Photos : Sergio Grazia

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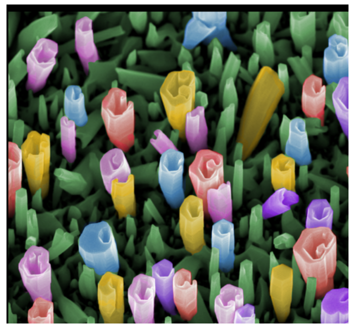
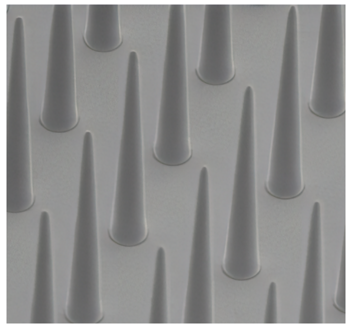
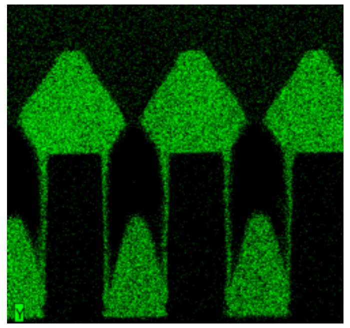
HIGHLIGHTS 2020 - *Centre de Nanosciences et de Nanotechnologies (C2N)*

Centre de Nanosciences & de Nanotechnologies

Highlights
2020







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C2N - Janvier 2021

This booklet presents some of the major facts, events and scientific results achieved in 2020 at C2N. Once again, they bear witness to the dynamism of "our laboratory", promoting research of the highest level.

The year 2020 has demanded from each and every one of us a strong capacity to adapt and mobilise in our research and training missions. In this constrained context, we are delighted with the diversity of our research projects as well as the excellence of our results to which we wish to fully associate our doctoral and post-doctoral students.

This year, once again, several C2N members have received awards and distinctions, signatures of our stimulating research environment. The C2N seminars have been maintained, with the assistance of leading speakers, thus providing a space for scientific exchanges and discussions.

Finally, we are delighted with the restart of many of our facilities, thanks to the implementation of palliative solutions. This has enabled a gradual recovery and then, as the achievements presented here demonstrate, a rise in scientific activities and in our mission as a micro- nano- technology facility belonging to the national nanofabrication network Renatech. We would like to underline the role of all those who have worked for this increase in power of our nanotechnology resources and to thank them for their commitment.

I wish to express my profound gratitude to all the contributors to the present «Highlights 2020» edition, in particular the researchers and engineers who contributed to the writing/editing/translating of each piece of news and with a special thanks to the C2N Communication team for their valuable contribution to this booklet.

At the time of printing this booklet, Emmanuel Macron has just announced the launch of the Quantum Plan at the C2N. This event confirms the positioning of the C2N as a flagship laboratory for research in nanosciences and nanotechnologies, in its local, national and international environment.

Giancarlo Faini
Head of C2N

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Reference
C. Barbier *et al.*, *Crystal Growth and Design* (2020)

M. Morassi *et al.*, *Crystal Growth and Design* (2019)

GaN grows epitaxially and selectively on graphene

GaN-based compounds are among the most coveted semiconductors for applications in optoelectronics and high-power electronics. Meanwhile, the epitaxy of high-quality single-crystalline III-N material on a cheap substrate is still challenging. Graphene is an attractive candidate, which can play the role of an ultimately thin substrate, available in large area at low-cost and transferable on various supports. Growing GaN on graphene, especially with a nanowire geometry, could drastically minimize the formation of crystalline defects. Indeed, the situation where the epilayer or the nanostructure becomes rapidly much thicker than its substrate is poorly explored, while it should give real benefit to accommodate large strain.

Aiming at this objective, we explored the epitaxy of GaN nanostructures on graphene sheets or patches transferred on an amorphous SiO_2 surface. Growth was performed by plasma-assisted molecular beam epitaxy. To investigate the mechanisms at play, experiments were carried out in a chamber installed on a synchrotron line equipped with a X-ray diffractometer. We followed in real time the evolution of the in-plane lattice parameters of both crystals, graphene and GaN *(Figure (a))*. The crystalline structure of graphene is preserved during the growth process. A 1-hour incubation delay precedes the observation of the first GaN signal, which confirms the weak reactivity of the graphene exposed to the nitrogen plasma and the Ga flux. Then, the first GaN nanocrystals nucleate with a tensile strain, which relaxes rapidly as growth proceeds *(Figure (b))*. This phenomenon suggests that chemical bonds are formed at the interface between the two materials and that the compliance of the ultra-thin graphene quickly enables the GaN relaxation. Incorporation of N atoms in the graphene lattice may occur during the incubation time and these substitutional atoms could be involved in the interfacial bonds. Anyhow, the initial GaN in-plane extension of 0.8 % that we observed experimentally is consistent with our previous work pointing that the two lattices present a supercell of coincidence.

Besides this original result, we have found a range of temperatures for which GaN growth is highly selective between graphene and SiO_2. Hence, patterning 100-nm-diameter dots of graphene on SiO_2 allowed us to organize the growth of GaN nanostructures. Thereby, we obtained regular arrays of vertical and in-plane oriented ensembles of nanowires, which formed on the graphene dots with a perfect selectivity with respect to the SiO_2 surrounding surface *(Figure (c))*. This result demonstrates that a single monolayer of graphene can withstand the lithography process without losing its ability to induce epitaxial growth. GaN nucleation takes place preferentially at the borders of the graphene dots, resulting in a linear dependence of the number of nanowires per dot, versus the dot radius. By means of a detailed statistical analysis and a theoretical model developed in collaboration with ITMO University in Saint Petersburg, we have shown that the incubation time of the nanostructures depends on the size of the graphene motif. This aspect leads to an asymmetric distribution of the lengths of the nanowires *(Figure (d))*, and to an incomplete nucleation on the smaller graphene dots.

This graphene-based selective area growth approach combined with the easy peel-off of the epitaxial material that the weak adhesion of graphene on the carrier surface of SiO_2 enables, opens new fabrication routes for mechanically flexible GaN-based devices.

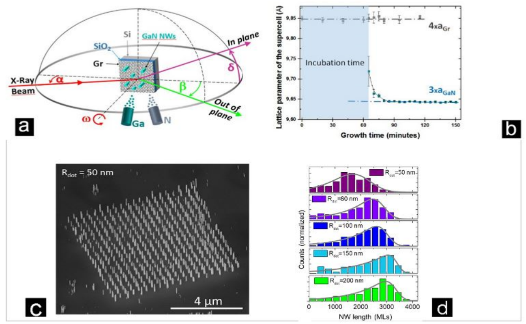

Figure : *(a) Schematic of the in-situ X-ray diffraction experiments and b) evolution of the in-plane supercell lattice parameters of graphene and GaN during plasma-assisted molecular beam growth of GaN nanowires on graphene. c) 45° tilted SEM image of a GaN nanowires array on 100 nm radius graphene dots. d) Length distributions of GaN nanowires for different radii of graphene dots (histograms) fitted by our model equation (fill lines).*

Reference

In Situ X-ray Diffraction Study of GaN Nucleation on Transferred Graphene
C. Barbier, T. Zhou, G. Renaud, O. Geaymond, P. Le Fèvre, F. Glas, A. Madouri, A. Cavanna, L. Travers, M. Morassi, N. Gogneau, M. Tchernycheva, J.-C. Harmand, and L. Largeau
Crystal Growth and Design 6, 4013-4019 (2020)
https://doi.org/10.1021/acs.cgd.0c00306

Selective Area Growth of GaN Nanowires on Graphene Nanodots
M. Morassi, N. Guan, V. G. Dubrovskii, Y. Berdnikov, C. Barbier, L. Mancini, L. Largeau, A. V. Babichev, V. Kumaresan, F. H. Julien, L. Travers, N. Gogneau, J.-C. Harmand, and M. Tchernycheva
Crystal Growth and Design, 2, 552-559 (2019)
https://doi.org/10.1021/acs.cgd.9b00556

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POEM Platform
PlatfOrm elaboration of Materials

PIMENT Platform
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Reference

A. Maestrini *et al.*, 27th International Symposium on Space Terahertz Technology 12-15 April 2016

A. Maestrini *et al.*, 43rd International Conference on Infrared, Millimeter, and Terahertz Waves, 9-14 Sept 2018

L. Gatilova *et al.*, IRRMW-THz 1-6 Sep. 2019

The key components of a terahertz receiver, fabricated in the C2N cleanroom facility, will be on board of the ESA mission JUICE

The C2N and the *Laboratoire d'Etude du Rayonnement et de la Matière en Astrophysique et Atmosphères* – LERMA[1] have jointly developed a process to fabricate terahertz Schottky nano-diodes, leading to the realisation of the world most sensitive heterodyne receiver at 1080-1275 GHz. This device was selected to equip an instrument of the ESA mission JUICE, which will take off in 2022.

Schottky diodes are basic building blocks of terahertz and sub-terahertz frequency mixers and multipliers that can operate at room and cryogenic temperature. They are necessary to meet the needs of different CNES (*Centre National d'Etudes Spatiales*) and ESA (European Space Agency) space missions. CNES and LERMA have long sought a French supplier of such mixers / multipliers to build receivers and heterodyne submillimetre instruments for astronomy, planetary science and atmospheric remote sensing.

The C2N, in close collaboration with the LERMA since 2006, has developed a manufacturing process for THz Schottky nanodiodes integrated on a gallium arsenide (GaAs) membrane, which has enabled to realize the most sensitive 1080-1275 GHz Schottky receiver in the world. This required nearly ten years of research and development: for the growth of the components materials (many attempts were necessary to obtain a fine calibration and an extremely critical doping adjustment to reach the final performances of the device), and to develop the fabrication process by taking advantage of the unique knowledge in electronic components of the C2N Technology Facility members. The design, fabrication and characterization were performed at the *Observatoire de Paris* by the LERMA. By bringing together the knowledge and skills of both laboratories, the submillimeter devices at 300GHz, 600GHz and 1.2 THz, with state-of-the-art performances have been realized since 2016.

JUICE, for JUpiter ICy moons Explorer, is the first large-scale mission of the Cosmic Vision 2015-2025 program of the European Space Agency scheduled to be launched in 2022 and arrive in the vicinity of Jupiter in 2030. This planetary probe will spend at least three years making detailed observations of Jupiter and three of its largest moons, Ganymede, Callisto and Europa. The payload is made up of ten instruments including the SWI, which will study the structure, composition and dynamics of temperatures in Jupiter's stratosphere and troposphere, as well as the exospheres and surfaces of icy moons.

SWI, *for Submillimetre Wave Instrument*, is a submillimetre wave heterodyne spectrometer, built by an international consortium leaded by the Max Planck institute for solar system research (*Max-Planck-Institut für Sonnensystemforschung*) in Gottingen, Germany. SWI consists of a 30 cm parabolic antenna and of two channels that measure the spectra in ranges: 530-625 GHz and 1080-1275 GHz (corresponding to the wavelength 480-566 µm and 235-277 µm). It will be the first planetary instrument capable of observing spectral lines with a relative resolution of 10^7 and a frequency accuracy of 10^{-8} at these spectral ranges. SWI includes 3 components and sub-systems from C2N/LERMA: the 300 GHz and the 600 GHz multipliers, and the 1,2 THz mixer.

The results obtained with these components and sub-systems should enable the SWI to reach a sensitivity twice greater than that initially planned, thus making it possible to reduce by four the integration times necessary for observations of the Jovian system; Jupiter and objects in its sphere of influence.

Finally, In order to ensure the correct operation of such complex components and subsystems during the JUICE space mission, numerous verifications and tests are necessary for the qualifications: launching, separation of stages, temperature variations, aging of components, radiation. LERMA has carried out these qualifications on several versions of components and subsystems: structural and thermal models, engineering models and qualification models. Most of the stages have been successfully completed, the latest operations are currently in progress on the flight models which will be delivered in June 2020.

The realization of these components benefited from the contribution of several members[4] of the C2N Technology Facility, and of the LERMA. Since 2011, a research engineer from the *Observatoire de Paris* is working at C2N as part of a joint agreement to develop Schottky diodes technology. This research was supported by CNES over several years, by ESA and also from 2013 by the Labex ESEP as part of a thesis from the SMAER doctoral school.

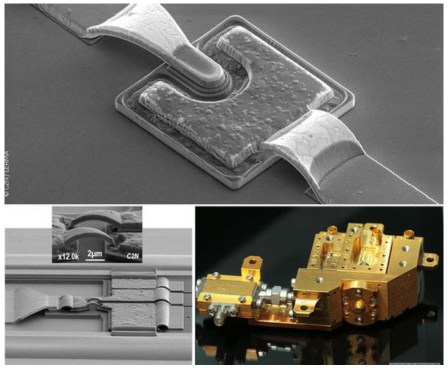

Figure *Top: SEM image – Schottky Diode of SWI, one of the 10 instruments of the JUICE mission / Bottom-left: SEM images: Parts of the 1.2 THz Monolithic Microwave Integrated Circuits (MMICs) fabricated at C2N, based on a sub-µm anode Schottky diode fabricated on thin GaAs membranes and featuring front side beamleads for precise RF grounding. / Bottom-right: Engineering Model (EM) of LERMA's 1200GHz front-end receiver, consisting of D300X2 doubler, D600GHz doubler and 1.2THz mixer.*

Reference

1200GHz and 600GHz Schottky receivers for JUICE SWI, A. Maestrini *et al.* (27th International Symposium on Space Terahertz Technology, 12-15 April 2016, Nanjing, China)

The 1200GHz Receiver Frontend Of The Submillimetre Wave Instrument Of ESA JUpiter ICy Moons Explorer
A. Maestrini *et al.* (43rd International Conference on Infrared, Millimeter, and Terahertz Waves, 9-14 Sept 2018, Nagoya, Japan)

Recent Progress In The Development Of French THz Schottky Diodes For Astrophysics, Planetology And Atmospheric Study, L. Gatilova *et al.* (IRRMW-THz, 1-6 Sep. 2019, Paris, France)

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- The collaboration started with the Laboratoire de Photonique et de Nanostructures – LPN (CNRS) until June 2016 when LPN merged with the Institut d'Electronique Fondamentale – IEF (CNRS/UPSUD) to create the C2N
- Cleanroom, member of the national network RENATECH
- C2N: Edmond Cambril, Laurent Couraud, Laetitia Leroy, Alan Durnez, Stéphane Guilet, Christian Ulysse (PIMENT platform) and Antonella Cavanna (POEM platform). LERMA : Jerome Valentin.

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Reference
Y. Fan *et al*, *Appl. Mater. Interfaces* (2020)

Generation of a guided-wave “Bessel-Gaussian” beam using an integrated 2D array of plasmonic nanoresonators

Researchers at the *Centre de Nanosciences et de Nanotechnologies* (C2N), in collaboration with *Laboratoire Interdisciplinaire Carnot de Bourgogne* (ICB) have demonstrated the generation of a non-diffractive guided-wave optical beam over a long distance. The exploited concept of Bessel beam, based on the use of a lens with conical surface formed by a 2D array of integrated plasmonic nanoresonators, can be easily adapted to other spectral domains.

Diffraction of electromagnetic waves in 2D or 3D unbounded media and which do not exert any confinement transverse to the propagation direction is one of the worst impairments for application to data transmission in the radio-wave, micro-wave or infrared domains. To counteract this issue, one solution is to shape the intensity profile of the beam with Bessel-like functions, leading to a beam that propagates without being diffracted or spread out. To this end, an axicon-type lens, based on a conical surface, can be used to generate an annular light distribution which remains laterally constant along the optical axis during propagation on a certain distance. Though most efforts devoted to the study of propagation of non-diffractive beams are focused on free space optical applications, the concept could also be useful for planar guided-wave optics to insure propagation of collimated beams over a long distance. The conventional approach relies on self-collimation properties that can be obtained using 2D photonic crystal (PhC) structures. However, its application is essentially limited to the propagation of single lobe Gaussian beams and is not suited for the implementation of Bessel type beam intensity profiles.

In a work published in April 2020 in ACS Applied Materials & Interfaces 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 Interdisciplinaire Carnot de Bourgogne* – ICB (CNRS/Univ. de Bourgogne/Univ. de Technologie Belfort-Montbeliard), presented a new strategy for the generation of a guided-wave Bessellian beam. To attain this objective, they used an integrated dielectric waveguide metasurface axicon lens with a footprint as small as 11µm². The control of the lightwave local phase and amplitude is achieved by adjusting the parameters of such hybrid metasurface-dielectric waveguide, namely the force of the evanescent coupling with plasmonic nanoresonators, their surface density, resonance frequency and quality factor.

The design, modeling and fabrication of the experimental structure, a Bessel beam generator formed by a 2D array of plasmonic nanoresonators integrated on an SOI waveguide (see Figure), were performed at C2N* while the beam propagation measurements were carried out by ICB partners. Near-field scanning optical microscopy technique was used to provide direct evidence of long-range propagation without diffraction of a planar guided beam and to determine its intensity profile. The results presented demonstrate the ability to control the light flux in guided wave structures by locally engineering the effective index by means of a thin metasurface over it. The wide variety of physical parameters that can be used to control the properties of plasmonic resonators offers the possibility of designing nanotechnology-based optical devices with advanced functionalities. The additive character of this generic technology makes it suitable to a wide variety of platforms, such as planar silica, silicon nitride, lithium niobate, II-VI, III-V, IV-IV semiconductors, and so forth.

The exploited concept can also be easily adapted to other spectral domains, especially for longer wavelengths, from mid- and far infrared to THz where the absorption losses of plasmonic resonators are greatly reduced. The sensitivity of the resonant frequency of localized surface plasmons to changes in their dielectric environment can be used for a multitude of applications in environmental and biochemical sensing, defense, security and medicine.

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

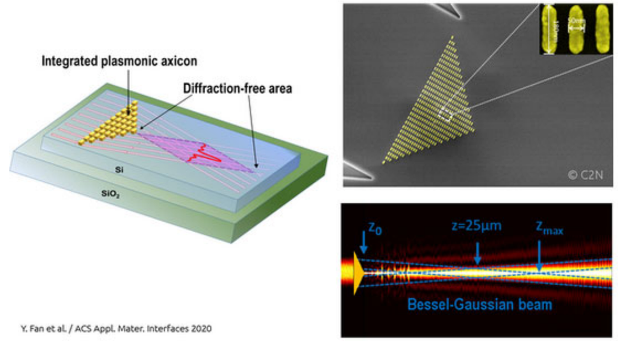

Figure (*Left) Schematic of Bessel beam generator formed by a 2D array of plasmonic nanoresonators integrated on an SOI (Silicon on Insulator) waveguide; (Top right) SEM (scanning electron microscope) image of the fabricated meta-axicon and magnified view of the gold nanoresonators; (Bottom right) SNOM (scanning near-field optical microscope) image of the evolution with propagation distance of the Bessel-Gaussian beam.*

Reference
2D Waveguided Bessel Beam Generated Using Integrated Metasurface-Based Plasmonic Axicon
Y. Fan, B. Cluzel, M. Petit, X. Le Roux, A. Lupu, A. de Lustrac
ACS Appl. Mater. Interfaces (2020)
DOI : doi.org/10.1021/acsami.0c03420

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EXPERFO PLATFORM

Reference
T. Vérolet *et al*, *Journal of Lightwave Technology* (2020)

Ultra-stable Frequency Comb Source based on self-injected quantum dash mode locked lasers : *application to multi-Terabit/s/per chip fiber communications*

A team of C2N researchers, within two collaborations with Dublin City University and Karlsruhe Institute of Technology, has demonstrated the potential of semiconductor mode locked laser based optical frequency combs for multi-Tbit/s communications.

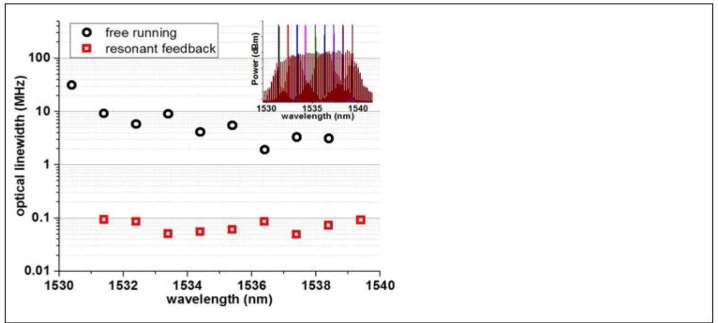
Optical frequency combs (OFC) are very attractive for many applications, in particular time and frequency metrology, signal processing, and more recently for massively parallel wavelength division multiplexing (WDM) fiber transmission. Semiconductor mode locked lasers (MLL) are ideal candidates for the generation of phase locked optical frequencies owing to their compactness, high repetition rates, low noise and high power performances. However, the spectral linewidth of semiconductor lasers usually amounts to several MHz which is not compatible with applications such as coherent optical communications, especially at high symbol rates. Today advanced signal modulation formats enable multi-Tbit/s capacity in optical fiber transmission by multiplexing optical channels provided by a *high number of discrete laser sources*.

Single section Quantum-Dash mode-locked lasers are very well suited for use as integrated comb sources that could provide stable optical carriers from one single chip in coherent transceivers for dense wavelength division multiplexing (dWDM) transmission.

A C2N team in collaboration with III-V Lab, and Almae technologies has developed such a device that yields tens of transmission channels covering around 1.5 THz spectral range within the 1.5µm optical fiber window.

An exhaustive analysis of the intrinsic component noise properties conducted by the C2N team with Télécom SudParis led to propose to exploit optical coherent feedback from an external cavity to reduce the phase noise of laser comb tones [1]. A drastic reduction of each longitudinal mode linewidth is indeed achieved across the entire optical comb bandwidth (cf Fig.), under controlled optical coherent feedback, paving the way to multi-Tbit/s data transmission based on a single laser chip. Within Dublin City University (DCU) partnership an increase of link budget has been obtained (for example more than 2dB margin in signal over noise ratio at 25Gbaud with 16QAM format) with a chip transmitting 47 channels with 32.5GHz spacing. Transmission over 50 km of fiber shows that the aggregation of the throughput of all the channels leads to 4.3Tbit/s line rate, without polarization multiplexing. A demonstration in collaboration with the Karlsruhe Institute of Technology (KIT) using a 60-channel chip spaced at 25 GHz, whose feedback control allowed vector modulation up to 32QAM, achieved a record transmission over 75km with a 11.2 Tbit/s aggregate rate[2].

These results highlight the potential of the passively mode-locked quantum-dash laser-chips for use as transmitters with extremely reduced energy consumption in multi-Tbit/s WDM systems.



Coherent feedback controlled optical linewidth of MLL frequency comb.

Reference

Ultra-stable Frequency Comb Source based on self-injected quantum dash mode locked lasers : application to multi-Terabit/s/per chip fiber communications
T. Verolet, G. Aubin, Y. Lin, C. Browning, K. Merghem, F. Lelarge, C. Calo, A. Delmade, K. Mekhazni, E. Giacoumidis, A. Shen, L. Barry, A. Ramdane
Journal of Lightwave Technology, 2020, Volume: 38, Issue: 20Page(s): 5708-5715
https://doi.org/10.1109/JLT.2020.3002653

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MATERIALS DEPARTMENT

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Phase transition in a memristive suspended MoS_2 monolayer probed by opto- and electro-mechanics
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Experimental quantification of atomically resolved HAADF-STEM images using EDX
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The metastable hexagonal phase in GaAs nanowires

By combining *in situ* transmission electron microscopy and theory, researchers at Centre de Nanosciences et de Nanotechnologies (C2N), with collaborators from universities in Singapore and Saint Petersburg, have shed new light on the mechanisms of phase selection and formation of individual atomic layers in semiconductor nanowires. Their studies demonstrate that, in such nanostructures, it is possible to control at will the atomic order at this elementary level.

Controlling the crystal phase of III-V nanowires is crucial for fundamental and technological applications because different crystal structures present different electronic, photonic or phononic properties, with discontinuities at their interfaces. For example, the valence and conduction bands of the two phases are misaligned so that small sections of one phase within the other effectively confine charge carriers. Controlled switching between the two phases enables the synthesis of novel heterostructures called crystal-phase quantum dots, which are highly promising for original applications in photonics and quantum computing.

GaAs nanowires were grown by molecular beam epitaxy in a dedicated transmission electron microscope (TEM) where the impact of changing the growth conditions can be observed in real time. Each nanowire grows from an apical gallium nanodroplet (*Figure 1, top*) by sequential addition of biatomic III-V monolayers. The different stacking of these bilayers results in either zinc blende or wurtzite crystal structures. The study showed that the occurrence of these two phases is determined by a single parameter, the droplet contact angle, which can be finely tuned by changing the group III and V vapor fluxes. The zinc blende phase forms at small and large contact angles, whereas pure wurtzite is observed for intermediate contact angles (*Figure 1, top*).

Each wurtzite monolayer grows in three stages: nucleation and fast initial propagation, slower step flow until completion, and waiting time before the next nucleation (*Roman numbers in Figure 1, bottom left*). The thermodynamics and kinetics of the process were studied theoretically and the three stages related quantitatively to the periodic variations of the arsenic content of the droplet (*Figure 1, bottom*), which is depleted by solid growth and refilled by the external fluxes. This establishes the basis for an investigation of the statistics of the formation of the monolayers over time, which control is the next step towards the deterministic formation of heterostructures in single nanowires and ensembles thereof.

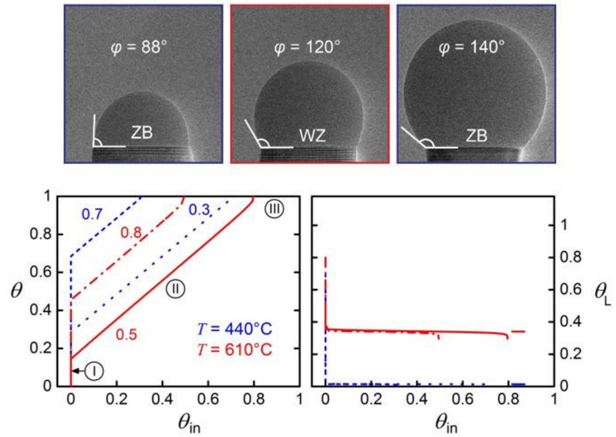

Figure ***Top.*** *TEM images recorded during the growth of a self-catalyzed GaAs nanowire (with a diameter of about 30 nm) under different fluxes of As and Ga. The As/Ga flux ratio was changed during growth to tune the volume of the catalyst droplet and consequently the contact angle φ. The images show that the two crystal phases grow with different contact angles. The zinc blende (ZB) phase forms at small (φ < 100°) and large (φ > 125°) contact angles, while a pure wurtzite (WZ) phase is observed for intermediate contact angles.* ***Bottom :*** *Modelling the growth of a single GaAs monolayer at two growth temperatures T. The three stages of the process are indicated by Roman numbers. Left: Variation with input θ_{in} of As into the droplet, of the grown fraction θ of solid monolayer (θ_{in} increases linearly with time at low growth temperature and sub-linearly at higher temperature, due to desorption). The figures near each curve indicate possible As contents of the liquid droplet at nucleation, expressed as a fraction of equivalent monolayer. Right: Corresponding variation of the As content θ_L of the droplet.*

Reference

Phase selection in self-catalyzed GaAs nanowires
F. Panciera, Z. Baraissov, G. Patriarche, V. G. Dubrovskii, F. Glas, L. Travers, U. Mirsaidov, J.-C. Harmand
Nano Letters 20, 1669 (2020)
DOI: https://doi.org/10.1021/acs.nanolett.9b04808

Energetics and kinetics of monolayer formation in vapor-liquid-solid nanowire growth
F. Glas, V. G. Dubrovski
Physical Review Materials 4, 083401 (2020)
DOI : https://doi.org/10.1103/PhysRevMaterials.4.083401

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- ITMO University and Ioffe Institute, Saint Petersburg, Russia. Collaboration within CNRS/RFBR International Research Project PHYNICS.

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Reference
J. Chaste, *et al.*
ACS nano.
(2020)

Phase transition in a memristive suspended MoS_2 monolayer probed by opto- and electro-mechanics

In recent years, new 2D semiconductor materials have shown exotic and exciting electronic or optoelectronic properties with multiple applications. In particular, several interesting mechanisms can hybridize in the same device. We have developed a new probe of these 2D materials through mechanical vibrations with an opto-electromechanical platform and have measured a phase transition in the device.

Nanomechanic have the advantage of being extremely sensitive compared to any other existing solutions, intrinsic, local, and compatible with in-situ measurements of electronics and optoelectronics. In our case, we have used this probe to identify the origin of electronic memristive effects in a suspended MoS_2 monolayer. We have demonstrated mechanically that this effect is linked to a local phase transition, for less than 1% of the material area. Also, the experiments and the numerical simulation demonstrate that this transition between the hexagonal (2H) and disordered octahedral (1T') phases of MoS_2 is associated with the presence and diffusion of sulfur vacancies in our samples. In fact, this method is almost universal because it is applicable to many phenomena of condensed matter.

This work allows to better understand the implications of sulfur vacancies in differents mechanism in MoS_2 as memristive effect and persistent photocurrents. Under light illumination, the energy barrier for diffusivity of sulfur vacancies is strongly reduced from 2.3 eV to 0.6 eV and is enough to explain the creation of small area of 1T' phase in the 2H phase of the MoS_2. For larger scale (micrometer) and much slower dynamic (hour), sulfur vacancies diffusion is also at the origin of a strong and persistent photocurrent in our sample which was, previously, mostly attributed to traps in the substrate.

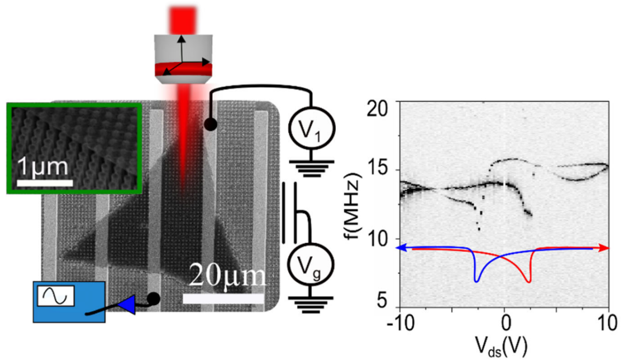

Figure : (*Left) A large flake of MoS_2 monolayer suspended over electrical contact and nanostructured Si/SIO_2 wafer. The vibration is excited by electrical capacitive coupling and measured optically with a laser. (Right) The mechanical resonance frequency along with the potential on the device. A huge softening of the mechanical mode and an hysteresis effect can be observed and correspond to a phase transition in the device which is, in this case, activated by a simple voltage. This is at the origin of memristive behavior in the electrical properties of the 2D material.*

Reference

Phase transition in a memristive suspended MoS2 monolayer probed by opto-and electro-mechanics.
J. Chaste, I. Hnid, L. Khalil, C. Si, A. Durnez, X. Lafosse, M.Q. Zhao, A.T. Charlie Johnson, S. Zhang, J. Bang and A. Ouerghi,
ACS nano, 14(10), 13611-13618 (2020)
DOI : https://doi.org/10.1021/acsnano.0c05721

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Reference
K. Pantzas and G. Patriarche, *Ultramicroscopy*, 2021

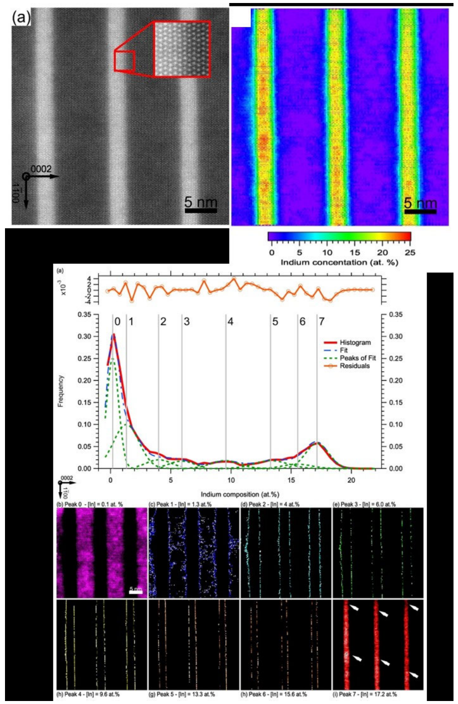
Experimental quantification of atomically resolved HAADF-STEM images using EDX

High-angle annular dark field (HAADF) images acquired in a scanning transmission electron microscope (STEM) contain a wealth of information on the structure and chemical composition of semiconductor crystals down to the atomic level. To date, tapping into this information has required prohibitively computation-intensive simulations. A team at C2N now proposes an experimental approach to extract the same information faster and for larger viewing fields by combining HAADF-STEM and energy-dispersive X-ray spectroscopy.

In high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM), images are formed by collecting Rutherford-scattered electrons, hence encoding the chemical composition of the crystal under observation in the microscope in the contrast of the acquired image. Decoding this information requires a mean of externally calibrating the HAADF-STEM contrast. Until recently, such a quantification at the atomic scale has only been possible by comparing the experimental image to images derived from atomistic simulations. Such simulations are complex and can rapidly become prohibitively time-consuming when applied to images with large viewing fields.

Researchers K. Pantzas and G. Patriarche recently developed an algorithm that relies on Energy-dispersive X-Ray spectroscopy (EDXS) as a substitute for simulations. This algorithm allows the user to straightforwardly compute atomically-resolved percent-wise precise compositional mappings of semiconductor alloys. In addition to compositional mappings, the algorithm also produces strain mappings from the HAADF-STEM image, giving the user a full picture of the structure of semiconductor crystals at the level of the single atomic column.

The team at C2N used the algorithm to study the interface between InGaN and GaN, the materials at the core of white light-emitting diodes. The team showed, for the first time, that the transition between the two materials occurs not continuously, but at discrete increments of composition. Beyond this applications, the capacity to measure strain and composition gives opens up new possibilities to study arbitrary quaternary alloys and semiconductor interfaces, such as those of the InAlGaAs superlattices, a system of paramount importance for the development of quantum cascade devices.



Figures : ***(Top)*** atomically resolved HAADF-STEM image (a) showing three InGaN wells in GaN barriers and (b) the corresponding mapping of the indium composition. ***(Bottom)*** Histogram of the indium compositions in the mapping and atomically resolved mappings of each of the distinct frequencies appearing in the histogram, revealing that the transition between GaN barriers and InGaN wells occurs through a succession of monolayers with distinct compositions.

Reference

Experimental quantification of atomically resolved HAADF-STEM images using EDX
K. Pantzas and G. Patriarche
Ultramicroscopy 220, 113152 (2021)
DOI : https://doi.org/10.1016/j.ultramic.2020.113152

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NANOELECTRONICS DEPARTMENT

Fractional statistics of anyons in a two-dimensional conductor
p. 26

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p. 32

Date
April 10, 2020

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Reference
H. Bartolomei *et al*
Science
2020

Fractional statistics of anyons in a two-dimensional conductor

By implementing a collider experiment between the elementary excitations of a two-dimensional conductor, physicists have revealed the fractional statistics of anyons, interpolating between fermionic and bosonic statistics. These results could open the way to topological quantum computing based on the exchange of some varieties of anyons.

In three-dimensional space, elementary particles are divided exclusively between fermions (like electrons for example) and bosons (like photons) according to the properties of symmetry of the wave function describing the state of the system when two particles are exchanged. When exchanging two fermions, the wave function acquires a phase, φ = π. On the other hand, in the case of bosons, this phase is zero, φ = 0. This difference leads to deeply distinct collective behaviors between fermions, which tend to exclude themselves, and bosons which tend to bunch together. The situation is different in two-dimensional systems which can host exotic quasiparticles, called anyons, that obey intermediate quantum statistics characterized by a phase φ varying between 0 and π. The existence of these quasiparticles was predicted, almost forty years ago, in two-dimensional conductors where the correlations between electrons are very strong, like for example in the quantum Hall regime for example.

This quantum Hall regime is obtained by applying a magnetic field perpendicular to the surface of a two-dimensional electron gas. In a quantum description of the system, the kinetic energy of the electrons is quantized and, for strong magnetic fields (typically around ten Tesla), all the electrons occupy a single energy level. The kinetic energy is then frozen and the interactions between electrons play a dominant role, resulting in very strong correlations between electrons which favor the emergence of these exotic quasiparticles. In the fractional quantum Hall regime, reached when a fraction $\upsilon = 1 / m$ (m = 3, 5, …) of the first kinetic energy level is occupied, the elementary excitations carry a fractional charge q = e / m and have been predicted to obey fractional statistic characterized by an exchange phase φ = π / m. Their fractional charge has been observed but, despite numerous studies over the past thirty years, no clear experimental evidence of fractional statistics has been obtained so far.

By implementing and studying anyon collisions in a two-dimensional electron gas, physicists from the Physics Laboratory of Ecole Normale Supérieure (LPENS) and from the *Centre de Nanosciences et de Nanotechnologies* (C2N) have demonstrated the fractional statistics of anyons. Their work has been published in Science and featured on the cover of this week's issue.

The collider, fabricated at C2N (figure A) is a small electronic chip (with a typical size of a few microns) designed in a high mobility two-dimensional electron gas in a GaAs/AlGaAs heterostructure. Metallic gates deposited at the surface of the electron gas and called quantum point contacts (QPC) can be used to randomly transmit quasiparticles. Two QPC's (QPC_1 and QPC_2 in the figure) emit quasiparticles towards the QPC located at the center of the sample (cQPC in the figure) and used as the beam-splitter in the collision.

The experiments were performed at LPENS in a dilution fridge allowing the researchers to cool down the chip to a few tens milliKelvins which is necessary to reach the fractional quantum Hall regime. The collisions were first studied in the integer quantum Hall regime (when the number υ of occupied energy levels is an integer, here υ=2).

This effect, related to the Pauli exclusion principle, can be revealed by measuring the cross-correlations of the current fluctuations at the output of the splitter (Figure B). The fermionic statistics leads to their complete suppression. The observed result is completely different for a fractional filling υ=1/3. Fractional statistics leads to a suppression of the antibunching effect and quasiparticles tend to bunch together in larger packets of charge in a single output of the splitter. This effect leads to the observation of negative correlations of the current fluctuations (Figure B) in perfect agreement with recent theoretical predictions for an exchange phase φ=π/3 expected for υ=1/3.

These experiments confirm the combined roles of strong correlations and low dimensionality for the emergence of anyons with statistics intermediate between those of electrons and bosons. They could be generalized, in the future, to other fractional fillings of the first energy level (like υ=2/3,1/5,…) for which other fractional statistics are expected. In particular, implementing these experiments in the non-abelian regime (for filling υ=5/2 for example), where exchange operations do not commute and thus cannot be described by a simple phase would open the way to topological quantum computing based on the braiding of these exotic quasiparticles.

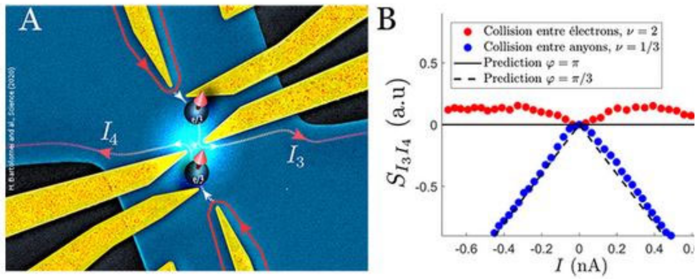

Figure: *A: Scanning electronic microscope image (in false colors) of the anyon collider. The two-dimensional electron gas is in blue. Quasiparticles move along the edge channels (in red). Pairs of electrodes (in gold) define beam-splitters called quantum point contacts (QPC). QPC_1 and QPC_2 emit quasiparticles colliding on cQPC. Figure B: measurements of the correlations $S_{i_3 i_4}$ of the fluctuations of the currents i_3 and i_4 at the output of the beam-splitter as a function of the incoming quasiparticle current.*

Reference

Fractional statistics in anyon collisions
H. Bartolomei, M. Kumar, R. Bisognin, A. Marguerite, J.-M. Berroir, E. Bocquillon, B. Plaçais, A. Cavanna, Q. Dong, U. Gennser, Y. Jin et G. Fève
Science, Vol. 368, Issue 6487, pp. 173-177 (2020)
DOI : 10.1126/science.aaz5601

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News released by the Institut de Physique (INP) of CNRS, February 18, 2020

Reference
H. Duprez *et al*, *Science* (2019)

Teleportation of a quantum state across a metallic island

A team of physicists at C2N have observed for the first time the transmission of the quantum state of an electron across a micron-scale metallic island. This is possible thanks to a mechanism connected to the Coulomb interaction, through which the overall charge of the micron-scale island is frozen at low temperature.

The basic principles of quantum physics do not permit to copy the quantum state from one system to another. However, it is possible to transfer the quantum state from one system to another. It is this transfer of information (and not transfer of matter) that one refer to as 'quantum teleportation'. Until now, physicists had succeeded in carrying out this operation with a photon, the spin of an atom or the pseudo-spin describing a superconducting quantum bit playing the role of the quantum system. To do so, they so far always used the so-called "standard" protocol, based on the use of a quantum entanglement between two particles. For the first time, physicists at C2N have now carried out the teleportation of a quantum state of electrons moving in a conductor, without the use of a prior entanglement. Their work was published in Science.

To obtain this result, the physicists at C2N used a micron-scale metallic island placed at an extremely low temperature (0.01 K). At this temperature, the electrical charge of the island is frozen, so when an electron enters into it, another electron must simultaneously exit it. When there is only one path allowing electrons to enter and leave the island (a single "channel" of electronic conduction) this mechanism results in the transfer of the quantum state of the incoming electrons on the quantum state of the outgoing electrons. With distant injection and electron emission points, this is a new form of quantum teleportation. The electrical connection to the island is made through a semiconductor material (AlGaAs, dark areas in the figure) of sufficiently low electronic density so that it is possible to control the contact by field effect with gates (colored in blue in the figure). Using this method to connect a single electronic channel to the island, the quantum state of the incoming electrons is printed on the quantum state of the outgoing electrons. The experiment is carried out in the quantum Hall regime, where a large perpendicular magnetic field breaks the temporal inversion symmetry, so that the injection and emission points are separated in space. Consequently, the transmission of the quantum state of the electrons is non-local (red arrow in the figure), mediated by the plasmons at the surface of the island. Without this mechanism, it would not have been possible to propagate the electrons through the island. Indeed, their quantum lifetime is at best only around 20 ns, whereas it takes about 60 µS (3000 times longer) for an electron to pass through. The very good fidelity of this quantum teleportation, perfect at the experimental resolution close to 1%, could be demonstrated by measuring the amplitude of quantum interferences between two paths involving, for one, the original electrons and, for the other, the electrons on which the original quantum state was transmitted.

Such a teleportation mechanism is a key element in order to use the electrons in propagation as platforms for the manipulation and transfer of quantum information.

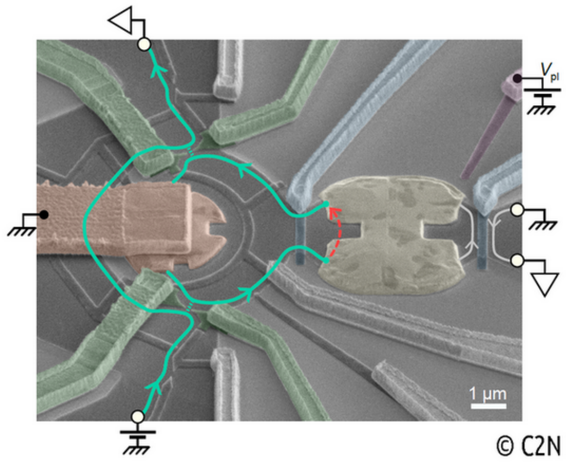

Figure : Coloured scanning electron micrograph of an electronic Mach-Zehnder interferometer, employed to test the quantum coherence of electrons going through a metallic island. The red dashed line visually represents the non-local quantum state transfer of electrons across the island. Crédits C2N/H. Duprez & al.

Reference

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, 366, 1243–1247 (2019)
DOI : 10.1126/science.aaw7856

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Date
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Reference
Louise Desplat
Joo-Von Kim
Physical Review Letters
(2020)

Entropy reduces the lifetime of magnetic bits

Retaining stored information in magnetic materials relies on making energy barriers difficult to overcome. In a theoretical study, two researchers at C2N show that the resulting entropy can have the opposite effect. Their results challenge some common assumptions about thermal stability in magnetic nanostructures.

Digital information is stored in magnetic memories as "up" or "down" states of magnetic moments, and predicting accurately the lifetime of such states is a difficult problem with strong practical implications. Estimates of this retention time are often based solely on the activation barrier, which represents the minimum energy needed to switch the moments from one state to the other. It is generally accepted that the higher the barrier, the less likely thermal fluctuations will cause a magnetic bit to flip erroneously from one state to the other. But the number of different ways to achieve this switching can become equally important in certain nanoscale magnets. The heart of the issue lies in the so-called Arrhenius law. It states that the rate of escape from an "up" or "down" configuration due to thermal fluctuations depends exponentially on the activation barrier and linearly on a quantity called the "attempt frequency". As a rule of thumb a frequency in the GHz range, which characterizes the damped resonant dynamics of the magnetic moments, is generally assumed.

In a work published in *Physical Review Letters* in September 2020, two researchers at C2N show theoretically that another contribution to this attempt frequency due to entropic effects can become equally important. The study focuses on thermal activation involving nonuniform magnetic states such as a domain wall, which represents the boundary between regions of "up" and "down" moments. Here, entropy expresses the many different ways in which fluctuations can combine with the domain wall to achieve switching. This switching mode is expected in nanometre-thick disks used in magnetoresistive random access memories.

Crucially, they find that the entropic component of the attempt frequency increases exponentially with the activation barrier, which then partially negates the stability afforded by a high barrier in the first place. While this phenomenon, known as entropy-enthalpy compensation or "Meyer-Neldel rule", has been observed for nearly a century across different fields of the natural sciences, it remains relatively rare in magnetism, but perhaps only because it has been overlooked.

The study suggests that compensation might be more prevalent than previously thought, which may encourage other researchers to revisit the issue of thermal stability in magnetic systems and spintronic devices.

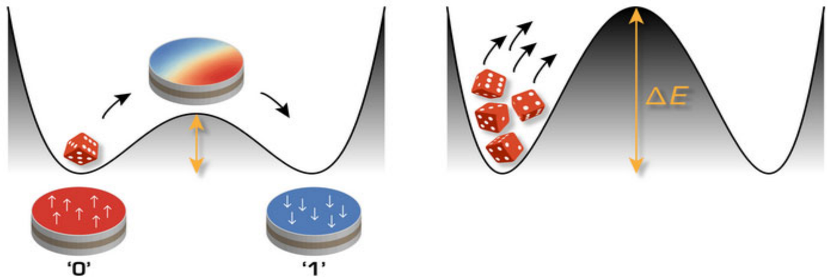

Figure : *Schematic illustration of thermally-activated magnetization reversal in a memory element between "up" ('0') and "down" ('1') states via a domain wall. As the energy barrier ΔE increases, the entropic contribution to the attempt frequency increases due to the exponentially larger number of ways thermal fluctuations can combine with the domain wall to achieve reversal.*

Reference

Entropy-reduced retention times in magnetic memory elements: A case of the Meyer-Neldel compensation rule
Louise Desplat, Joo-Von Kim
Physical Review Letters 125, 107201 (2020)
DOI: 10.1103/PhysRevLett.125.107201

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Chaos generated with a nanoscale magnetic vortex

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Reference
T. Devolder *et al*
Physical Review Letters
(2019)
M.-W. Yoo *et al*
Nature Communications
(2020)

Magnetic vortices are nanoscale whirls that gyrate like spinning tops, tracing out paths in a clockwise or counter-clockwise manner in nanometre-thick materials. Under certain conditions, this sense of gyration can flip repeatedly, resulting in complex patterns of behaviour. Now, physicists have shown that chaos underpins such nanoscale motion, which translates into arbitrarily complex electrical signals that could be used for generating random numbers or securing communications channels.

Chaos in physics and mathematics describes an unpredictable behaviour that can arise in a deterministic system. In magnetic materials, chaos can be found in the motion of a particular whirl of magnetic moments called a vortex. These whirls are characterized by a 'core', tens of nanometres in width, which gyrates like a spinning top and traces out elliptical orbits within the plane of the nanometre-thick magnetic films in which they reside. Depending on whether the moments of the core point 'up' or 'down' with respect to this plane, the core can rotate either in a clockwise or counter-clockwise sense along these orbits – much like the minute hand of a timer if it were allowed to run forwards and backwards. Under certain conditions, the core moments can flip their orientation, reversing in the sense of rotation. Crucially, such reversals can become chaotic, meaning that in our timer analogy, the minute hand could for example run forward for a minute, then backward for two, then forward again for two more minutes, and so on, but with a sequence that cannot be predicted with accuracy over the long term.

In a first work, published in Physical Review Letters, a team of researchers at the *Centre de Nanosciences et de Nanotechnologies* (C2N – CNRS/Univ. Paris-Saclay), in collaboration with researchers at the CNRS/Thales joint research lab, CentraleSupélec and University of Lorraine, have shown experimentally that this behaviour can be produced in a system called a "nanocontact vortex oscillator", where such motion can be controlled by changing the strength of the electrical currents flowing through such devices. The system, fabricated at the *Unité Mixte de Physique (CNRS/Thales)*, involves a nanoindentation technique to create a nanoscale metallic channel through which large current densities flow into a spin valve. These currents induce the chaotic motion, where variations in the magnetoresistance capture the position of the vortex core.

In a second work, published in Nature Communications, the researchers use an advanced filtering technique developed to demonstrate that simple waveform patterns can be produced, which either repeat periodically or chaotically depending on the current applied. With the same experimental system, the researchers discovered that the chaotic state of the core's gyration translates into the alternation of two distinct voltage waveforms over time. They have shown how to map these patterns onto random bits of information at a rate of a hundred million times per second.

These results open up avenues for using nanodevices to generate chaotic patterns for information technologies. Scaling up to produce an array of such vortex oscillators can be envisaged, which could result in GHz rates for random number generation on a single chip. Hardware-based fast random number generators are useful for encryption, but could also find use in neuro-inspired and probabilistic computing. The waveform patterns also reflect the inherent symbolic dynamics of the system, which can be exploited to improve signal to noise ratios in communications channels. By coupling such vortex oscillators to other spintronic components, such as magnetic memories and spin logic devices, one can also envisage a new paradigm in low-power computing, where the non-volatility and complexity of such systems are combined.

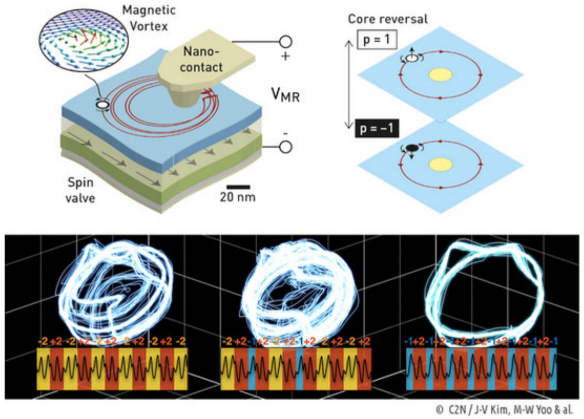

Figure: *(top): Left: Schematic of a nanocontact vortex oscillator. Right: Reversal of the vortex core leads to change in sense of vortex gyration around the nanocontact. / (bottom) Vortex trajectories in the phase space of the dynamical system illustrating periodic and chaotic behaviour. These trajectories generate distinct waveform patterns that can be used in information technologies. Crédits C2N/J-V Kim & al.*

Reference

Chaos in Magnetic Nanocontact Vortex Oscillators
T. Devolder, D. Rontani, S. Petit-Watelot, K. Bouzehouane, S. Andrieu, J. Létang, M.-W. Yoo, J.-P. Adam, C. Chappert, S. Girod, V. Cros, M. Sciamanna & J.-V. Kim
Physical Review Letters, vol. 123, 147701 (2019)
DOI: 10.1103/PhysRevLett.123.147701

Pattern generation and symbolic dynamics in a nanocontact vortex oscillator
M.-W. Yoo, D. Rontani, J. Létang, S. Petit-Watelot, T. Devolder, M. Sciamanna, K. Bouzehouane, V. Cros, & J.-V. Kim
Nature Communications, vol. 11, 601 (2020)
DOI: 10.1038/s41467-020-14328-7

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- Unité Mixte de Physique (UMPhy) CNRS/Thales

MICROSYSTEMS
AND
NANOBIOFLUIDICS DEPARTMENT

Deposition and patterning of electrodes on the vertical sidewalls of microstructures
p. 36

Design, realization and characterization of active biphasic cooling systems enhanced by EHD pumping
p. 38

Date
July 23, 2020

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Reference
L. Bonnin *et al*
Journal of Micromechanics and Microengineering
(2020)

Deposition and patterning of electrodes on the vertical sidewalls of microstructures

In the frame of research works with ONERA (French Aerospace lab) aimed to realize a piezoelectric triaxial vibrating gyrometer in semi-insulating GaAs, an original process of deposition and patterning of electrodes has been developed and modelled in C2N. This process combines e-beam evaporation under oblique incidence with an aligned shadow mask made from a laminated photoresist dry film. This process allow the fabrication of lateral electrodes connected or not to electrodes on the top and/or the bottom surface of a microstructure realized by through-wafer deep reactive ion etching. By making an analogy with sundials, an analytical model in good agreement with experimental results was established to predict the shape of the lateral electrodes as well as their thickness and density uniformity with or without substrate rotation during deposition, notably in the case where the wafer tilt axis is not in the wafer plane.

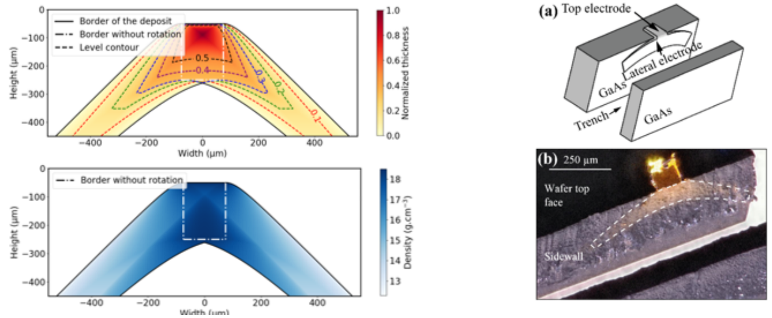

Figure : *Modelling of thickness and density distribution and result of the patterning of an Au/Cr electrode on the sidewall of a GaAs deep trench in the case of a rotating wafer during deposition*

Reference

Deposition and patterning of electrodes on the vertical sidewalls of deep trenches
L. Bonnin, A. Piot, N. Isac and A. Bosseboeuf
J. Micromech. Microeng. 30 p 105014 (14 pages), 2020
DOI : 10.1088/1361-6439/aba377

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Reference
IMAPS Thermal
February 5-6, 2020
IEEE DTIP
On-Line Symposium
June 15-26, 2020

Design, realization and characterization of active biphasic cooling systems enhanced by EHD pumping

In the frame of a collaboration between C2N an MBDA Systems Group, a new silicon-based MEMS active biphasic cooling system has been designed, realized and finely characterized. This kind of devices, such as conventional heat pipes, embed a capillary wick to induce a passive pumping of the working fluid within the thermal loop. Here, in addition to the use of a silicon-based MEMS technology, the originality of our approach, yet unreported in the literature, resides in enhancing the capillary pumping using an Electrohydrodynamic (EHD) system. This allows to override the capillary limit and so to ensure the proper functioning of the device in harsh environments such as in the case of the latest generation of smart weapons or avionic systems (wide temperature range and acceleration). Preliminary experiments have been carried out in C2N showing that the use of EHD phenomena allows for an increase up to 65% of the drained heat from the evaporator to the condenser. This work opens the way to broad research horizons that resulted in the funding of the ASTRID SYRCAPE (*SYstèmes de Refroidissement fluidiques intégrés sur CArte assistés par Pompage EHD*) project by the French National Research Agency (ANR).

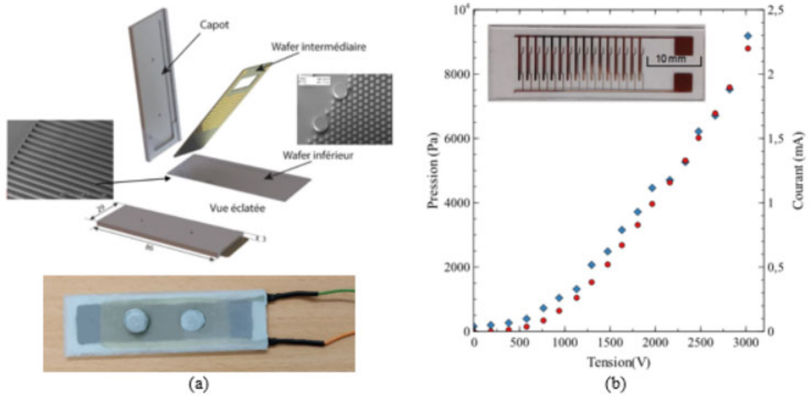

Figure : *Proposed biphasic cooling device enhanced by EHD pumping (a). Characteristics of a nElectrohydrodynamic (EHD) MEMS pump used to induce an efficient liquid flow in the system (b).*

Reference

L. Blanc, F. Parrain, A. Chaillot, M. Woytasik, O. Maire, A. Bosseboeuf, ***Conception of a New Characterization Bench for Thermal Measurements of Flat Heat Pipes in Harsh Environments***, IMAPS Thermal 2020, La Rochelle (France)
From 5 to 6 february 2020.

L. Blanc, F. Parrain, A. Chaillot, M. Woytasik, O. Maire, A. Bosseboeuf, ***Characterization of Mobility of Charged Dissociated Species in Dielectric Fluids for EHD Pumping Microsystems***, DTIP2020 – Online Symposium.
From 15 to 26 Juny 2020.

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PHOTONICS DEPARTMENT

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Date
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Reference
I. Massiot *et al.*,
Nature Energy
(2020)

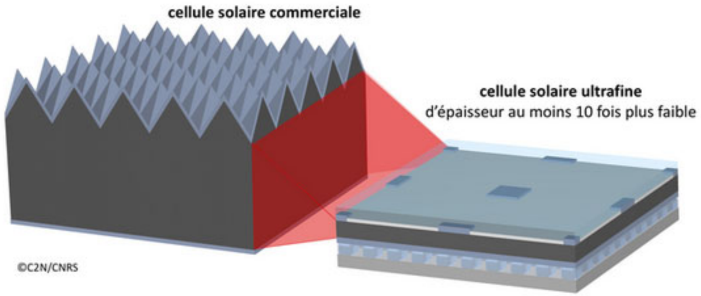
Ever thinner solar cells

Thickness reduction can be a key element in the quest for cheaper and more efficient solar cells. Making solar cells at least 10 times thinner than commercial ones would save material, reduce manufacturing costs, and enable new applications due to their greater flexibility. In a review on ultrathin solar cells published in *Nature Energy* on November 2nd, researchers from CNRS (C2N, IPVF and LAAS) highlight the very high potential of ultrathin solar cells, the challenges to overcome to get closer to the theoretical limits, and the most promising research directions.

The issue of sustainable energy production is a major societal challenge. Among the sources of renewable energy, solar photovoltaics - conversion of solar energy into electricity - has experienced a strong growth for more than 10 years. This growth must accelerate in order to fulfil the goals set for the energy transition. In the sustainable development scenarios of the International Energy Agency (IEA), the share of photovoltaics in electricity generation is expected to increase from 6% in 2017 to more than 21% in 2030. In order to reach this target, it is necessary to continue increasing the conversion efficiency of solar cells but also to reduce their cost. Most of solar modules on the market use silicon as a material that absorbs sunlight, achieving an average conversion efficiency of about 20% with thicknesses of more than 150 µm. However, reducing the thickness by a factor of 10 to 50 is a goal within reach.

In a review article published in *Nature Energy*, researchers from CNRS (C2N, IPVF and LAAS) highlight the dynamism and richness of the research work in the field of ultrathin solar cells. Upon its emergence about ten years ago, light trapping was the initial focus of researches: texturing at the sub-micrometer scale allows increasing the optical path, and thus the absorption in very thin layers. However, this review reveals that this optical approach is not sufficient: reducing the thickness of the absorber material challenges the complete architecture of the solar cell. Exploiting the full potential of ultrathin solar cells requires encompassing the aspects of photogeneration but also carrier collection, in particular surface passivation and contact selectivity. The crossover study of the industrially mature technologies (silicon, gallium arsenide, chalcogenides) allows identifying the most promising strategies to overcome the main technological obstacles.

The use of ultrathin layers opens up new prospects: their greater flexibility will facilitate the integration of photovoltaics into buildings, electric vehicles and aircrafts, and their higher tolerance to radiation exposure will increase the lifetime of modules in space. Current experimental performances are still far from the theoretical limits, but the research directions outlined in this review show that promising solutions are within reach.



Reference

Progress and prospects for ultrathin solar cells
Massiot, I., Cattoni, A. and Collin, S.
Nature Energy, 5, pages 959–972, published online on November 2nd, 2020.
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Reference
A.Elbaz *et al*
Nature Photonics
(2020)

First ultra-low threshold continuous-wave lasing in Germanium-Tin

Transistors in computer chips work electrically, but the data can be transmitted more quickly with light. Researchers have therefore been looking for a way to integrate a laser directly into silicon chips for a long time. Researchers at C2N, in collaboration in particular with researchers at Germany's *Forschungszentrum Jülich* (FZJ) and STMicroelectronics, have implemented a new material engineering method to fabricate a laser microdisk in strained Germanium-Tin (GeSn) alloy. They demonstrate for the first time the laser device with a group IV compound, compatible with Silicon, operating with ultra-low threshold and under continuous wave excitation.

Optical data transmission enables significantly higher data rates and ranges than conventional electronic processes, and at the same time requires less energy. In data centers, optical cables of a length of around one meter are therefore standard. In the future, optical solutions will be required for shorter distances to transfer data from board to board or chip to chip. An electrically pumped laser that is compatible with silicon-based CMOS technology would be ideal to achieve very high data rates.

Germanium-Tin alloys (GeSn) are promising for realizing light emitters, such as lasers. Based entirely on group IV semiconductor elements, this alloy is compatible with Silicon and can be fully integrated in the CMOS fabrication chain, widely used to produce electronic chips for mainstream applications. Today, the main approach consists in introducing as much tin as possible in the GeSn alloy (in the range of 10-16%). The obtained compound thus provides direct alignment of the band structure, which makes it possible the laser emission. However, this approach has major drawbacks: due to the lattice mismatch between the Germanium (strained relaxed) substrate on silicon and the Sn-rich GeSn alloys, a very dense dislocation defects network is formed at the interface. It thus takes extremely high densities of power pumping (hundreds of kW/cm² at cryogenic temperature) to reach the laser emission regime.

Using a different approach based on specific material engineering, a team composed of researchers at C2N, at the *Forschungszentrum Jülich* (FZJ Germany) and at STMicroelectronics, has obtained a laser emission in a microdisk of GeSn alloy fully encapsulated by a stressor layermade of dielectric Silicon Nitride (SiN_x). With this device, they have demonstrated for the first time the laser emission in the alloy able to operate under continuous-wave (cw) excitation. Laser effect is reached under cw and pulsed excitations, with ultra-low thresholds compared to the current state of the art. Their results are published in Nature Photonics.

This device uses a 300 nm thick GeSn layer with a tin content as low as 5.4% which was encapsulated by a SiN_x stressor layer to produce a tensile strain of the lattice. The as-grown alloy layer is initially an indirect band-gap semiconductor that does not support laser effect and is a very poor emitter. Researchers evidenced that it can be transformed into a truly direct band-gap semiconductor that can support laser effect, and thus becomes an efficient emitter by applying the tensile strain to it. Additionally the tensile strain delivers a low density of

states at the valence band edge, which is the light hole band thus enabling to reduce required excitation level to reach laser action. Thanks to the low concentration of tin, the dislocation networks is less dense and can be more easily treated. A specific[1] microdisk cavity design was developed to allow high strain transfer from the stressor layer to the active region, remove the interface defects, and enhanced thermal cooling of the active region.
With this device, the researchers demonstrate for the first time continuous wave (cw) lasing up to 70 K, while pulsed lasing is reached at temperatures up to 100 K. Lasers operating at a wavelength of 2.5 µm have ultra-reduced thresholds of 0.8 kW/cm^2 for nanosecond-pulsed optical excitation, and 1.1 kW/cm^2 under cw optical excitation. Since these thresholds are 2 order of magnitude lower than reported in the literature, the results open a new path towards the integration of group IV laser on a Si-photonic platform.

[1] Patent PCT/FR2017/052881 "Structure comprising a semiconductor strained layer on a heat sink"

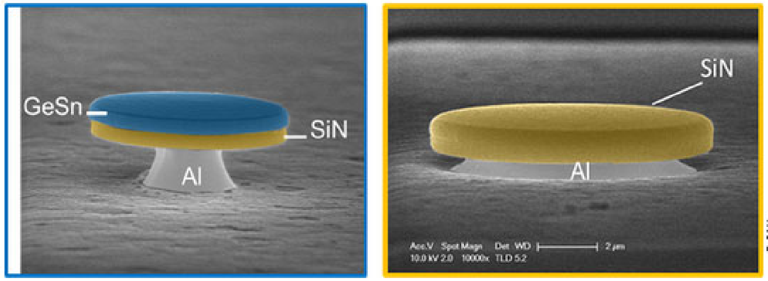

Figure : *Scanning Electron Micrographs: (left) A layer of GeSn is transferred onto a silicon substrate and then structured as a microdisk to form an optical cavity. During transfer, the defective layer in the GeSn, which was at the interface with the Ge/Si substrate, was removed by etching. The transfer also makes it possible to insert a stressed SiNx layer underneath the GeSn layer. An Aluminum layer was used to maintain the cavity while allowing excellent thermal cooling of the laser device trough the substrate. (right) A final conformal deposition of a strained film on the microdisk allows to obtain an "all-around" configuration of the stress transfer from the SiNx to the GeSn. The GeSn is then under a tensile strain of 1.6% very homogeneously distributed in its active volume. Credit: C2N / M. El Kurdi & al.*

Reference

Ultra-low-threshold continuous-wave and pulsed lasing in tensile-strained GeSn alloys
A. Elbaz, D. Buca, N. von den Driesch, K. Pantzas, G. Patriarche, N. Zerounian, E. Herth, X. Checoury, S. Sauvage, I. Sagnes, A. Foti, R. Ossikovski, J.-M. Hartmann, F. Bœuf, Z. Ikonic, P. Boucaud, D. Grutzmacher, M. El Kurdi
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Reference
D. Oser *et al*,
npj Quantum Information
(2020)

A stand-alone, telecom-complint, silicon chip for new generation quantum communication systems

Thanks to the expertise in integrated photonics of the Centre de Nanosciences et de Nanotechnologies - C2N and in quantum photonics of the Institut de Physique de Nice – INPHYNI, a team of physicists have developed a new silicon photonic chip architecture. This type of photonic chip is genuinely compliant with telecommunication standards.

Quantum information technologies are identified as major emerging key technologies, with protocols allowing absolute security in data exchange and massively parallel processing capabilities. These quantum advantages are based on the exploitation of properties that are exclusive to quantum physics, such as entanglement. For enabling quantum communication across metropolitan networks, actual quantum systems have to be developed along reliable, functional, and scalable architectures. Photonics integrated on silicon stands as one of the key solutions to meet these requirements. It permits the dense integration of linear and non-linear optical functionalities on monolithic substrates, encompassing generation, routing, advanced manipulation, as well as detection of photonic quantum states. Such a level of integration remains a major challenge, mainly due to the limited performance of on-chip optical pump rejection filters. The latter must reduce the laser pump by more than 9 orders of magnitude while preserving photon-pair entanglement.

Researchers from the Centre de Nanosciences et de Nanotechnologies - C2N (CNRS/Université Paris-Saclay) and from the Institut de Physique de Nice – INPHYNI (CNRS/Université Côte d'Azur) have joined their expertise to develop a novel, telecom compliant, silicon chip integrating both a non-linear photon-pair generator and a passive pump rejection filter. The researchers have thus qualified the entanglement out of such an innovative photonic circuit and demonstrated its applicability to quantum communication networks. This work has recently been published in the journal npj Quantum Information.

The experimental setup (see figure) consists in a continuous-wave laser pumping a photonic chip fabricated at the C2N, in which a micro-cavity generates, through four-wave mixing, pairs of entangled photons. Preserving the quantum properties of information requires high filtering of the pump laser. The breakthrough of this demonstration lies in the design and realization of a filtering stage integrated directly on the chip for attenuating, at a tremendous level, the guided pump signal compared to the quantum signal. The proposed approach exploits a multimode waveguide with an all-passive Bragg corrugation (a periodic variation of the waveguide width that reduces the impact of fabrication errors). This generic strategy leads to high rejection rates without requiring the use of active control and the realized filter shows a record rejection estimated at more than 85 dB over a 5 nm bandwidth with losses equivalent to that of a standard silicon waveguide.

Energy-time entangled photons are naturally produced over a frequency-comb matching the channel-grid of the telecom C-band, symmetrically to the pump channel. Researchers at the INPHYNI have demonstrated the first entanglement qualification, showing the highest raw quantum interference visibility (exceeding 92 %) obtained to date with such a stand-alone circuit. This demonstration therefore attests the validity of the approach for the filtering stage.

These results will certainly further promote the development of more advanced and scalable photonic-based quantum circuits, compliant with telecommunication standards. In the perspective of a large-scale deployment over telecommunication networks, a partnership has been established with a global semiconductor company able to produce such integrated circuits with world-class manufacturing capabilities.

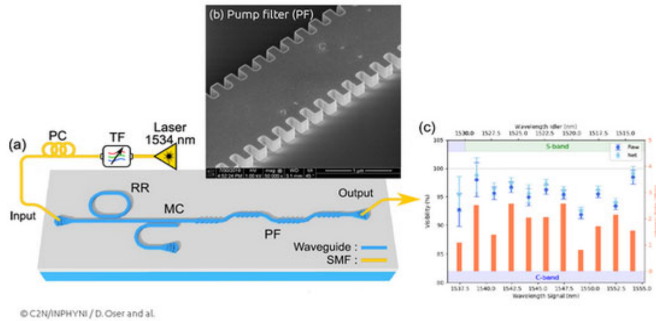

Figure: *1: a) experimental setup. TF: band pass filter, PC: polarization controller, RR: micro-cavity, MC: modal coupler, PF stop filter. b) SEM image of the filter made at C2N. c) summary of results. Credits: C2N/INPHYNI*

Reference

High quality photonic entanglement out of a stand-alone silicon chip
D. Oser, S. Tanzilli, F. Mazeas, C. Alonso Ramos, X. Le Roux, G. Sauder, X. Hua, O. Alibart, L. Vivien, E. Cassan, L. Labonté
npj Quantum Information 6, 31 (2020)
DOI : https://doi.org/10.1038/s41534-020-0263-7

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Reference
A. Chowdhury *et al*, *Nature Communications* (2020)

Amplifying a weak signal by manipulating the nonlinear resonance in a nano-electromechanical resonator

A team of researchers at C2N has experimentally demonstrated an enhancement by more than an order of magnitude of a weak electrical signal thanks to nano-electromechanical resonator. Their results, supported by theory, illustrate a general mechanism which potentially applies to a wide range of physical systems.

In signal processing and for any kind of communication channels, amplification of weak signals carrying information is an important challenge to solve in order to counter the unavoidable losses. Driven non-linear resonators can display sharp resonances or even multistable behaviours amenable to induce strong enhancements of weak signals. Such enhancements can make use of the phenomenon of vibrational resonance, whereby a weak low-frequency signal applied to a bistable resonator can be amplified by driving the nonlinear oscillator with another appropriately-adjusted non-resonant high-frequency field.

In a recent study published in Nature Communications, a team at C2N in collaboration with researchers at *Laboratoire Charles Coulomb* – L2C (CNRS/Univ. Montpellier) and University of Chile proposed a new method to enhance weak signals in communication channels using a forced nano-electromechanical resonator. The method relies on the manipulation of a nonlinear resonance with a high frequency non-resonant drive added to the signal. The results illustrate a general non-linear mechanism which might have applications in the fields of microwave signal amplification or sensing for instance.

The researchers have investigated the vibrational resonance behaviour in a nonlinear oscillator consisting of an optically-probed, electrically driven nano-electromechanical resonator. The system is by nature monostable, which means that it is not directly suited for vibrational resonance. Nevertheless, the researchers have developed an unconventional vibrational resonance scheme based on three distinct time-scales. First, a near-resonant excitation pushes the resonator into a bistable regime. Then, the amplification by vibrational resonance of the signal, encoded in a slowly varying amplitude modulation of near-resonant excitation, is obtained by use of the high-frequency non-resonant drive.

The researchers at C2N show experimentally an enhancement by a factor up to 20 of the weak signals. Thanks to the theoretical contribution of a partner at University of Chile, the researchers could even predict much higher amplification factors. Interestingly, the intermediate frequency signal needs not to be resonant with any of the resonator frequencies, thus leaving a large freedom in its choice.

As a general mechanism for nonlinear resonators, this model describing vibrational resonance in a monostable forced nonlinear oscillator is quite general and applies to a broad range of physical systems. Beyond its fundamental vivid prospects, this demonstration of nonlinear resonance manipulation could be envisioned as potential means for various pervasive biharmonic signal applications, including radio-frequency signal processing or sensing to name a few.

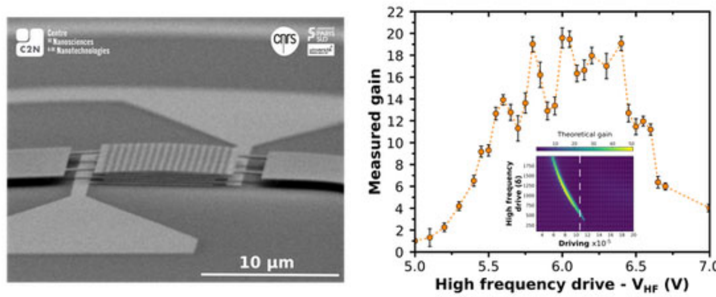

Figure *(Side view) Scanning electron microscope image of the suspended optomechanical cavity. (View from above) Focus on the center of the cavity confining both optics and mechanics. The holes in the center and the indentations at the edges of the beam with a different periodicity induce the bichromatic character of the confinement.*
Copyright C2N/Thalès TRT

Reference

Weak signal enhancement by nonlinear resonance control in a forced nano-electromechanical resonator,
A. Chowdhury, M. G. Clerc, S. Barbay, I.Robert-Philip, R. Braive
Nature Communications, 11, Mai 2020
DOI : https://doi.org/10.1038/s41467-020-15827-3

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Reference
V. Goblot *et al*,
Nature Physics
(2020)

The cascade to criticality

Researchers at C2N (CNRS/Université Paris-Saclay), PhLAM laboratory (CNRS/Univ. de Lille) and ETH Zurich have unveiled a novel mechanism describing how criticality - a phase in which waves are neither extended nor localized but in a so-called "critical state" - emerges in quasiperiodic structures. Combining experimental and theoretical work, their finding provides newinsight into the physics at the middle ground between order and disorder.

Quasiperiodic structures, which are ordered but are not strictly periodic, are the source of extraordinary beauty in nature, art, and science (butterfly wings iridescence, Islamic art, Penrose tiling, …). They are at the crossroads between periodic and randomly disordered systems. For physicists, quasiperiodic order is both aesthetically and intellectually appealing. Numerous physical processes, such as localization of classical and quantum waves, that are well described in periodic structures, fundamentally change their character when they happen in quasiperiodic systems. Writing in Nature Physics, an international team of researchers at the *Centre de Nanosciences et de Nanotechnologies* – C2N (CNRS/Univ. Paris-Saclay), at Phlam laboratory (CNRS/Université de Lille), and at ETH Zurich now describes combined theoretical and experimental work in which they explore wave localization in one-dimensional quasiperiodic structures. They discover a new mechanism by which criticality develops in such media.

Two famous paradigmatic examples of quasi-periodic models are the Aubry–André and the Fibonacci models. Strikingly, they show very different localization properties. In the Aubry–André model, there are two distinct parameter regions in which waves can be in either 'extended' or 'localized' states (in the same sense as electrons can either propagate through a material or be stuck in an insulating state). At the boundary between these two regimes, waves are 'critically localized', showing a power law decay with self-similar features that are characteristic of fractality. By contrast, in the Fibonacci model, there is not one specific critical point separating two distinct regimes, but the waves are critically localized for any parameter of the system. Despite their sharply contrasting behaviours, the two models are connected, and can be continuously transformed into one another*. How such different localization behaviours are connected through this continuous transformation? This is the question that the researchers have answered in this work.

The C2N physicists had perfected a photonic platform** - so-called cavity-polariton lattices - in which light can be guided through semiconductor nanostructures while experiencing interactions similar to those acting on electrons moving through a crystal. Using the technological means at C2N, the researchers have fabricated with exquisite control photonic wires featuring quasiperiodic modulations in their width. This enabled them to implement experimentally, for the first time in any system, quasicrystals interpolating between the Aubry-André and the Fibonacci models. Optical spectroscopy experiments performed locally on these photonic quasi-crystals offer the invaluable advantage of being able to directly image light localization in the systems. At first sight, the structures shown in the figure look very similar. Surprisingly, the minimal differences implemented between these structures are sufficient to radically modify wave localization properties.

By combining their theoretical and experimental tools, the researchers were able to trace how the Aubry–André model evolves to become fully critical in the limit of the Fibonacci model. Counter naïve expectation, the team showed that this does not not happen in a smooth way, but through a cascade of localization–delocalization transitions. Starting, for example, from the region of the Aubry–André model where waves are localized (dark red in the above phase diagram), at each step of the cascade process energy bands merge in a phase transition (blue streaks in the phase diagram), during which particles become delocalized. At the other side of the cascaded transition, the localization roughly doubles, sending the states of Aubry–André model gradually towards full criticality as it morphs into the Fibonacci model.

With this work, the researchers have provided an additional illustration of how powerful the polaritonic platform can be as a tool to tackle complex physical problems. The teams have successfully unveiled a general mechanism for the emergence of criticality in quasicrystals. The significance of these experiments goes firmly beyond light properties, as it also applies to the behaviour of electrons, atoms and other quantum entities that are governed by the same physics. In addition, this newly discovered mechanism is anticipated to inspire new ways of controlling conduction in quantum devices. Finally, the polaritonic quasi-crystals offer the potential to explore wave localization in presence of interactions, a topic of high interest linked to the recently discovered many-body localization.

** Y. E. Kraus and O. Zilberberg, "Topological Equivalence between the Fibonacci Quasicrystal and the Harper Model", Phys. Rev. Lett. 109, 116404 (2012)*

*** A. Amo and J. Bloch, "Exciton-polaritons in lattices: A non-linear photonic simulator", C. R. Physique 17, 934 (2016).*

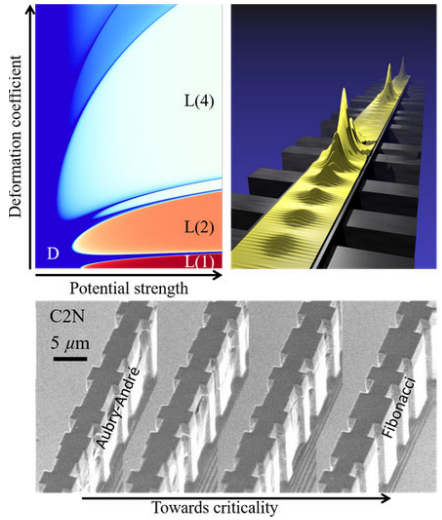

Figure : *(top left) Calculated localization (L) and delocalization (D) phase diagram vs potential strength and quasicrystal deformation. The vertical axis origin corresponds to the Aubry-André limit (leftmost structure in the bottom Scanning Electron Microscopy (SEM) image), and asymptotically points towards the Fibonacci limit (rightmost structure in the bottom SEM image). Colors in the phase diagram encode the extent of the waves from fully delocalized (D – dark blue) to fully localized on one lattice site (L(1) – dark red). Intermediate shades of color L(N) represent waves that are localized on N lattice sites. (top-right): artistic view of a critical mode. (bottom) : SEM images showing four different polaritonic structures used in the experiment to explore the phase diagram. The two central structures correspond to interpolations between the Aubry-André and Fibonacci models / Credits SEM images: C2N*

Reference

Emergence of criticality through a cascade of delocalization transitions in quasiperiodic chains,
V. Goblot, A. Štrkalj, N. Pernet, J. L. Lado, C. Dorow, A. Lemaître, L. Le Gratiet, A. Harouri, I. Sagnes, S. Ravets, A. Amo, J. Bloch, O. Zilberberg
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Reference
M. Marconi *et al*, *Physical Review Letters* (2020)

Mesoscopic limit cycles in coupled nanolasers under strong fluctuations

Using two coupled nanolasers, researchers have demonstrated the existence of limit cycles with only a thousand photons in the cavities, in spite of the strong spontaneous emission quantum noise influencing the system dynamics.

Any freely decaying dissipative dynamical system, like a pendulum undergoing friction in the air, ends up in a state of rest. However if the system is non-linear, and if it is continuously fed with some amount of external energy, it can develop a periodic movement known as a limit cycle. The resulting oscillations are said to spontaneously break the time-translation symmetry, because the forces acting on the system do not have any "external clock". In photonics, the limit cycle phenomenon gathers a great amount of interest as an embryo for many applications such as frequency combs, pulsed light sources, the so-called "parametric" instabilities and because it constitutes a possible route towards chaos. Although it is well-understood in classical physics, the existence of the limit cycle in the quantum domain is still controversial. In 2012, Nobel Prize winner in physics Frank Wilczek predicted the existence of a quantum periodic motion breaking the time translation symmetry, opening up a new field of research called "time crystals" by analogy to the spatial periodicity of crystals. Since then, some experimental demonstrations have emerged but, above all, intense debates have followed one another within the scientific community.

Today, the question of the survival - or not - of limit cycles under large quantum fluctuations remains open. Researchers at C2N, in collaboration with the University of California San Diego (USA) and the University of Baleares (Spain), have developed a new approach to address the question of the existence of limit cycles under strong fluctuations. It consists of using nanolasers, which are intrinsically influenced by the quantum fluctuations of the spontaneous emission noise. The researchers provided an experimental statistical proof of the existence of limit cycles of stochastic nature, called "mesoscopic limit cycles", halfway between nanoscopic (a few photons) and macroscopic (a conventional laser field). Their work* has been published in Physical Review Letters.

The study showed that in a nanolaser, made up of two coupled nanocavities, limit cycles are generated at the mode switching point, and that they survive to strong fluctuations. These limit cycles can be statistically characterized even though their very high frequency (hundreds of GHz) and their ultra low energy (only a thousand photons) make their direct observation very difficult. The relatively small number of photons in the cavities (several orders of magnitude below conventional "macroscopic" lasers) has fundamental consequences on the temporal dynamics. The authors called these oscillatory states "mesoscopic limit cycles".

The nanolasers, made of semiconductor photonic crystals, have been designed, fabricated and experimentally studied at C2N. They turn out to be an interesting laboratory not only as testbeds to study the influence of quantum fluctuations on the limit cycles, but also for the investigation of the spontaneous breaking of the time-translation symmetry, a key element of time crystals which has largely motivated a large amount of research during the last years.

**This work was supported by the French-American International Research Project (IRP CNRS) « Nanoelectronics », together with a Chateaubriand Grant from the French Embassy in the US.*

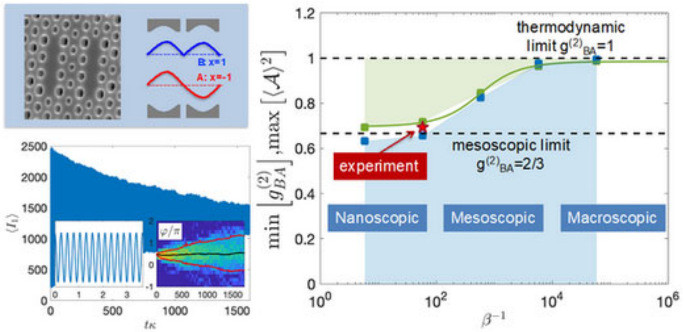

Figure : *Mode beating in coupled photonic crystal nanolasers (top left), leading to "mesoscopic limit cycles". Despite the strong quantum fluctuations that drastically decrease the lifetime of the limit cycle, the intensity in one of the cavities undergoes thousands of oscillations before it dies out (bottom left). Right: numerical simulations of the order parameter accounting for the limit cycle amplitude (A) together with zero-time-delay second order cross-correlations [$g^{(2)}BA(0)$] showing a crossover between the macroscopic regime [$g^{(2)}BA(0)=1$] and the so-called mesoscopic regime [$g^{(2)}BA(0)=2/3$], as a function of the inverse of the spontaneous emission factor (1/β). The latter is related to the characteristic intracavity photon number, hence the "system size". The red star indicates our experimental result.*

Reference

Mesoscopic limit cycles in coupled nanolasers,
M. Marconi, F. Raineri, A. Levenson, A. M. Yacomotti, J. Javaloyes, S. H. Pan, A. El Amili, and Y. Fainman
Physical Review Letters 124, 213602 (2020)
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AWARDS AND DISTINCTIONS

Rebeca Ribeiro-Palau is awarded the 2020 Nicholas Kurti Science Prize

Rebeca Ribeiro-Palau, CNRS Researcher at the C2N is the joint winner of the 2020 Nicholas Kurti Science Prize. The Nicholas Kurti Science Prize promotes and recognises the novel work of young scientists working in the fields of low temperatures and/or high magnetic fields in Europe.
Rebeca Ribeiro-Palau is recognised for her outstanding contributions in research on electronics quantum transport in graphene and van der Waals heterostructures; in particular her contributions to the development of new graphene-based quantum Hall resistance standard and development of the dynamically rotatable van der Waals heterostructures technique.

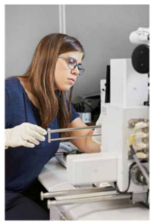
Valentin Goblot is awarded the thesis prize 2019 of the EDOM Doctoral School

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

Physical Society of Berlin honors a Physics graduate of the C2N

Daniel Vajner, student in a French-German double degree master's program, received the Physics Study Award of the Physical Society of Berlin (Physikalischen Gesellschaft zu Berlin - PGzB) for the outstanding master's project he conducted at C2N, in the group of Jacqueline Bloch.

He investigated the behavior of so-called exciton-polaritons, a quantum mechanical superposition of semiconductor excitons, and bound photonic states in a microcavity, which can be described as a bosonic quasi-particle in its own right.



Farsane Tabataba-Vakili is the winner of the PhOM 2020 thesis prize, in the field of Optics

Farsane Tabataba-Vakili has been awarded the PhOM 2020 PhD prize in the field of Optics for her work: IIInitrides on silicon: a plat-form for integrated photonics from the ultra-violet to the near-infrared.

Credit : Carl Diner for the L'Oreal Foundation

Laurent Vivien, appointed member of the *European Optical Society*

Laurent VIVIEN, Director of Research at C2N, appointed Fellow of the *European Optical Society* (EOS) for his contribution to silicon photonics and optoelectronics.

Photo NANOP 2016

Sylvain Ravets wins an ERC "Starting Grants" 2020 for his project ARQADIA

The ARQADIA project finds its inspiration in the physics of condensed matter and in particular in so-called "quantum" materials. Quantum materials have very special properties (superconductivity, quantum magnetism, fractional quantum Hall effect) which cannot be described simply by models involving only one particle (atom or electron) at a time, but which need to take into account the interactions between a large number of particles. The objective of the ARQADIA project is to build, with light, synthetic quantum materials that are the seat of such collective behaviours. The objective is twofold: to use these artificial materials to help understand these complex phenomena by studying them in well-controlled systems, and to use these collective effects as a resource applicable to quantum technologies.

The project "Quantropy, Entropy in engineered quantum systems - Mesoscopic thermodynamics of correlated quantum states" involving Frédéric Pierre is selected by the Synergy Grant 2020 call for proposals.

The results of the ERC Synergy Grant 2020 call were published on 5 November : the 13 projects, which have a French partner, involve researchers from the CNRS or from mixed units, including Frédéric Pierre's project: Quantropy, Entropy in engineered quantum systems - Mesoscopic thermodynamics of correlated quantum states.
His challenge : to develop new approaches for measuring thermodynamic properties in correlated quantum electron circuits.

EVENTS AT C2N IN 2020

20 PhD Defended

Louis GOUILLART, Rafael CORDERO ÁLAVREZ, Nicola CARLON ZAMBON, Quentin CHATEILLER, Romaric DE LÉPINAU, Maxence ERNOULT, Jérémy LÉTANG, Omar SAKET, Paul BOUQUIN, Farsane TABATABA-VAKILI, Tifenn HIRTZLIN, Théo VEROLET, Justine VORONKOFF, Guilhem MADIOT, Faten BEN-CHAABANE, Lucas BONNIN, Julie LACHAUX, Hadrien DUPREZ, Giulia RIZZO, Thomas BIDAUD.

1 HdR Defended

Fabrice RAINERI

10 C2N General Seminars

Riwal PLOUGONVEN (LMD, Ecole Polytechnique, IP Paris)
Pascale SENELLART (C2N)
Manuel BIBES (UMP, CNRS, Thales, Université Paris-Saclay)
Makoto KOHDA (Tohoku University)
Agnès TEMPEZ (HORIBA FRANCE)
Noëlle GOGNEAU (C2N)
Sylvia MATZEN (C2N)
Sara DUCCI (LMPQ, Paris)
Gilgueng HWANG (LIMMS - CNRS, Tokyo)
Joo-Von KIM (C2N)

Conferences / Workshop

The 22nd edition of the European Conference on Integrated Optics (ECIO 2020) will take place (online)

The second Taiwanese-French bilateral symposium involving National Tsing Hua University (NTHU) and Université Paris Saclay (UPSaclay) took place in the form of a virtual on-line conference, between Nov. 18-20, 2020. It was organized by NTHU and co-organized on the French side by C2N for UPSaclay.