHAROUBA is a third-year PhD student in the Microsystems and Nano Bio-fluidics Department at C2N. She holds a Bachelor's degree in Electronics, Electrical Energy and Automation, and a Master's degree in Sensors, Instrumentation and Measurements from Sorbonne Universi-ty. During her second year of the Master's program, she completed a work-study placement at the SOLEIL Synchrotron in the Surface Science Laboratory, where she worked with instruments such as STM, AFM, and interferometers, and contribut-ed to various laboratory projects.

She then joined C2N to pursue a PhD fo-cused on the development of an induc-tive and multi-frequency radiofrequency electromagnetic approach for the characterization of organic media, with a view toward designing a smart wound dressing. Her project aims to develop a new non-contact technique for characterizing skin wounds, enabling quantitative and continuous monitoring of the healing process. This characterization relies on the use of passive, planar, and flexible electromagnetic resonators that can be integrated into a medical dressing. These resonators allow non-invasive measurement of the skin's complex dielectric properties via inductive coupling in the radiofrequency (RF) range, which are well-suited for monitoring the pathophysiological state of organic tissues.



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The passive sensor operates as a high-sensitivity transmitter/receiver antenna in the 20 to 400 MHz RF range, remotely operated by an RF reader. Currently, Hana is working on developing a microfluidic circuit to be coupled with the electromagnetic sensor. This setup will be used to explore the sensor's relevance for non-contact and continuous monitoring of a reconstructed human epidermis model in a culture environment.

In June 2024, Hana took part in the 18th edition of the *IEEE International Symposium on Medical Measurements and Applications* held in the Netherlands. This international symposium covers all aspects of interactions related to instrumentation and measurement, biomedical engineering, materials science, and chemical and biological measurements. Hana was awarded 3rd place in the «Best Student Paper Presentation Award» for her paper and presentation titled «*Non-contact Monitoring of D-Glucose Concentration in Saline Solution Using a Passive Transmission Line-Based RF Resonator.*»

The paper presents results obtained using a prototype of the passive electromagnetic sensor she is developing, implemented here to monitor variations in glucose concentration in a saline solution mimicking the dielectric properties of blood.

8

The C2N Technological Facilities

RENATECH
NanoFutur - PIA3 • ESR/EquipEx


LASSYS

© Laurent Ardhuin

THE C2N TECHNOLOGICAL FACILITIES

The C2N Technological Facilities are situated in a 2,900 sqm clean room that is exclusively used for micro and nanofabrication processes (PIMENT platform), epitaxy (POEM platform), and material characterization (PANAM platform). Additionally, there are areas dedicated to education and continuous training in micro-nanotechnologies. 250sqm of space is reserved for start-up or SME activities. The facilities are managed by 40 engineers and technicians who oversee 150 pieces of equipment, representing a total investment of over 50 M€. The C2N clean room is an essential resource for laboratory research. It is also a part of the French network (RENATECH) coordinated by the CNRS to support research and innovation in the fi eld of micro-nanotechnologies at the national level. Currently, our facilities support over two hundred academic and industrial projects, with 25% of them coming from external laboratories.

CONTACT

To access our facilities, contact directly the Technological Facility staff by e-mail :

renatech@c2n.upsaclay.fr