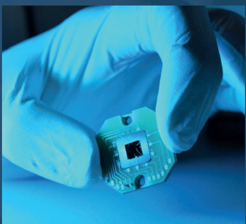
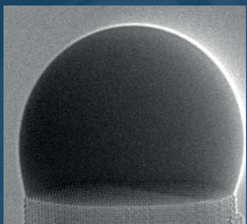
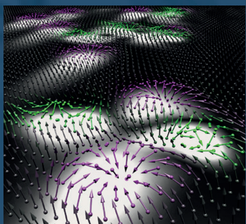
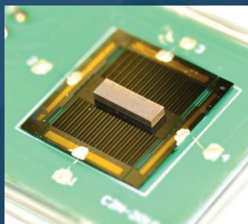
Highlights 2018

Centre de Nanosciences et de Nanotechnologies (C2N)

A joint research unit

Editorial

I am delighted to share with you some of the major scientific accomplishments of C2N in 2018, reported in this booklet. They cover the entire value chain from basic science research to its applications, one of the hallmarks of the C2N's identity, but also highlight the recognition by our peers with the presentation of awards to our researchers. Founded in June 2016, the *Centre de Nanosciences et de Nanotechnologies* and its nearly 400 members moved together in a new building at the hearth of Campus Paris-Saclay, in the fall 2018.

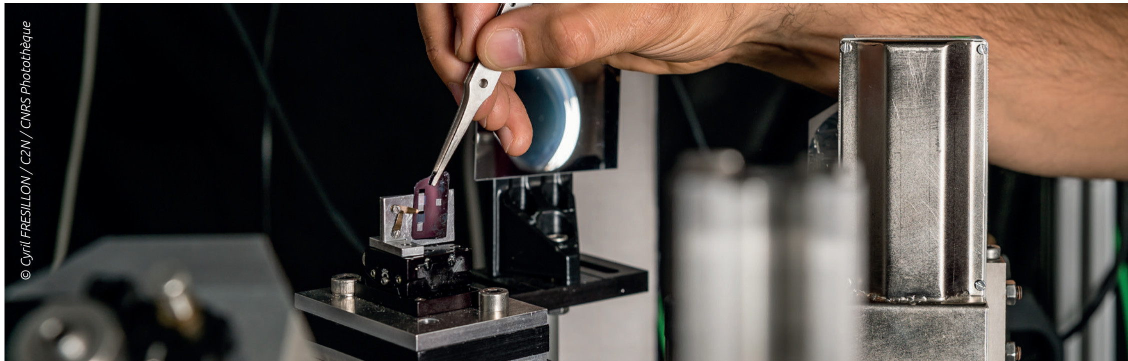
Among the research activity of the year, one of the European largest research department in the field of photonics published state-of-the-art works including non-linear photonics, silicon photonics, quantum photonics and nanophononics. The startup Quandela, hosted at the lab and developing the cutting-edge technology of single photon sources for applications in quantum technologies, marked a step in its development by being awarded with a *Grand Prix i-Lab* 2018. Bio-inspired nanoelectronics and quantum physics in circuits were the topics of the most selective publications of C2N in the nanoelectronics field. One of the ten world highlight of the year in physics was published by the C2N Materials Department according to the American Physical Society: the observation of the growth of a crystal in a TEM was a world premiere, recognized by the community worldwide. Researchs in Microsystems and Nanobiofluidics performed at C2N proved their ability for concrete applications with several patents registered and technologies highlighted in the newsletter «CNRS *La Lettre Innovation*».

The C2N hosts now the largest academic micro-nano-technology facility in France belonging to the national nanofabrication network *Renatech*, and, in this context, it is also part of the construction of the European network *EuroNanoLab*. The scientific excellence and the state-of-the-art tools are gathered for C2N to sit its position of flagship laboratory for research in nanoscience and nanotechnology in France, and in the world, open to academic and industrial partnerships with a particular attention to the Paris region stakeholders. I wish to express my profound gratitude to all the contributors to the present «Highlights 2018» and to give a special thanks to the C2N Communication team for their valuable contribution to this booklet.

Giancarlo Faini,
Head of C2N

Summary

Photonics



Centre de Nanosciences & de Nanotechnologies C2N

Date:
May 15, 2018

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INP CNRS News

Reference:
M. Marconi and al,
Physical Review X
(2018)

"Super-thermal" emission of photons by coupled nanolasers

Thanks to two coupled nanolasers, physicists were able to generate an out-of-equilibrium system emitting multi-photon bursts, known as "super-thermal" light. This approach is not restricted to lasers but it can be extended to other nanoscale systems.

Due to their small size, nanolasers have remarkable properties, including low power consumption and small footprint. They are the subject of intense research aiming at various applications, from telecommunications to quantum information. By coupling them in a compact way, it is possible to tailor the statistics of the emitted photons, producing in particular « extra noise » or « extra correlations », which is an asset for applications such as the non-linear energy conversion, the "ghost" imaging that is developed for astrophysics and the quantum information.

When the coupling between the nanolasers is weak, the emission of each laser can be well distinguished. But if the coupling is strong enough, the photons get distributed between the two hybrid modes, and become quite insensitive to perturbations. It is the energy exchange between these modes that is studied here, when the system is excited by light pulses shorter than the electronic characteristic times involved. Such excitation places the system out of equilibrium. One of these modes behaves as a « conventional laser » mode and it is subjected to small fluctuations, while the other one undergoes a particular noisy regime. It emits flashes of photons with a so-called "super-thermal" statistics: the photons are not emitted one by one or randomly –in the sense of Poisson– , but in the form of bursts where the quanta are concentrated in short times. This demonstration was made possible thanks to an original set-up enabling the measurement of the complete statistics of the emitted photons, in spite of the very short times in play. Researchers are now aiming to mold the statistics with very few photons, in the quantum regime.

This approach does not require the engineering of special emitters or the interaction between modes, as it has been implemented so far.

Such a “generic route”, obtained by driving the system far-from-equilibrium through a rapid variation of a parameter or « quench », can be transposed to many other systems. This is for instance the case of Brownian motion experiments applied to suspended pollen. In this analogy, the pollen grains and their potential energy can be mapped to photonic states. The system gets out of equilibrium due to a sudden drop in temperature. It can therefore be observed that grain distribution in the space/time also follows a "super-thermal" statistics.

The nascent study of out-of-equilibrium statistics in nanoscale, low photon number systems is particularly promising. This work, published in the journal Physical Review X by a team of physicists from the *Centre de Nanosciences et de Nanotechnologies* - C2N (CNRS / Université Paris-Sud) was produced in collaboration with the University of the Balearic Islands.

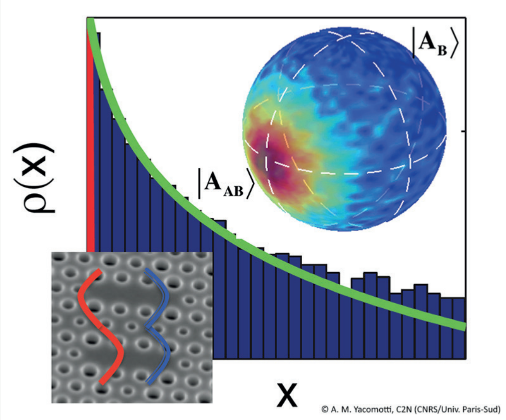

Figure: Simulated response of coupled nanolasers under excitation of a short pulse showing the distribution of the population difference between the modes and more generally the distribution of the optical field. © A. M. Yacomotti, C2N (CNRS/Univ. Paris-Sud)

Reference
Far-from-equilibrium route to superthermal light in bimodal nanolasers,
M. Marconi, J. Javaloyes, P. Hamel, F. Raineri, A. Levenson and A. M. Yacomotti
Physical Review X (2018), doi: doi.org/10.1103/PhysRevX.8.011013

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Centre de Nanosciences & de Nanotechnologies

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C2N News

Reference:
F. Tabataba-Vakili and al,
ACS Photonics
(July 2018)

The first blue microlaser integrated into a photonic circuit on silicon

A consortium of researchers has fabricated the first blue microlaser integrated into a photonic circuit. This device is a step towards demonstrating the viability of the III-nitride on silicon semiconductor photonic platform.

Nanophotonics utilizing the group III-nitride on silicon platform is an exciting new field that opens potential applications from the ultraviolet (UV) to the infrared (IR) spectral range. These applications could span innovative display, lighting and communication technologies, quantum information processing, and biocompatible applications. Despite abounding research and demonstration of elementary building blocks like single microlasers and passive photonic circuits, the monolithic coupling between an active source in the blue and a photonic circuit integrated on silicon was still to be demonstrated.

Within a consortium of researchers, Farsane Tabataba-Vakili, PhD Student at the *Centre de Nanosciences et de Nanotechnologies* - C2N (CNRS/Univ. Paris-Sud) and the *Institut Nanosciences et Cryogénie* – INAC (CEA/Univ. Grenoble Alpes), demonstrated the first blue microlaser integrated into a photonic circuit. The work was recently published in the ACS Photonics journal. Farsane received the Best Student Poster Award for the presentation of this work during the 34th International Conference on the Physics of Semiconductors (ICPS 2018) that took place in Montpellier from 29 July to 3 August 2018.

The monolithic device consists in an active microdisk of 3-5µm diameter side-coupled to a bus waveguide. Out-coupling gratings terminating the waveguide ensure the side extraction of the coherent light. The gap between the microdisk and the waveguide is a key design parameter that must be finely tuned for efficient light coupling. One of the challenges was to fabricate gaps smaller than 100 nm, which was achieved thanks to the group-III nitride technology developed in the C2N team. Under low-power continuous-wave excitation the researchers observe large loaded quality factors (Q factors) for these materials, of around 2000. Under pulsed optical pumping they observe lasing with a threshold of 15 mJ/cm² per pulse.

Electrical injection in these low footprint resonators is under development for integration purposes. Supported by an international research project*, of which Farsane is a very active member, the researchers now seek blue/UV lasing of electrically injected microdisks to provide highly efficient white light sources. Indeed, unlike white LEDs, laser based micro-emitters do not have a decreased efficiency at high injection, a well-known limiting phenomenon in LED technologies known as “droop”.

This work thus represents an important step towards showing the viability of the III-nitride on silicon photonic platform.

* ANR MilaGaN : collaboration between C2N (CNRS/UPSud), CRHEA (CNRS/ Univ. Côte d’Azur), INAC (CEA/Univ. Grenoble Alpes), L2C (CNRS/Univ. Montpellier), and the Hong Kong University (HKU). Funded by Agence Nationale de la Recherche (ANR-17-CE08-0043-02).

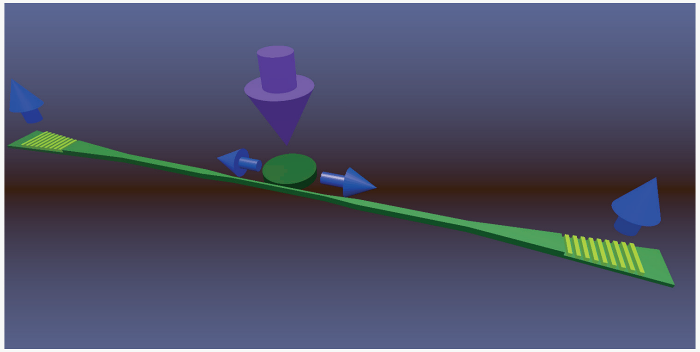

Figure: III-nitride microdisk laser photonic circuit consisting of a disk coupled to a bus waveguide terminated by out-coupling gratings. Copyright © 2018 American Chemical Society

Reference
Blue Microlasers Integrated on a Photonic Platform on Silicon,
F. Tabataba-Vakili, L. Doyennette, C. Brimont, T. Guillet, S. Rennesson, E. Frayssinet, B. Damilano, J.-Y. Duboz, F. Semond, I. Roland, M. El Kurdi, X. Checoury, S Sauvage, B. Gayral and P. Boucaud
ACS Photonics (July 2018), doi: 10.1021/acsphotonics.8b00542

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Centre de Nanosciences & de Nanotechnologies

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October 25, 2018

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INSIS CNRS News

Reference:
Q. Liu and al,
Optical Materials Express
8 (5), 1305 (2018)

Photonic integrated circuits for gas detection

Mid-infrared (mid-IR) spectroscopy is a nearly universal way to identify chemical and biological substances. Researchers from the *Centre de nanosciences et de nanotechnologies* and from *Politecnico di Milano* have developed photonic integrated circuits in the mid-infrared, based on silicon-germanium waveguides. These structures make it possible to achieve integrated sensors capable of detecting concentrations of a few hundred ppm. This work is published in *Optical Materials Express*.

In the spectral range of the mid-infrared, spectroscopy makes it possible to efficiently identify and quantify different chemical and biological substances. Its exploitation in various applications, especially mobile one, requires components compatible with this range of wavelengths. Researchers from the *Centre de nanosciences et de nanotechnologies* (C2N, CNRS / Université Paris-Sud) and from *Politecnico di Milano* are developing photonic integrated circuits in the mid-infrared, based on silicon-germanium waveguides (SiGe). They demonstrated for the first time the potential of these structures for integrated sensors.

SiGe alloys offer flexible control of the properties of the guide, while taking benefit from the wide transparency of germanium in the mid-infrared. The use of spiral guides increases the surface of interactions while keeping a compact device. The detection takes place with the evanescent part of the optical mode, the part of the wave that propagates along the outer surface of the guide. It thus comes into direct contact with the environment to be analysed. As a first proof of concept, the researchers were able to detect the specific absorption lines between 5.8 and 6.2 µm of a photoresist deposited on the SiGe guides. The results obtained showed that these components should allow the detection of methane at concentrations of a few hundred ppm[1], which is lower than the occupational exposure limit recommended by international environmental standards.

This work benefited from the ERC Starting Grant INSPIRE and the C2N platform belonging to the RENATECH² network.

Notes:

[1] ppm : parts per million, 1ppm = 1 mg/kg.

[2] RENATECH : French network of academic micro-nano fabrication clean-rooms.

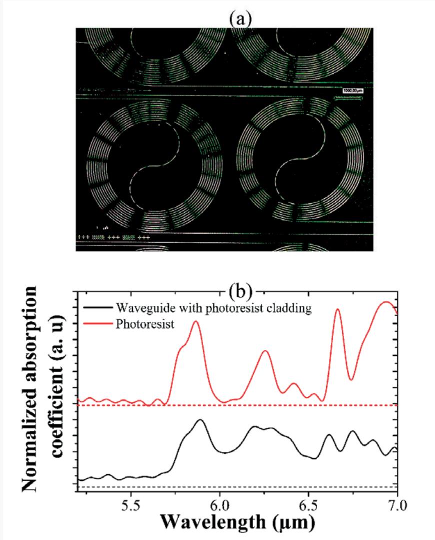

Figure:
(a): SiGe spiral waveguides.
(b): comparison between the losses of the waveguide covered by the photoresist and the absorption of the photoresist. The absorption peaks of the resin at 5.8 µm; 6.25 and 6.6 µm are clearly visible when measuring waveguide transmission.
© C2N – CNRS/UPSUD

Reference
Mid-infrared sensing between 5.2 and 6.6 µm wavelengths using Ge-rich SiGe waveguides,
Q. Liu, J. Manel Ramirez, V. Vakarin, X. Le Roux, A. Ballabio, J. Frigerio, D. Chrastina, G. Isella, D. Bouville, L. Vivien, C. Alonso Ramos, D. Marris-Morini
Optical Materials Express, 8 (5), 1305 (2018), doi: https://doi.org/10.1364/OME.8.001305

Centre de Nanosciences & de Nanotechnologies

Date:
December 14, 2018

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C2N News

Reference:
A. Elbaz and al,
ALP Photonics
(August 2018)

First laser effect observed in germanium direct bandgap

A collaboration of researchers from C2N and STMicroelectronics has obtained, for the first time, a laser effect with germanium as active material thanks to direct alignment of the electronic band diagram. Until now, this material was known to be unable to emit light.

Germanium (Ge) belongs to the same family as silicon and is a perfect match for CMOS chip fabrication processes, which are Si-based and low-cost technologies widely used in microelectronics, but also for photonics to achieve integrated optical functions. Nevertheless, the optical source is now the missing block in the development of complex photonic devices using the CMOS environment. So far, neither silicon nor germanium have been able to emit light because of a physical limiting factor: the indirect nature of their band structure.

Thanks to work on the properties of the electronic structure of the Ge, C2N researchers have been able to transform it into a direct bandgap material, allowing the emission of light. To do so, they applied strong tensile strain to the material. They were inspired by CMOS methods, namely the use of films stressor to strain transistor channels and enhance the carrier transport properties. In order to demonstrate a laser, they have revisited this method to strain resonant optical cavities, on much larger volumes than transistors channels. In collaboration with researchers from STMicroelectronics, they were able to obtain for the first time a laser effect with germanium as active material with a direct alignment of the electronic band diagram. Their work has been published in APL Photonics journal. The structure realized consists of microdisks of Ge fully wrapped by a silicon nitride stressor layer. This allowed to reach high level of tensile strain in Ge and to obtain the direct band gap regime. The strained Ge microdisk is sustained by an Aluminium pedestal, which is an excellent heat sink. Thanks to both strain and thermal, management in Ge microdisk cavities, the researchers were able to reach continuous wave laser emission regime under optical pumping.

Researchers at C2N are now working on alloying of Ge with tin, another element of column IV that is compatible with silicon technologies. This would allow to increase the directness of the band structure to boost the device performance and obtain laser effect up to room temperature. This would feed future developments in the field of silicon photonics, especially for the development of active sources.

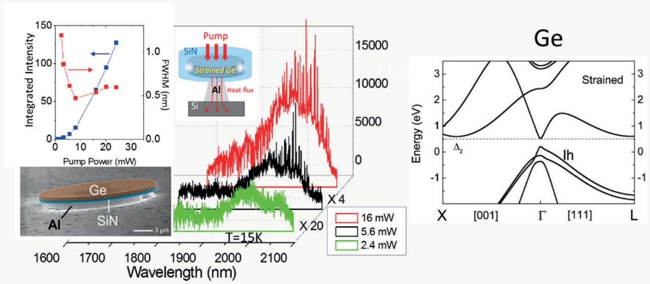

Figure: Left: CW Photoluminescence spectrum of a 12µm diameter strained Ge disk under various incident pump power, water vapor absorption lines modulate the emission below 1940 nm. Resonant mode contribution occurs after a given incident power threshold is reached. The inset gives the integrated intensity and width for a resonant whispering gallery mode as a function of incident power. SEM picture of a Ge disk with a SiN stressor layer at its bottom side and sustained by an Al pedestal. This picture was taken before a final SiN layer deposition. This final SiN deposition allows to realize the ''all around stressor'' structure as shown on the schematic view. Right: electronic band diagram of tensile strained Ge calculated in the framework of a 30-band k.p model. The tensile strain induces a direct alignment of the band structure for biaxial strain as large as 1.7% and above. © C2N/El Kurdi

Reference

Germanium microlasers on metallic pedestals,
A. Elbaz, M. El Kurdi, A. Aassime, S. Sauvage, X. Checoury, I. Sagnes, C. Baudot, F. Boeuf and P. Boucaud
APL Photonics (August 2018), doi: https://doi.org/10.1063/1.5025705

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CNRS *La Lettre Innovation*

Reference:
www.quandela.com

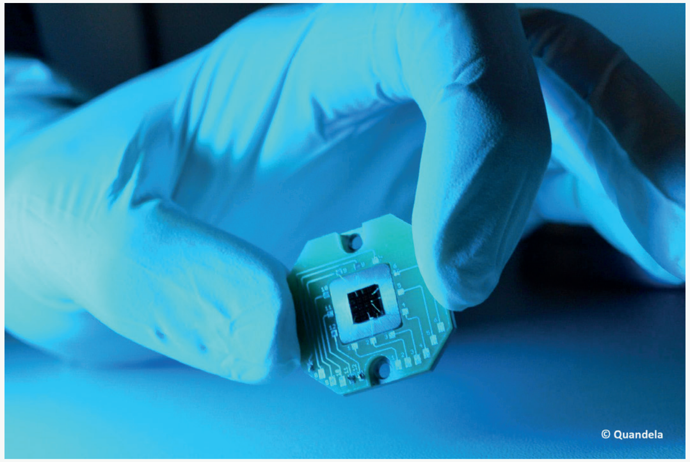
Quandela: ultrabright single photon sources

Based on a lithography technique developed at the *Centre de nanosciences et de nanotechnologies*, Quandela manufactures and delivers sources of light delivering a single photon at each pulse. Its products are of interest to academia and industry in the fields of quantum computation and cryptography, and more broadly for research in quantum physics.

For several years, researchers at the *Centre de nanosciences et de nanotechnologies* – C2N[1] have been developing a lithography technique that makes it possible to produce a quantum dot based emitter of single photons - a single photon per pulse. These sources of light, which operate at a cryogenic temperature, have the advantage of emitting single photons with very high efficiency and with identical characteristics, making them a tool of choice for researchers of quantum photonics in academia and industry. They are of interest for both the emerging field of quantum computers and the field of perfectly secure quantum telecommunications. The start-up Quandela, issued from the *Centre de nanosciences et de nanotechnologies*, was founded in June 2017 to provide sources of light for these applications and more broadly to develop the building blocks for quantum technologies.

A prematuration program, funded by the CNRS and Labex NanoSaclay, led to a robust and reproducible manufacturing process. The goal was also to work on the integration of the transmitter component on an optical fiber, which requires a precision of alignment to the tenth of a micron. These studies will create a next generation of "plug-and-play" sources: users will no longer need to mount a complex optical system to collect the emitted photons, which should help commercializing to a widespread these sources. "*Thanks to this program, the founders[2], researchers from the laboratory, were also able to follow HEC Challenge Plus classes to learn about entrepreneurship*" says Valerian Giesz, CEO of Quandela. The start-up registered its first order at the end of 2017, from a research laboratory abroad.

Quandela manufactures its components and continues its development by renting premises and using equipment from the Centre de nanosciences et de *nanotechnologies*. The company plans eventually to invest in its own equipment, in order to increase its production and development capacity. It plans to open its capital at the end of 2018.



[1] CNRS / Université Paris-Sud

[2] Valerian Giesz, CEO of Quandela; Pascale Senellart, Scientific Advisor (Senior CNRS researcher at C2N) and Niccolo Somaschi, CTO of Quandela.

Centre de Nanosciences & de Nanotechnologies

Date:
February 9, 2018

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C2N News

Reference:
E. A. Rojas Gonzalez and al,
Physical Review Letters
(January 2018)

Towards the optimized generation of continuous variables triple-photon states quantum entanglement

Physicists have discovered an unexpected theoretical track to optimize the non-linear generation of triple-photon quantum states. The conclusion: it is better to avoid a blindly taking inspiration from the analoguous and well-controlled process of double-photon quantum states generation.

The generation of entangled triple-photons by nonlinear optical interaction would be the most direct way of producing non-Gaussian quantum statistics, which are the key to many advanced quantum protocols. What could be more natural than to draw on the knowledge acquired over the past three decades on double-photons (or twin photons), which have enabled the most astonishing demonstrations of quantum optics, to optimize the triple-photons generation? However in the best experimental conditions, less than a triple-photon every three months could theoretically be emitted from a non-linear cristal by spontaneous emission. The third order non-linear coefficient generating the triple-photons is indeed several orders of magnitude lower than that of second order, generating the twins. Physicists from the Centre of Nanoscience and Nanotechnology – C2N (CNRS/Univ. Paris-Sud) and from Neel Institute (CNRS) have theoretically demonstrated the possibility of going beyond these limits by getting out from the analogy with the twin photons generation mechanism. Their results were published in the Physical Review Letters.

The equations controling the continuous variables triple-photon states quantum entanglement generation process do not have known analytical solution. Physicists have proceeded by a so-called perturbative method by considering up to the fifth order terms. They solved the resulting equations by numerical methods. They demonstrated that simultaneously with pumping, triggering the non-linear effect with seed photons at the same frequency as the emitted triple-photons is necessary to reach the triple-photons continuous variable entanglement. Researchers have also shown that entanglement increases when the seeding rate increases. A singular mechanism since in the case of twin photons generation, the quantum entanglement is destroyed by the injection.

The injection mechanism also makes it possible to increase by several orders of magnitude the efficiency of the third-order non-linear interaction. These theoretical results break down the barriers to an experimental realization on which the teams from C2N and Neel Institute began to work as part of a joint research project.

This work opens the way for a deep investigation of triple-photons quantum properties, as well as the development of advanced quantum protocols for cryptography.

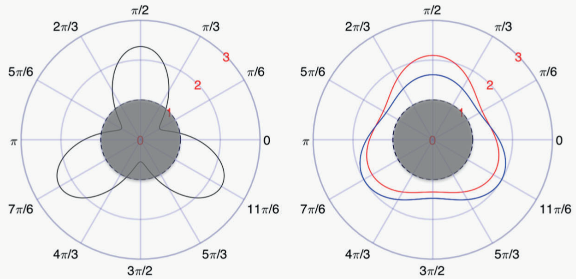

Figure: Gain (left) and variances (right) distribution of triple-photons quautum states showing the three lobes as a function of the phase. © C2N / K. Bencheikh

Reference
Continuous variables triple-photon states quantum entanglement,
E. A. Rojas Gonzalez, A. Borne, B. Boulanger, J. A. Levenson, and K. Bencheikh
Physical Review Letters (January 2018), doi: https://doi.org/10.1103/PhysRevLett.120.043601

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Centre de Nanosciences & de Nanotechnologies

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October 22, 2018

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CNRS *La Lettre Innovation*

Reference:
H. Bertin and al.,
ACS Photonics
(May 2018)

Adjust the reflectance of a glass while preserving its transparency quality

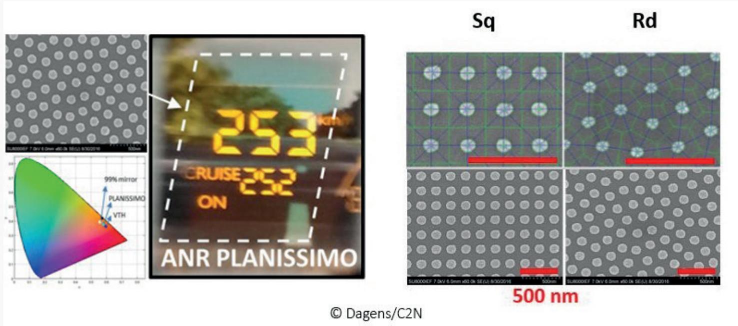
Researchers from the Centre for Nanoscience and Nanotechnology[1], the Institut Fresnel[2] and the PSA Group have designed an innovative glass support that can display virtual images even in unfavourable ambient lighting conditions while remaining transparent. It could lead to applications of augmented reality, especially in the automotive sector.

With an head-up system, the driver of a car no longer needs to look down to consult his dashboard or his GPS: the information is displayed directly in front of the windshield, without forcing to leave the eyes from the road and while preserving a clear vision through the glazing. To achieve this type of display, which also concerns aeronautics and other applications of "augmented reality", it requires a support that reflects the image that is projected while remaining perfectly transparent. The innovative process developed by researchers at the Centre for Nanoscience and Nanotechnology[1] and Institut Fresnel[2], in collaboration with the PSA Group, aims to improve the performance of an augmented reality display increasing its reflectance for a given wavelength, without impairing its transparency. In addition, it allows to see the data displayed regardless of the angle of incidence (the position of the head of the observer), and overcomes the problems of diffraction or light scattering that could impair vision in transparency.

To achieve augmented reality support, researchers have developed an original pathway[3]: the creation of nanostructures - silver nanoparticles of controlled dimensions - on the surface of a glass plate. These nanoparticles locally create a plasmonic resonance phenomenon[4], responsible for increasing the reflectance of the glass around the chosen wavelength. For the support to remain transparent, the particles must be sufficiently spaced. A periodic network has the disadvantage of generating diffraction, which affects the visual quality. The researchers opted for a "correlated disorder" arrangement, in which the distance between nearest particles is almost constant. "The correlated disorder arrangement makes it possible to overcome diffraction problems without creating diffusion, which is also detrimental to transparency vision," said Béatrice Dagens, CNRS Senior Research at the Centre for Nanoscience and Nanotechnology.

Tests have validated these performances on a display surface of approximately 1 cm² and the technology will soon be validated for larger areas, in particular using nano-printing techniques.

The Centre for Nanoscience and Nanotechnology and the PSA Group have also decided to expand their collaboration by creating a joint research laboratory in the field of optoelectronics and photonics. Several teams from the Centre for Nanoscience and Nanotechnology will participate in this "OpenLab", called PhOVeA, for Photonics and Optoelectronics for Vehicles and Automotives.



© Dagens/C2N

[1] CNRS / University Paris-Sud

[2] CNRS / Aix-Marseille University / Central School Marseille

[3] *Correlated Disordered Plasmonic Nanostructures Arrays for Augmented Reality*, Hervé Bertin, Yoann Brûlé, Giovanni Magno, Thomas Lopez, Philippe Gogol, Laetitia Pradere,Boris Gralak, David Barat, Guillaume Demésy, and Beatrice Dagens. *ACS Photonics*, May 2018, DOI: 10.1021/acsphotonics.8b00168

[4] The phenomenon of plasmonic resonance results from the interaction between an electromagnetic wave and conduction electrons on the surface of a metal. Here, the interaction between the incident wave and the silver nanoparticles, for a precise wavelength, creates an oscillation coupled with the electrons (a "plasmon"). The nanoparticle then behaves like an antenna that re-emits light: the reflection of the incident light is increased.

Centre de Nanosciences & de Nanotechnologies

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April 23, 2018

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C2N News

Reference:
M. Esmann and al,
Physical Review B
(2018)

Topological acoustics at the nanoscale

Nanometric semiconductor structures have been used to confine ultrahigh frequency sound by exploiting their topological properties.

The 2016 Nobel Prize in Physics was awarded to the field of topological matter. A key result was the demonstration that topology can be used to predict the behavior of solids. An example is the trapping of electrons at the interface between two topologically different crystalline insulators. Recently, similar phenomena have been observed in optics and macroscopic acoustics.

Researchers from the *Centre de Nanosciences et de Nanotechnologies* – C2N (CNRS/Université Paris-Sud) and the laboratory Matériaux et Phénomènes Quantiques – MPQ (CNRS/Université Paris Diderot) present a completely new platform to study confinement properties predicted by topology at the nanoscale. Their work is published in the journal Physical Review B.

For the first time, the researchers experimentally demonstrated the topological trapping of sound at the nanoscale. Acoustic phonons with frequencies around 350 GHz are trapped in semiconductor multilayer stacks of a few nanometers thickness. The structures are formed by concatenated phononic crystals with different topological phases, i.e. their acoustic bands are inverted. They show by Raman scattering experiments that acoustic phonons are topologically confined at their interface.

The reported robust topological interface states could become a key element in engineering nanophononic resonators for sensors and phonon lasers. Other potential applications are resonators in optomechanics, in nanoscale thermal transport and for the control of decoherence in solid state systems.

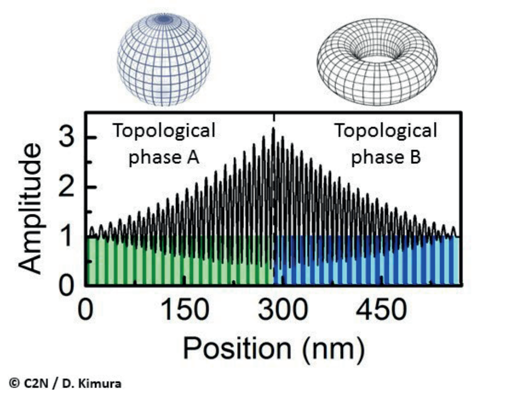

Figure: Spatial displacement pattern |u(z)| of the topological interface phonon at 350GHz (black) together with a sketch of the semiconductor multilayer structure. The mode envelope shows a maximum at the interface between the two topologically different structures and decays evanescently into both directions away from the interface. Green and blue color schemes denote spatial regions with different topological phase. © C2N / D. Kimura

Reference

Topological nanophononic states by band inversion,,
M. Esmann, F. R. Lamberti, P. Senellart, I. Favero, O. Krebs, L. Lanco, C. Gomez Carbonell, A. Lemaître, and N. D. Lanzillotti-Kimura
Physical Review B (2018), doi: doi.org/10.1103/PhysRevB.97.155422

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Centre de Nanosciences & de Nanotechnologies

C2N

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C2N News

Reference:
M. Esmann and al,
Physical Review B
98, 161109 – Rapid Communications
(October 2018)

Taming sound at the nanoscale

Physicists have proposed a new way to control the propagation of sound at the nanoscale. They put in evidence new ways of trapping sound at the interface between two chains of nano-resonators.

Topology offers new degrees of freedom to control fundamental excitations in periodic systems, based on geometrical properties. The Su-Schrieffer-Heeger (SSH) model is likely the simplest one-dimensional concept to study nontrivial topological phases and topological excitations.

Researchers from the *Centre de Nanosciences et de Nanotechnologies* – C2N (CNRS / University Paris Sud), have proposed a new way to control the propagation of mechanical vibrations at the nanoscale. They have developed a simple scheme to confine sound in the 100 GHz range, based on the use of topological invariants. By attaching individual acoustic nanoresonators, and designing how they exchange energy, this work puts in evidence new ways of trapping sound at the interface between two chains of resonators. Their work has been published in *Physical Review B – Rapid Comm.*

By coupling semiconductor acoustic nanocavity arrays, they propose an implementation of the Su-Schrieffer-Heeger (SSH) model enabling to design acoustic edge and interface states that are robust against fabrication defects. This topological phenomenon is not unique to sound but shared with other wave phenomena such as light and electronic wavefunctions. In electronic systems, the experimental studies of topological properties rely on naturally existing materials and structures. In nanophononics, the building blocks are artificially created, and thus a bigger parameter space can be explored. While the access to the details of the dynamics of these confined modes is challenging for light and electrons, a simple way of probing the spatial complex wavefunction in acoustic nanocavity arrays is also proposed based on ultrafast optical measurements. Briefly, a new acoustic confinement phenomenon has been proposed, which can provide insight into the dynamics of other topological solid state systems.

Finally, the proposed opto-acoustic experiments could even open the door to novel ways of controlling other excitations in the solid state, such as excitons or spin waves by topologically confined vibrations.

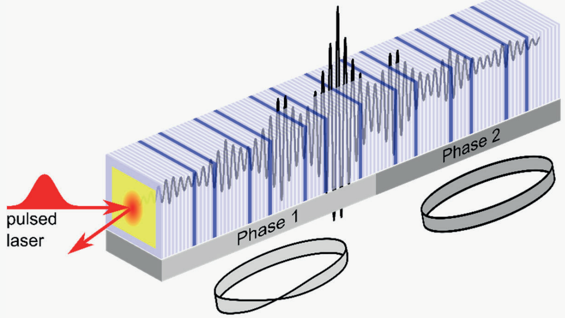

Figure: Schematic representation of two arrays of nanoresonators confining a topological mode at the interface. By means of ultrafast laser pulses these modes can be excited and detected. Copyright Esmann/C2N

Reference
Topological acoustics in coupled nanocavity arrays,
M. Esmann, F. R. Lamberti, A. Lemaître, and N. D. Lanzillotti-Kimura
Phys. Rev. B 98, 161109 – Rapid Communications (Octobre 2018), doi: https://doi.org/10.1103/PhysRevB.98.161109

Nanoelectronics

Centre DE Nanosciences & DE Nanotechnologies

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CNRS Press Release

Reference:
A. Mizraahi and al.,
Nature Communications
(April 2018)

Taking a step towards intelligent miniature chips

Researchers from the Unité Mixte de Physique CNRS/Thales and the Centre de Nanosciences et de Nanotechnologies - C2N (CNRS/Université Paris-Sud), in collaboration with Japanese scientists, have developed a new type of sensory nano-neuron. This time[1] it uses the properties of superparamagnetism[2] to better mimic the properties of the sensory parts of the nervous system. The researchers used neuron assemblies for inspiration. Those can propagate learning to a larger population when they are taught to do something. Once functions are implemented, the nano-neurons can, for example, decode them and if need be reproduce cursive letters. This innovation in the domain of nanotechnologies draws inspiration from neuroscience by imitating strategies used by the visual and motor cortices. Eventually, the researchers plan to assemble, in collaboration with other laboratories, several types of nano-neurons and nano-synapses to create a single neuromorphic network, a future artificial nervous system that would involve the team developing ever more complex networks uniting sensory functions (sight, touch, etc.) and use less energy than current computers.

This article was published on April 18, 2018 in *Nature Communications*.

[1] Press release "Le premier nano-neurone capable de reconnaissance vocale voit le jour" - September 19, 2017

[2] Nano-magnets which, because they are so small, exhibit an unstable, random nature

Reference
« Neural-like computing with populations of superparamagnetic basis functions »
Alice Mizraahi, Tifenn Hirtzlin, Akio Fukushima, Hitoshi Kubota, Shinji Yuasa, Julie Grollier, Damien Querlioz

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C2N News

Reference:
M. Romera and al, *Nature* (2018)

Coupled nano-oscillators capable of recognizing vowels according to a learning rule

Physicists have succeeded in fabricating a network of four coupled nano-oscillators capable of recognizing spoken vowels by tuning their frequencies according to an automatic rule of real-time learning. They show that high experimental recognition rates are a result of the exceptional ability of the oscillators to synchronize.

In contrast with the flagship algorithms used in artificial intelligence that lie in artificial neural networks, physicists work on physical components inspired by biological neurons. Each of these nanoscale components plays the role of a nano-neuron capable of solving complex problems, using the synchronization phenomena of its magnetic oscillations.

The component[1] studied by researchers from the U*nité Mixte de Physique CNRS/Thales*, the *Centre de Nanosciences et de Nanotechnologies* – C2N (CNRS/UPSud) and the AIST in Japan is composed of magnetic and non-magnetic layers at the nanoscale. A year ago, a study by the same authors showed that a single of these components could behave like an artificial neuron and detect spoken numbers with a high recognition rate (state-of-the-art). The single component realized the neural network all by itself by successively performing the work of each neuron.

Dynamic couplings between several components could be used to play the role of synaptic communication between neurons. However, a major challenge for implementing these models with nano-devices is to achieve learning, which requires finely controlling and tuning the coupled oscillation of the components. The dynamic characteristics of nanodevices can indeed be difficult to control, and subject to noise and variability. It is this challenge of fine adjustment of oscillations that has been taken up in these new works. The researchers show that the exceptional tunability of spintronic nano-oscillators, that is to say the ability to control their frequency widely and precisely through the electric current and the magnetic field, can solve this problem. They successfully form a hardware network of four spin-spin nano-oscillators to recognize spoken vowels by tuning their frequencies according to an automatic real-time learning rule. They show that high experimental recognition rates are a result of the oscillators' exceptional ability to synchronize. Their work is published in *Nature*.

The four neurons are experimentally implemented with four nano-spin-transfer oscillators; magnetic circular tunnel junctions of 375 nm of diameter and a free layer of Iron Boron with a vortex as a ground state. Symmetrical neural interconnections are implemented by electrically connecting the four oscillators using millimeter wires: in this configuration, the microwave current generated by each oscillator propagates in the microwave electric loop and in turn influences the dynamics - in

particular the frequency – of other oscillators. The oscillators are thus coupled. The sum of all microwave emissions is detected by a spectrum analyzer. With this network of neurons, the researchers recognized vowels pronounced by different people. The audio signals of each vowel are transformed by Fourier analysis into two frequencies, accelerated a hundred thousand times and then applied by an antenna to nano-oscillators in the form of microwave signals of high amplitude, which can synchronize the oscillators. The vowels are correctly recognized and classified if each vowel leads to a specific synchronization configuration whatever the person who pronounces it: for example for the vowel "ih" a single oscillator is synchronized, for the vowel "ah", two oscillators are synchronized. This behavior is not innate: the network must be trained to achieve it. To do so, the researchers gradually modified the frequency of each oscillator by adjusting the DC current flowing in each according to a learning law.Their approach opens the path to in-depth investigations of various facets of correlated physics, and sheds a new light on the modified transport properties of quantum components when embedded into a circuit. It also constitutes a landmark toward quantum simulation in the strongest sense, by elucidating interaction regimes which resist theoretical solutions.

These results demonstrate that classification tasks of non-trivial forms can be performed with small physical neural networks by giving them nonlinear dynamic characteristics: here, oscillations and synchronization. This demonstration of real-time learning with a set of four nano-oscillators with spin transfer torque is an important step for neuromorphic computing based on spintronics. The research perspectives will consist in coupling a larger number of components together.

[1] same component as in their previous work (Torrejon et al., Nature, 2017)

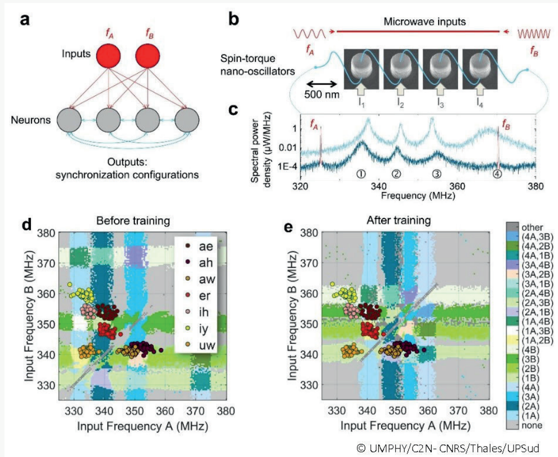

Figure: Approach for pattern classification with coupled spin-torque nano-oscillators. (a) Schematic of the emulated neural network. (b) Schematic of the experimental set-up with four spin torque nano-oscillators electrically connected in series and coupled through their own emitted microwave currents. Two microwave signals encoding information in their frequencies fA and fB are applied as inputs to the system through a strip line, which translates into two microwave fields. The total microwave output of the oscillator network is recorded with a spectrum analyzer. (c) Microwave output emitted by the network of four oscillators without (light blue) and with (dark blue) the two microwave signals applied to the system. The two curves have been shifted vertically for clarity. The four peaks in the light blue curve correspond to the emissions of the four oscillators. The two red narrow peaks in the dark blue curve correspond to the external microwave signals with frequencies fA and fB. (d-e) Learning to classify patterns by tuning the frequencies of oscillators. Experimental synchronization map as a function of the frequencies of the external signals (d) before training (e) after training. The colored dots represent the inputs applied to the oscillatory network: vowels pronounced by different speakers. Different vowels are in different colors. / Copyright UMPHY/C2N - CNRS/Thales/UPSud

Reference

Vowel recognition with four coupled spin-torque nano-oscillators,
M. Romera, P. Talatchian, S. Tsunegi, F. Abreu Araujo, V. Cros, P. Bortolotti, J. Trastoy, K. Yakushiji, A. Fukushima, H. Kubota, S. Yuasa, M. Ernoult, D. Vodenicarevic, T. Hirtzlin, N. Locatelli, D. Querlioz and J. Grollier
Nature (2018), doi: 10.1038/s41586-018-0632-y

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C2N News

Reference:
Y. Zhang and al,
Advanced Electronic Materials
(2018)

A new memory resistive device developed with magnetic nanopillars surrounded by resistive silicon switches

Magnetic nanopillars surrounded by resistive silicon filaments have been used to develop a novel memristive memory.

Emerging non-volatile memories (NVMs) combined with novel computing architectures have recently been considered as the most promising solution to overcome the "memory wall" of von Neumann computing systems. For instance, in-memory computing architectures based on closely integrating fast NVMs with logic functions have been proposed to minimize the power consumption and pave the way toward normally-off/instant-on computing. Along this direction, two of the most promising NVMs, i.e., magnetic random access memory (MRAM) and resistive random access memory RRAM have attracted increasing interest, but each of them still shows a few shortcomings.

A collaboration between the *Centre de Nanosciences et de Nanotechnologies* – C2N (CNRS/Université Paris-Sud) and Beihang University in China demonstrates a novel memory resistive ("memristive") device combining the advantages of MRAM and RRAM in a single element. It is based on a magnetic tunnel junction nanopillar surrounded by resistive silicon filaments. It features spin transfer torque fast switching for computation together with multilevel resistive switching for non-volatile memory. Their work is published in the magazine Advanced Electronic Materials and is used as a cover of the March 2018 issue.

This work provides new functionalities that are inaccessible to conventional NVMs, e.g., for in-memory computing and neuromorphic computing as non-von Neumann computing architectures.

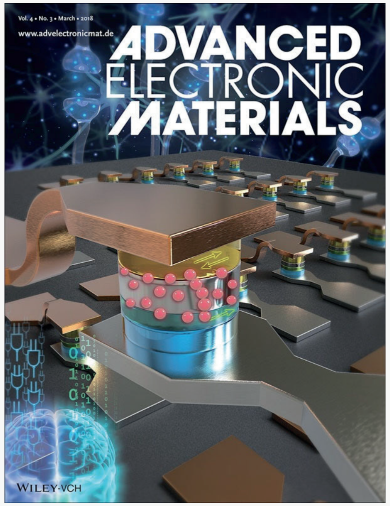

Figure: This works was published in Advanced Electronic Materials (volume 4, issue 3, March 2018) and was chosen as cover picture.

Reference

Memristors: Heterogeneous Memristive Devices Enabled by Magnetic Tunnel Junction Nanopillars Surrounded by Resistive Silicon Switches,
Y. Zhang, X. Lin, J.-P. Adam, G. Agnus, W. Kang, W. Cai, J.-R. Coudevylle, N. Isac, J. Yang, H. Yang, K. Cao, H. Cui Deming Zhang, Y. Zhang, C. Zhao, W. Zhao, D. Ravelosona
Advanced Electronic Materials (2018), doi: https://doi.org/10.1002/aelm.201870014

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Centre de Nanosciences & de Nanotechnologies

C2N

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C2N News

Reference:
X. Zhang and al,
Physical Review Applied
(2018)

Studying thin magnetic layers using an analogy with the physics of soap bubbles

Physicists have studied thin films of magnetic material and applied concepts of the physics of soap bubbles. With this approach, which had been barely used so far, they were able to explain new phenomena.

There is a very interesting analogy between the physics of magnetic thin films and those of soap bubbles: in both cases, it is possible to think in terms of interfaces, in terms of energy associated with the surface area of these interfaces, and in terms of difference of pressure on both sides of an interface. In thin film physics, the soap film is replaced by the magnetic domain wall, which separates two areas in which the magnetization is uniform. The pressure of the gas contained in the soap bubbles is replaced by the action of the applied magnetic field (B), which creates a difference of pressure (with a value equal to 2MB, where M is the magnetization density). These basic concepts were used by the soap bubble specialists and allowed the researchers to explain in a simple way many properties observed so far. In the case of magnetic thin films, despite its strengths, this approach had been barely used so far.

Researchers from the *Centre de Nanosciences et de Nanotechnologies* - C2N (CNRS / Paris-Sud University), in collaboration with Beihang University in China and the Spintec laboratory (CEA/CNRS/Univ Grenoble Alpes), have observed phenomena similar to those known for soap bubbles in ultra-soft films of CoFeB, and they could demonstrate the soap bubble analogy. To begin, they found that magnetic domains of semicircular shape were not stable without a field. This first effect is explained by the Laplace pressure induced by the curvature of the domain wall, which tends to reduce the radius of the semicircular domain it delimits. By determining the external field that must be applied to stabilize the domain, they were able to determine the interfacial tension energy associated with the domain wall. They were also able to observe the repulsion between two domains almost in contact: in a way totally analogous to the classical experience of soap bubbles in contact, where the big bubble "eats" the little one, the big domain crushes the little one. Their work was published in the journal Physical Review Applied.

With the approach adopted here they could also explain a very common magnetic domain wall pinning phenomenon, which occurs at an abrupt widening of the nanowire section. This trapping is explained by the interfacial tension force applied at the enlargement, which tends to hold the wall and must be overcome. The measurement of the field required to depin appears as a second method to directly measure the interfacial wall energy. This energy is a very important parameter, but remains to access because the potential experiments to measure it are likely to be distorted by formidable artifacts, which means artificial signals related to the experimental method which cause an error of analysis. The current experiments offer at last a reliable measurement method, with a simple and intuitive understanding of the phenomena.

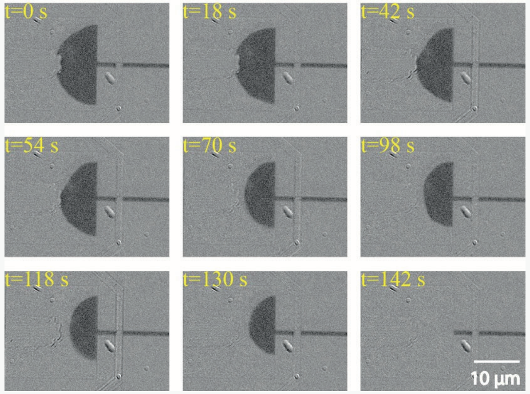

Figure: Kerr images (dark parts correspond to the reversed magnetization area) showing the spontaneous collapse of the half bubble after its creation using a pulse of magnetic field applied at time t=0. The time of acquiring for each picture is given at the top left of each picture. After the field pulse, during all this process, the magnetic field was zero. From X. Zhang - C2N (CNRS/Univ. Paris-Sud)

Reference
Direct Observation of Domain-Wall Surface Tension by Deflating or Inflating a Magnetic Bubble,
X. Zhang, N. Vernier, W. Zhao, H. Yu, L. Vila, Y. Zhang and D. Ravelosona
Physical Review Applied (2018), doi: 10.1103/PhysRevApplied.9.024032

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INP CNRS News

Reference:
Z. Iftikhar and al,
Science (2018)

Beyond a material's limit of conductance by controlling the interactions between electrons

Physicists have observed that the conductance of an electrical current can go beyond its theoretical quantum limit, by exploiting the correlations developing in the vicinity of a quantum phase transition.

How high can the electrical conductance be? In contrast to resistance, this quantity measures the ease with which current flows. In fundamental physics, conductance is a very important characterization tool. In electronic chips, increasing the conductance of interconnects would reduce heating that limits performance.

The standard theory of quantum transport, however, predicts an upper limit for conductance, even in the absence of defects. This limitation reflects the fact that electrons crossing a narrow conductor must pass one after the other, each with a minimal extension imposed by quantum mechanics. However, when the interactions are very strong, the electrons can no longer be considered separately. They are then in an intermediate state, between free electrons and superconductivity. The limit can then be exceeded by a collective effect between the electrons, similar to that of a viscous behavior of an electronic fluid. This phenomenon has just been observed in graphene at the University of Manchester.

Researchers have now also observed it in a quantum circuit where the magnitude of the overshoot of the standard conductance limit, as well as the temperature range where it occurs, can be controlled in situ. To do this, physicists at the *Centre de nanosciences et de nanotechnologies* - C2N (CNRS / UPSud / Univ Paris Diderot), in collaboration with theoreticians at the University College Dublin, University of Paris-Sud and University of Paris Diderot, are exploiting the electronic correlations that develop in the vicinity of a quantum phase transition, and which occur at a few thousandths of degrees above absolute zero.

At the heart of the quantum circuit is a metal island tuned so that the increase of its charge by an electron does not change its energy. This is fundamental, because then the system will not be frozen in one of these two states (with or without an additional electron charge), even at the lowest temperatures. In the contrary case, the system would freeze in the state of lower energy and one would lose this degree of freedom of a charge addition. However, it is the coupling of this charge with the electrons entering and leaving the island by three small individually adjustable contacts that generates strong correlations between these electrons, and which leads to the appearance of a quantum phase transition. The very existence and magnitude of the overshoot of the standard conductance limit is then controlled by the degree of symmetry between the different contacts.

This work published in the journal Science opens a research path for low-power electronics. The implemented device has no applications but is a model study system. More generally, this work is part of the exploration of a wide variety of unconventional phenomena associated with quantum phase transitions.

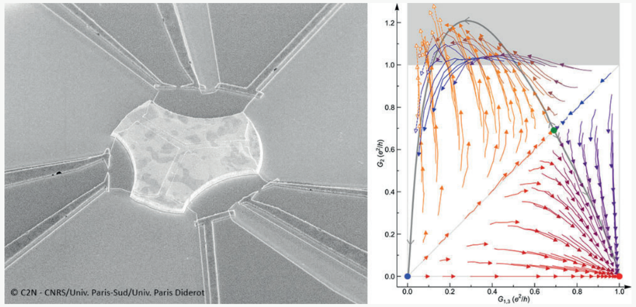

Figure: Evolution of the conductances of 3 quantum contacts connected in parallel to a small metal island as a function of the temperature. Each colored arrow represents the variation of the conductance G2 of one of the contacts as a function of the conductance of the other two contacts (set such as G1=G3) when the temperature varies from 55 mK to 8 mK for different initial configurations. The conductance G2 exceeds the quantum limit e2/h (e is the charge of the electron and h the Planck constant) in the gray zone due to strong electronic correlations. The gray lines represent the theoretical predictions (NRG) for a very small asymmetry. ©C2N, CNRS/UPSud/Univ. Paris Diderot

Reference
Tunable quantum criticality and super-ballistic transport in a "charge" Kondo circuit
Z. Iftikhar, A. Anthore, A. K. Mitchell, F. D. Parmentier, U. Gennser, A. Ouerghi, A. Cavanna, C. Mora, P. Simon, F. Pierre
Science (2018), doi:10.1126/science.aan5592

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C2N News

Reference:
A. Anthore and al,
Physical Review X
(September 2018)

Quantum simulation of one-dimensional systems with a solid-state circuit

Researchers have implemented an electronic circuit that can simulate the many-body physics expected to take place in one-dimensional (1D) quantum systems, constituted of either bosonic or fermionic particles with repulsive interactions. The presence of a single impurity induces in 1D conductors a transition toward an insulating state, revealing of the underlying correlations. By simulating this transition, the researchers were able to test previously inaccessible aspects of fundamental theory for 1D quantum systems.

Strong many-body correlations give rise to intriguing states of matter and unconventional behaviors of immense potential. Quantum phase transitions at zero temperature are believed to underpin many such phenomena, yet the complexity of real-world strongly-correlated materials and the theoretical challenge posed even by simplified models impedes a microscopic understanding. The realization of simple, well-characterized systems for studying the strongly-correlated and quantum critical physics is therefore highly desirable. In one-dimensional systems, the enhanced interactions give rise to paradigmatic phases of strongly-correlated matter described by the 'Tomonaga-Luttinger liquid' concept. However, the metal-insulator quantum phase transition induced by even a single impurity impedes experimental exploration. Furthermore, this hallmark signature still eludes a full theoretical treatment.

A team of researchers from the *Centre de Nanosciences et de Nanotechnologies* - C2N (CNRS/Université Paris-Sud – Université Paris Diderot) and the laboratory *Matériaux et Phénomènes Quantiques* – MPQ (CNRS/Université Paris Diderot) have deeply investigated the collective physics at one dimension and the resulting metal-insulator quantum phase transition by means of quantum simulation with a nano-engineered circuit. Their work was published in Physical Review X, and was featured by a ViewPoint* published on the American Physical Society website "Physics".

Their measurements reveal the universal scaling flows to an insulating state, establish a quantitative relation with the circuit parameters, and explore the out-of-equilibrium regime.

With the quantum simulator benchmarked by the precise agreement with untested and novel predictions, they then achieved quantum simulation in its strongest sense by elucidating theoretically unsolved regimes. Quantum simulation can provide a powerful workaround, as shown with this quantum circuit implementing a Tomonaga-Luttinger liquid analog with adjustable electronic interactions and a fully tunable scattering impurity.

Their approach opens the path to in-depth investigations of various facets of correlated physics, and sheds a new light on the modified transport properties of quantum components when embedded into a circuit. It also constitutes a landmark toward quantum simulation in the strongest sense, by elucidating interaction regimes which resist theoretical solutions.

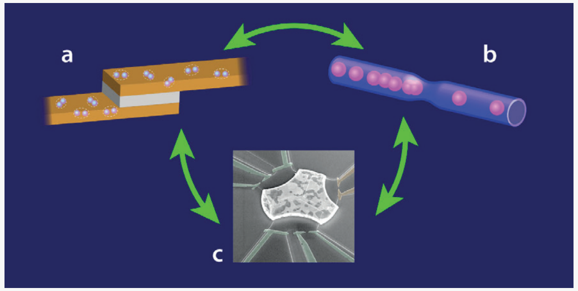

Figure : Three physical systems can exhibit the same insulator-to-metal quantum phase transition thought to occur in a 1D system of quantum particles, known as a Tomonaga-Luttinger liquid (TLL). The systems are: Two superconductors separated by a thin resistive layer (top left); a 1D array of electrons in the presence of an impurity (top right); and a micrometer-sized electronic device made of nanochannels connected to a central quantum dot (bottom). Here, researchers have used the latter as a quantum simulator, which allows them to investigate features of the TLL phase transition that can't be studied in the other two systems. (APS/Alan Stonebraker)

Reference

Circuit Quantum Simulation of a Tomonaga-Luttinger Liquid with an Impurity,
A. Anthore, Z. Iftikhar, E. Boulat, F. D. Parmentier, A. Cavanna, A. Ouerghi, U. Gennser and F. Pierre
Physical Review X, 8, 031075 (September 2018), doi: https://doi.org/10.1103/PhysRevX.8.031075

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INSIS CNRS News

Reference:
U. Ritzmann and al,
Nature Electronics
(2018)

Antiskyrmions: New horizons for information technologies

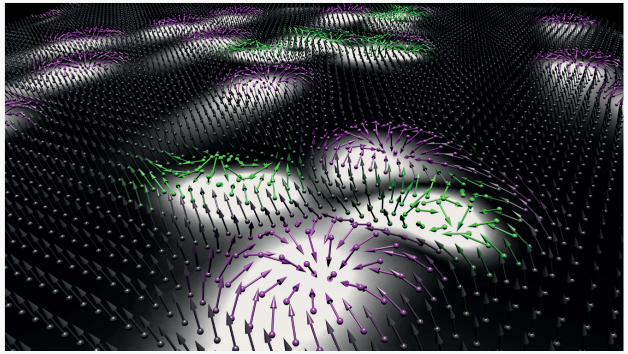
Researchers from the Centre for Nanoscience and Nanotechnology (C2N) and their European colleagues have brought to light some surprising behaviour of nanoscale magnetic particles called skyrmions, and antiskyrmions, their antiparticle counterpart, in a ferromagnetic material. These results, published in the journal Nature Electronics, offer new avenues for information technologies.

Skyrmions are nanoscale magnetic particles that represent an excitation in magnetic materials[1] and are promising candidates for future information storage and processing devices. Theoretically, skyrmions and their antiparticle counterpart, antiskyrmions, possess a property called "topological charge" which governs their dynamics. When skyrmions and antiskyrmions are subjected to a force, one charge gets deflected to the right, for example, while the opposite charge is deflected to the left. This simple picture remains to be tested, which motivated a theoretical study involving scientists from the Centre of Nanoscience and Nanotechnology (C2N, CNRS/Université Paris-Sud). They modelled the behaviour of such particles in a ferromagnetic ultrathin film under the influence of applied electrical currents.

While the simple picture is confirmed at low currents, the scientists showed that departures from the expected behaviour appear when progressively larger amounts of energy are transferred to the antiskyrmions. For the antiskyrmions, deviations from the usual rectilinear motion in the form of curved trajectories first occur as transients, then continuously[2] as the current is progressively increased, while skyrmions undergo rectilinear motion for all values of the applied current. These results show that opposite topological charges can behave very differently. Another discovery involves higher energies, where antiskyrmions generate skyrmion-antiskyrmion pairs periodically. The skyrmions created propagate away readily, while their antiparticle counterparts remain closer to the point of generation and subsequently become new sources of pairs. An excess in skyrmions is often found, indicating an imbalance between topological matter and antimatter in these magnetic films. This work might therefore provide hints for solving another mystery on a cosmological scale, namely, why there exists more matter than antimatter in the universe.

[1] For example, in nanoscale magnetic films that form the basis of hard disk drives and magnetic memories such as "STT-RAM".

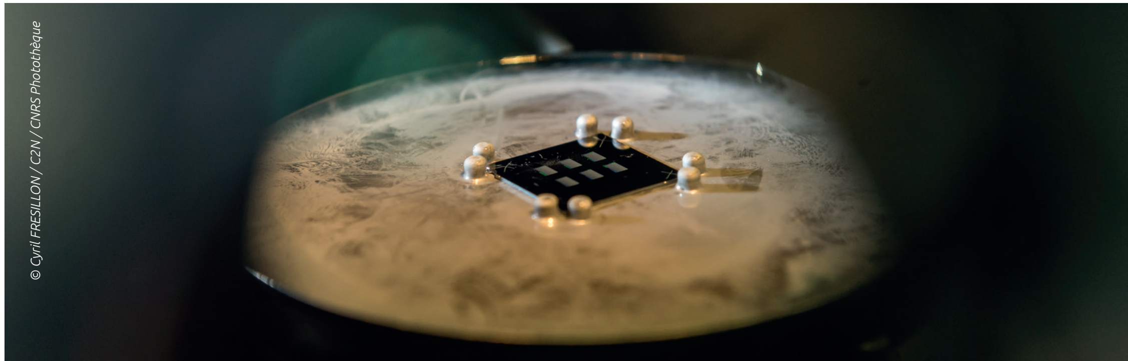
[2] In this case the trajectories are described by trochoids, which are like curves traced out by the pedal of a bicycle that is pedalled along a straight line.



Caption: Matter and antimatter in the nanoscale magnetic universe: A gas of skyrmions (purple) and antiskyrmions (green) generated from the trochoidal dynamics of a single antiskyrmion seed. [https://doi.org/10.6084/m9.figshare.6977366.v1] © C2N

Reference
Trochoidal motion and pair generation in skyrmion and antiskyrmion dynamics under spin–orbit torques,
U. Ritzmann, S. von Malottki, J.-V. Kim, S. Heinze, J. Sinova, B. Dupé
Nature Electronics, vol. 1, 451-457 (2018), doi: https://doi.org/10.1038/s41928-018-0114-0

Materials



Centre de Nanosciences & de Nanotechnologies

Date:
October 30, 2018

Contact:
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INP CNRS News

Reference:
J.-C. Harmand and al,
Physical Review Letters
(2018)

Observing the growth of crystals in a transmission electron microscope

A unique instrument has been developed to grow nanocrystals by molecular beam epitaxy in a transmission electron microscope. The crystal formation is observed in situ and in real time with the atomic resolution.

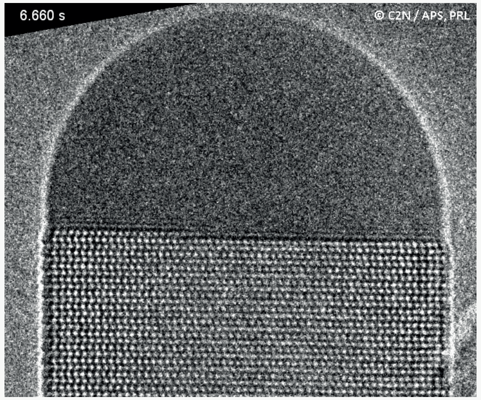
Nanotechnology uses nano-sized crystalline materials that can be fabricated by different techniques. Understanding and controlling the formation of these nanocrystals represents a major challenge to master their properties and thus achieve a given functionality. To probe and to study their morphology, crystalline structure or chemical composition, transmission electron microscopy (TEM) is a technique of choice. Indeed, the TEM analyzes can be conducted at the atomic scale. In the recent years, an impressive improvement of their spatial resolution has been achieved, enabled by the development of aberration correctors.

Molecular beam epitaxy (MBE) is known as an ultimately precise technique for growing thin films or nanostructures of semiconductors or metals. This technique has never been implemented before in an operational transmission electron microscope. This instrumental challenge has been recently achieved within the framework of the NanoMAX project, by researchers and engineers from the *Centre de Nanosciences et de Nanotechnologies* (C2N, CNRS / Univ Paris-Sud) and the *Laboratoire de physique des interfaces et des couches minces* (LPICM, CNRS / École Polytechnique). They have observed in real time and at the atomic scale the formation of gallium arsenide (GaAs) nanowires. These nanowires grow from atomic or molecular beams of gallium and arsenic directed to a thin heating membrane, transparent to the electron beam of the microscope. The membrane is covered with gold nanoparticles that catalyze the growth of nanocrystals. With this preparation, the atomic layers of the crystal grow one by one at the interface between the nanowire and the catalyst droplet.

Each new atomic layer begins with a convex boundary. Indeed, this configuration minimizes the total length of this boundary. Then, during the layer spreading, the curvature of the boundary is reversed: the edge of the layer prefers to elongate at the periphery of the droplet than inside the liquid.

This configuration remains until the layer is completed. The researchers interpreted these observations using a simple model based on the geometry of the system. They consider a lower energy per unit length of the layer boundary at the periphery than inside the liquid droplet. This characteristic layer progression thus allows the system to minimize its energy.

More generally, the use of this original NanoMAX equipment opens access to crucial information on the mechanisms involved during the growth of nanostructures. This includes the morphology of the catalyst, the structure of the growth front, the location of layer nucleation or the kinetics of the atomic step flow. This knowledge will lead to a better control of the nanocrystal properties. Finally, other sources of matter can be fitted to this unique instrument and a wide range of materials - semiconductors, carbon objects, metals, oxides – can be studied. A great tool for material sciences!



NanoMAX is one of the three pillars of the TEMPOS Equipex, funded in 2010 by the Programme d'Investissements d'Avenir and led by Odile Stephan from the Laboratoire de Physique des Solides, LPS (CNRS / Paris-Sud University) in Orsay. TEMPOS aims at being a world-class electronic microscopy center on the Plateau de Saclay. NanoMAX is installed at École polytechnique in Palaiseau. It brings together researchers and engineers from CNRS, École Polytechnique, Université Paris-Sud and CEA as part of Paris-Saclay. The goal of NanoMAX is to observe the growth of nanostructures in real time and at the atomic scale. In this microscope of unique design, beams of matter, gas, gaseous radicals or molecules are injected directly onto the sample.

Reference
Atomic step flow on a nanofacet
J.-C. Harmand, G. Patriarche, F. Glas, F. Panciera, I. Florea, J.-L. Maurice, L. Travers and Y. Ollivier
Physical Review Letters, 121, 166101 (2018)
DOI: 10.1103/PhysRevLett.121.166101

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- Laboratoire de physique des interfaces et des couches minces (LPICM, CNRS/École Polytechnique)

- The publication was featured on the *Physics* website of the American Physical Society (APS): Focus: Video—Growing a Crystal One Atomic Layer at a Time

Centre de Nanosciences & de Nanotechnologies
C2N

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April 5, 2018

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C2N News

Reference:
F. Chiodi and al, *Nature Communications* (Jan. 2018)

Silicon light-emitting diodes: spin-dependent efficient emission

Physicists from the *Centre de Nanosciences et de Nanotechnologies*, the *Laboratoire de Physique des Solides*, and the University of Cambridge have demonstrated efficient silicon light-emitting diodes using an original manufacturing method. The device is very simple and provides a luminescence at once strong and controllable by a magnetic field at room temperature.

Spin-dependent recombination, where only the singlet state of an electron-hole pair can recombine radiatively, can provide a precious insight on the role of spin in low spin-orbit coupling materials, such as organic semiconductors or silicon. However, in silicon, electron-hole pair recombination is highly improbable due to its indirect gap band structure. Despite the clear potential of silicon for applications, making an efficient light emitting diode (LED) with this material is a challenge, and generally requires a complex design and engineering.

Physicists from the *Centre de Nanosciences et de Nanotechnologies* - C2N (CNRS / Paris-Sud University) and the *Laboratoire de Physique des Solides* - LPS (CNRS / Paris-Sud University), in collaboration with the Optoelectronics group of University of Cambridge, have taken up this challenge. Their work, published in the journal Nature Communications, shows the possibility of producing efficient silicon LED diodes thanks to an original fabrication method based on Gas Immersion Laser Doping (GILD).

A specificity of this technique is that the doping levels obtained are extreme, which intensifies the emission in the LEDs consisting of a junction between boron-doped silicon, intrinsic silicon and phosphorus-doped silicon (Si:B / Si / Si:P). In addition, laser doping allows to maintain a well-defined planar geometry, necessary to be able to align the magnetic and electrical fields in the LEDs and thus to overcome conventional magnetoresistance effects. By probing the spin-dependent recombination in these silicon LEDs, a spectacular increase in electroluminescence with the magnetic field has been demonstrated: 100% at room temperature and up to 300% at 150K.

The proposed model describes this phenomenon by a spin-dependent radiative recombination of weakly bound electron-hole pairs. By this optoelectronic approach, it is thus possible to study the impact of the spin statistics on the luminescent emission of silicon, which appears to be a leading candidate for large-scale quantum spin electronics.

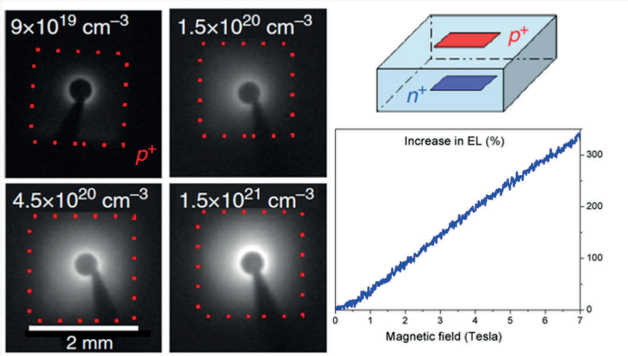

Figure: Diagram and infrared images of Si-LEDs polarized at I = 20mA at room temperature for different levels of doping. Magneto-EL at T=150 K and I=5 mA. © C2N / F. Chiodi

Reference

Room temperature magneto-optic effect in silicon light-emitting diodes
F. Chiodi, S.L. Bayliss, L. Barast, D. Débarre, H. Bouchiat, R.H. Friend and A.D. Chepelianskii
Nature Communications (January 2018)
DOI: https://www.nature.com/articles/s41467-017-02804-6

Affiliations

- Centre de Nanosciences et de Nanotechnologies – C2N (CNRS/Université Paris-Sud)
- Laboratoire de Physique des solides – LPS (CNRS / Univ. Paris-Sud)
- Cavendish Laboratory, University of Cambridge, UK

Centre de Nanosciences & de Nanotechnologies C2N

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C2N News

Reference:
J. Chaste and al,
ACS Nano (2018)

Intrinsic Properties of Suspended MoS_2 on SiO_2/Si Pillar Arrays for Nanomechanics and Optics

Since a few years, it is possible to isolate sheets with thickness of an atom and width of dozens of micrometers. It is possible to proceed with metallic, insulating, or semi-conductors materials and to assemble them in various heterostructures. One of these materials is the MoS_2. However, few experiences were made on suspended membranes of this material in a controlled way and where the strain can be modulated. By taking into account the 2D confinment and the high tunability of the crystalline structure, for example by means of the mechanical stress, this interseting material possesses various surprising properties for electrons, as for photons or phonons.

Researchers of the *Centre de Nanosciences et de Nanotechnologies* – C2N (CNRS/Université Paris-Sud), in collaboration with the University of Pennsylvania, have studied a new sample type with large monolayer MoS_2 deposited on carpets of SiO_2 pillars, with electrical contacts. With the control over pillars geometry, they were able to create periodic networks of high-quality mechanical resonators. Their work is published in the journal ACS Nano.

To reach it, it was necessary, at first, to extract by microRaman, the intrinsic properties of our system: the doping, the thermal conductivity and especially the stress engendered by pillars, and this for numerous types of geometries. The researchers demonstrated for the first time that it is possible to obtain a high-quality and homogeneous system over many periods of pillars. This type of hybrid structure of opto-electro-mechanic (NOEMS) couples at the same time the nanomechanics with interesting properties of the MoS_2 as very strong photocurrent, electronical memory effects or another localized optical emission engendered by the fold of the MoS_2 by pillars.

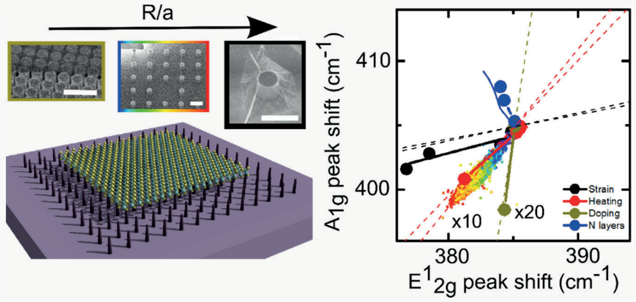

Figure: On the left, some sample of monolayer MoS2 suspended on SiO2 pillars array with a schematic. On the right, a diagram of the respective peak position obtained by Raman spectroscopy, which discriminate the strain, doping or heating. It is possible to correlate a predominant MoS2 property variation with a specific pillars array design. © C2N / J. Chaste

Reference

Intrinsic Properties of Suspended MoS2 on SiO2/Si Pillar Arrays for Nanomechanics and Optics
J. Chaste[1], A. Missaoui[1], S. Huang[1], H. Henck[1], Z. Ben Aziza[1], L. Ferlazzo[1], C. Naylor[2], A. Balan[2], A. T. C. Johnson[2], R. Braive[1,3], A. Ouerghi[1]
ACS Nano (2018)
DOI: doi:10.1021/acsnano.7b07689

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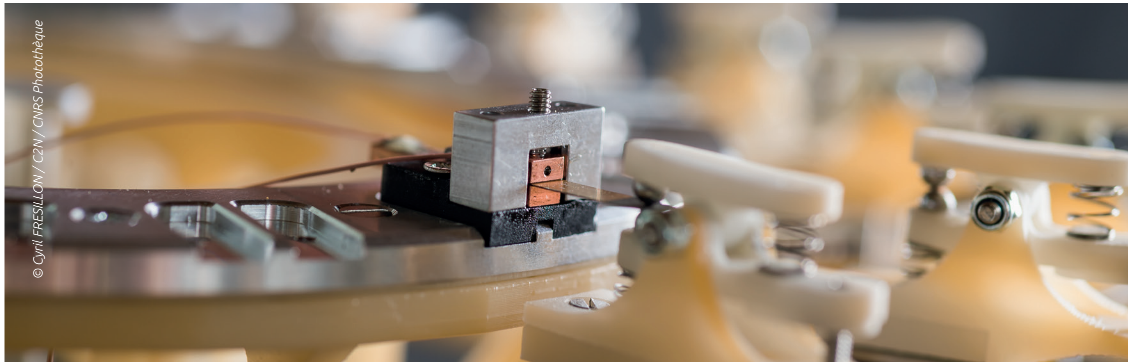
Microsystems and NanoBioFluidics



Centre DE Nanosciences & DE Nanotechnologies

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CNRS *La Lettre Innovation*

Reference:
Patent FR1660855
in CNRS property,
registered on 9/11/2016

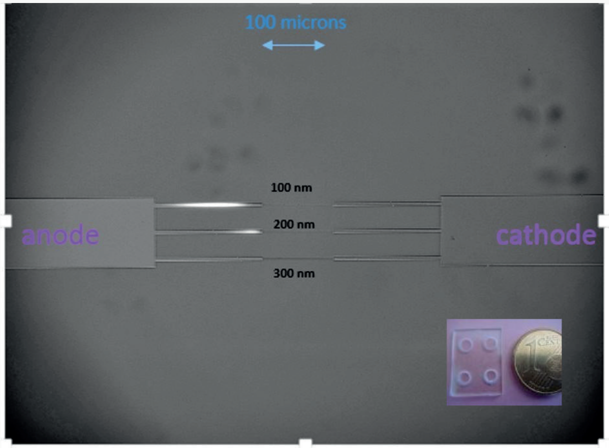
A « barcode » for the fast identification of very dilute biomolecules

A team from the *Centre de Nanosciences et de Nanotechnologies* (C2N)[1] has developed a microfluidic chip integrating a series of nanochannels. Under a specific electrophoretic protocol this new nanofluidic chip produces a fluorescence « barcode », which acts as a specific signature of the target biomolecule. This new technique enables the determination of molecular concentration and identification in just a few minutes, in contrast to several hours to several days with previous techniques.

In order to concentrate and identify very dilute molecules in a solution (biological markers, pollutants, toxins...), the techniques currently available require hours, sometimes days of manipulation. The biochip invented[2] at the *Centre de Nanosciences et de Nanotechnologies* (C2N)[1] makes it possible to perform such analyses in a few minutes. Thanks to slots of different nanometric size, this biochip concentrates molecules in focal points which are located upstream or downstream relative to each nanochannel producing a « barcode », that is simply readable by optical fluorescence.

The microfluidic chip of C2N is based on the well-known principle of electrophoresis to separate molecules: the more or less rapid migration of ions in a solution in an electric field, according to their mass and their electric charge. But the researchers have in addition used a different phenomenon, also studied for years in the laboratory, the « electropreconcentration ». Indeed, their microfluidic device – a chip on a glass – contains an element of even smaller size: a nanochannel of a few tens of nanometers in width. This nanometric channel has a high selective permeability that creates areas in the microfluidic circuit where the investigated molecules are locally concentrated. If these molecules have been marked fluorescently, they form a spot detectable by optical reading. Better: the researchers found a way to realize several nanochannels in parallel on a single chip. These channels have different widths, so that their effect can be modulated by acting on the pressure applied in the microfluidic circuit, generating a series of fluorescent spots which form a « barcode » that is specific to the molecule to be identified. A patent has been filed for the particular geometry of the chip, with several adjacent nanometric channels in the vertical direction[2].

The principle, validated with a model molecule (fluorescein), will be further tested with real biological solutions or samples containing pollutants or toxin markers. «*We want to build a compact and transportable test bench, in order to work more easily with our partners*», says Anne-Marie Haghiri, CNRS researcher at C2N. Presently, the fabrication of the chips is realized using electron-beam lithography. But it may be possible to use nano-printing techniques, which are less time-consuming and better suited for mass production. In the meantime, the laboratory continues to explore the fundamental phenomena that govern the efficiency of chips with nanochannels.



[1] CNRS / Université Paris-Sud

[2] Patent FR1660855 in CNRS property, registered on 9/11/2016

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CNRS *La Lettre Innovation*

Reference 1:
B. Vysotskyi and al.,
Journal of Micromechanics and Microengineering (2018)

Reference 2:
Patent FR3023999A1
in co-ownership CNRS/UPSud,
published on January 1st, 2016.

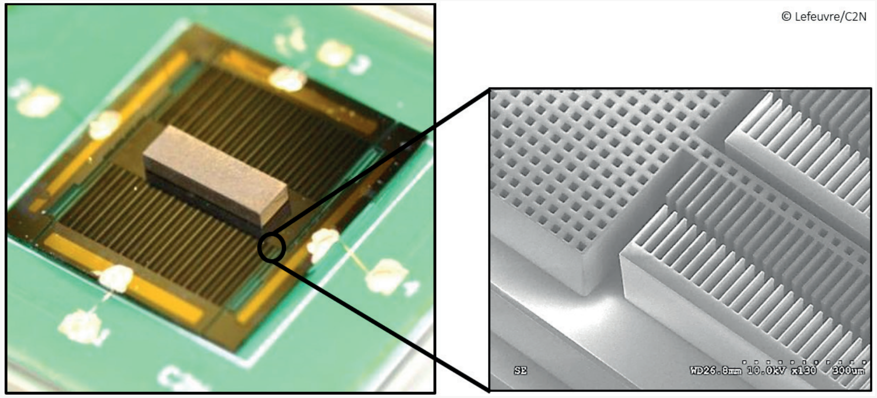
An electromechanical energy harvesting micro-system for medical implants

The microsystem developed and fabricated at the *Centre de Nanosciences et de Nanotechnologies*[1], in collaboration with the *Laboratoire mécanique des sols, structures et matériaux*[2], is able to harvest mechanical energy from the heartbeat. This patented device could be used to power a pacemaker.

A pacemaker autonomous in energy? This is possible if it goes together with a device capable of delivering a power of a few microwatts without the need to be replaced or recharged. All in a volume small enough to fit in the capsule of a pacemaker. A promising solution has been developed by a team from the *Centre de Nanosciences et de Nanotechnologies*[1] and the *Laboratoire mécanique des sols, structures et matériaux*[2]: a micro electromechanical system (MEMS) capable of harvesting mechanical energy from the heartbeat. The researchers have published[3] the results of their work, which has also resulted in a filed patent[4].

To capture the mechanical energy of the heartbeat - the acceleration of the walls of the heart with each contraction or dilation - the researchers chose to use a bistable structure: a micro-beam pre-shaped by ad hoc combination of vibration modes, which switches between two stable states when it receives mechanical energy. This type of device is well adapted to heartbeats, characterized by a variable acceleration spectrum at very low frequencies (1-40Hz). But another difficulty had to be solved: the influence of gravity. Depending on the orientation of the movement in the gravitational field, it can limit the sensitivity of the sensor, which can no longer detect the accelerations of the walls of the heart. The researchers have found a solution by adding to the device two springs, made of silicon at the same time as the rest of the MEMS, and whose function is to compensate the effects of gravity. The sensitivity is then sufficient in all directions. The transformation of the mechanical energy into electrical energy, usable by the pacemaker, passes through a capacitive micro-transducer (a capacitor whose distance between the armatures varies).

To realize this innovative MEMS, the Center for Nanoscience and Nanotechnology has developed a dedicated silicon-on-glass technology, designed to be industrializable. These researchers have been working for several years in collaboration with leading Companies in the field of implantable medical devices. "*Discussions are underway to test with them the new device, which marks a significant advance in terms of miniaturization*," says Elie Lefeuvre, Professor of University Paris-Sud at *Centre de Nanosciences et de Nanotechnologies*. But other applications are envisaged, in connected objects and autonomous sensor networks.



© Lefeuvre/C2N

[1] Centre de nanosciences et de nanotechnologies (CNRS/Université Paris-Sud)

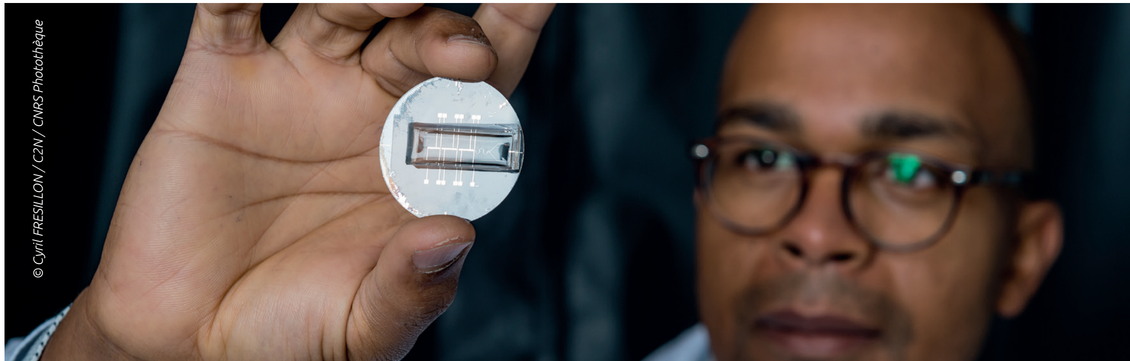
[2] Laboratoire mécanique des sols, structures et matériaux (CNRS/CentraleSupélec)

[3] Nonlinear electrostatic energy harvester using compensational springs in gravity field
Bogdan Vysotskyi, Denis Aubry, Philippe Gaucher, Xavier Le Roux, Fabien Parrain et Elie Lefeuvre.
Journal of Micromechanics and Microengineering, Volume 28, Number 7(1) (2018).
DOI: http://iopscience.iop.org/article/10.1088/1361-6439/aabc90

[4] Patent FR 30239993A1 « Dispositif électronique autonome à alimentation par transduction électrostatique produite par une capacité variable », in co-ownership CNRS/Université Paris Sud, published on January 1st, 2016.

Awards* in 2018

**the list is not exhaustive but highlights the most significative distinctions received in 2018 by C2N members.*



© Cyril FRESILLON / C2N / CNRS Photothèque

Frédéric Pierre, CNRS senior researcher at C2N, was awarded the **Prize Madame Victor Noury**, née Catherine Victoire Langlois - Fondation de l'Institut de France 2018 during a ceremony held at the *Académie des Sciences* in October 2018, under the dome of the Institut de France.

Frédéric Pierre is a young condensed matter physicist, a very inventive experimentalist, whose scientific output is on the rise. His work is characterized by the development and fabrication of original quantum electronic circuits to test the elementary building blocks of mesoscopic quantum transport, and also by the development of unparalleled instrumentation for the measurement of their electrical and thermal transport properties at very low temperatures. Frédéric Pierre's work has led to remarkable advances in the physics of electronic interactions in quantum systems of low dimensionality by testing theoretical predictions, which have not been tested for the time being, and stimulating new developments in the field.

Read about recent Frederic Pierre's works on pages 34 and 36

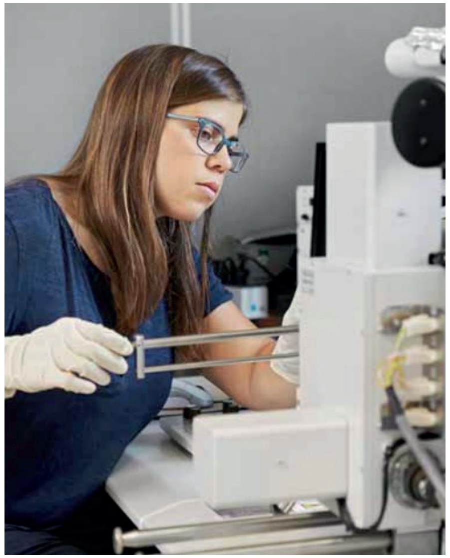
Delphine Marris-Morini, Professor of University Paris-Sud at C2N, was rewarded with the **Fabry - de Gramont prize** 2017 from the French Society of Optics (SFO) during the Optique Toulouse 2018 conference.

The prize rewards a young researcher (below 40), internationally recognized, whose research works have been noteworthy for their quality, originality and potential impact. Delphine Marris-Morini was rewarded for her works in the field of photonic on silicon, integrated optoelectronic devices, optical propreties of quantum well heterostructures and integrated photonic circuits in mid-infrared.

Read about recent Delphine Marris-Morini's work on page 10

Pascale Senellart-Mardon, CNRS senior researcher at C2N, was elected as a **Fellow Member 2018 of the Optical Society of America (OSA)** during the CLEO conference about laser science and their applications in photonics, that took place in May 2018 at San Jose, California.

She was elected "for inventing in-situ optical lithography that couples quantum dots and optical cavities with nanometric precision, realising solid-state single and entangled photon sources of unsurpassed performance that are moving quantum optics towards a scalable future".



The **L'Oréal-UNESCO program «For Women in Science» 2018** aims at promoting women in science and encourage them to pursue their scientific career by rewarding young researchers in PhD or post-doc. Farsane Tabataba-Vakili, PhD student at C2N and at Institut Nanosciences et Cryogénie - INAC (CEA / Université Grenoble Alpes), is a 2018 laureate.

Within a consortium of researchers, Farsane Tabataba-Vakili, PhD Student at the C2N demonstrated the first blue microlaser integrated into a photonic circuit. The work was published in the ACS Photonics journal. Farsane received the Best Student Poster Award for the presentation of this work during the 34th International Conference on the Physics of Semiconductors (ICPS 2018) that took place in Montpellier from 29 July to 3 August 2018.

Read about recent Farsane Tabataba-Vakili's work on page 8

The start-up Quandela, co-founded by Valérian Giesz, Niccolo Somaschi and Pascale Senellart, CNRS Senior Researcher, received one of the 14 **Grands Prix** of the French national competition to support the creation of innovative technology companies **«i-LAB 2018»** from the hands of Frédérique Vidal, French Minister of Higher Education and Research.

Based on a lithography technique developed at the Centre de nanosciences et de nanotechnologies – C2N (CNRS/ Université Paris-Sud), Quandela manufactures and delivers sources of light delivering a single photon in each pulse. These sources of light, which operate at a cryogenic temperature, have the advantage of emitting single photons with very high efficiency and with identical characteristics, making them a tool of choice for researchers of quantum photonics in academia and industry, and more broadly for research in quantum physics. As a result of fundamental research of the highest level conducted for many years by Pascale Senellart, laureate of a CNRS silver medal in 2014, Quandela's singlephoton source technology now follows a robust and reproducible manufacturing process. This was made possible in particular by the prematuration program of CNRS and the Labex Nanosaclay in 2016, before the creation of Quandela in 2017. In June 2018, Quandela successfully installed a first single photon source at the University of Brisbane in Australia.

Read the highlight about Quandela on page 14

Photos du nouveau bâtiment du C2N, Palaiseau (2018) © Sergio Grazia

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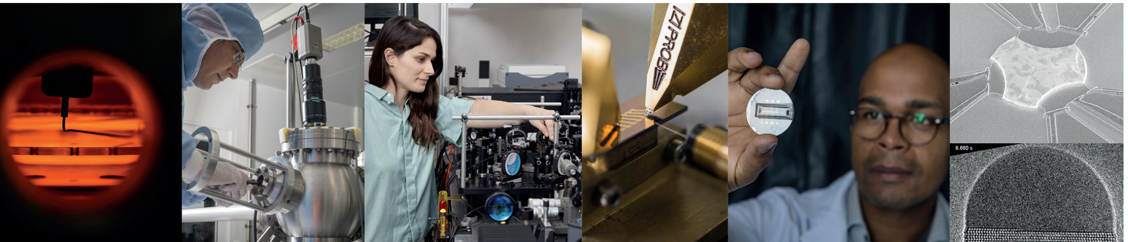

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