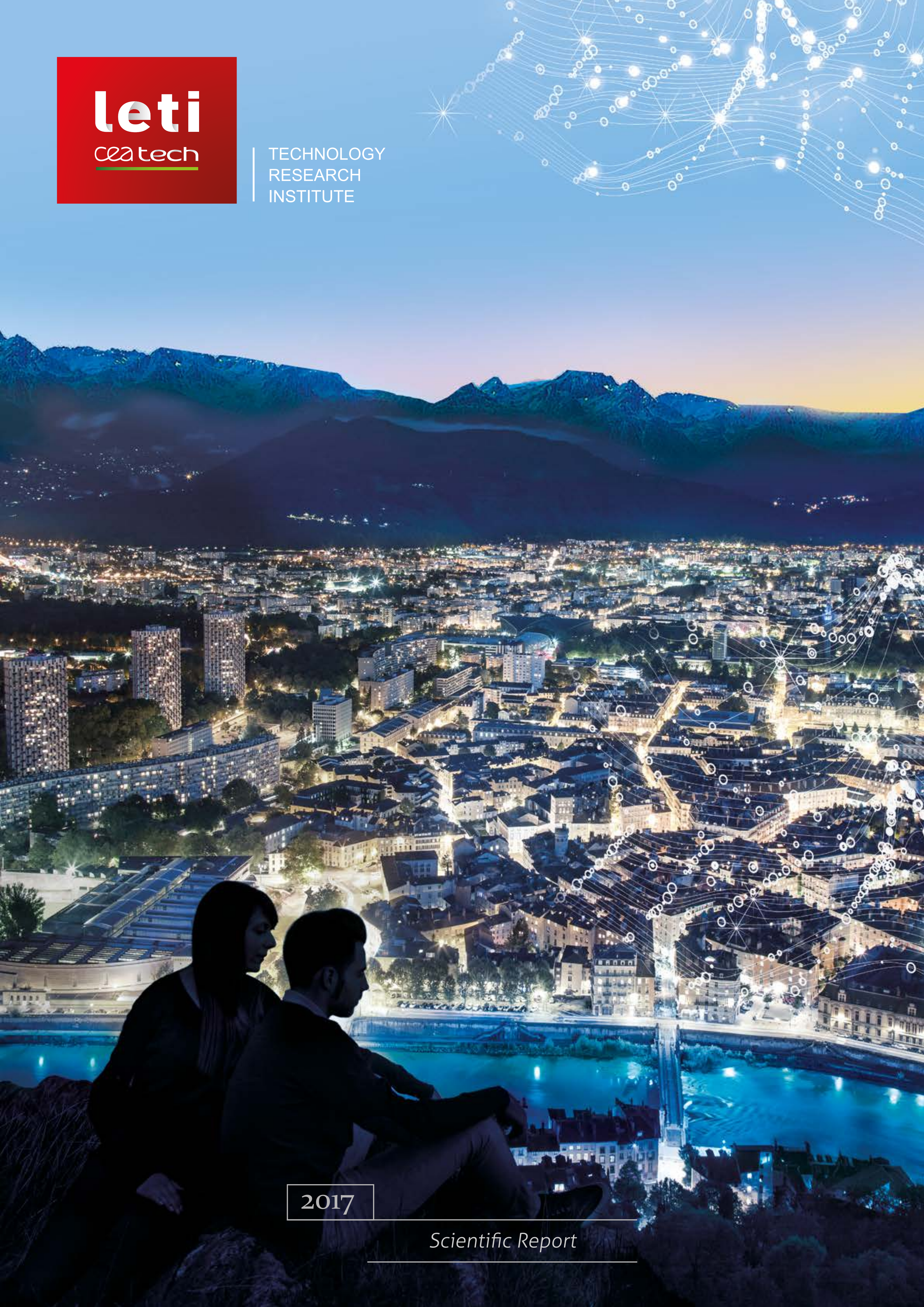

leti
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TECHNOLOGY
RESEARCH
INSTITUTE

2017

Scientific Report

2017

Scientific Report


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Emmanuel Sabonnadière,
CEO – Leti

Leti, alongside List and Liten, is a technology research institute of CEA Tech, supporting its mission to innovate and drive the digital revolution, forging a more creative and productive industry through innovation. With top level expertise and know-how in nanotechnologies for More Moore, Beyond CMOS and More than Moore, Leti has distinguished itself for its leadership in developing and transferring new digital technologies to enterprises worldwide.

In 2017, Leti celebrated its 50th anniversary. I would like to take this opportunity to thank Marie Noëlle Semeria and all my predecessors for their contributions to Leti. I would also like to thank our industrial partners, institutional fellows and academic collaborators, who have worked closely with us for many years to identify new paths towards breakthrough technologies. Finally, I would like to acknowledge the young researchers and students that join us each year to carry out some of the world's most advanced research projects and to become the next generation of innovators.

Appointed CEO of Leti this year, I wish to share my 25 years of experience in industry and my passion for technology with you. I look forward to pursuing Leti's tradition of seamlessly and successfully bridging industry and academia. With the management team, I intend to strengthen Leti's reputation for scientific excellence and pioneering research at the international level. Leti will spearhead novel technologies to enable pervasive artificial intelligence, higher performance augmented reality, cybersecurity, personalized health for all and many more digital tools that will help us tackle the societal challenges of the next 50 years. Naturally, we will continue to reinforce our collaborations with the best universities in the world to expand our scientific foresight.

I hope you will find in Leti's 2017 Scientific Report inspiration for your future developments and research.


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Barbara de Salvo,
Deputy Director for
Science and Technology

According to the ancient Indian myth of the Jewel Net of Indra, *"there is a wonderful net which has been hung by some cunning artificer in such a manner that it stretches out indefinitely in all directions, with no beginning or end. A single jewel hangs at every node of the net, glittering like a star of the first magnitude. In the polished surface of each jewel all the other jewels in the net are reflected, infinite in number. Everything is related to everything else; nothing is isolated"*(1). This poetic description of the inter-dependence among all the elements of the cosmos resonates with the Greek seminal image of the *"anima mundi"*, a concept which still stirs the imagination of contemporary societies in their quest for symbolic significance.

With this report, we would like to share our recent scientific highlights on the transformative technologies which make the *hyperconnected* world a reality. Our approach is transdisciplinary and aims at overcoming the limits of both reductionist and holistic paradigms by integrating them into a wider perspective, investigating the structure of interconnections in the real world at different levels of complexity. It is crucial today to conceive the pervasive technologies of tomorrow in symbiosis with people and the environment, to strongly increase their associated potential.

To this aim, in the era of *hyperconnectivity*, we propose a *human-centered research approach* and *symbiotic development strategy* along five research axes that span from the nano- to the macro-world:

- Advanced Materials: The Fuel of Innovation
- The Virtues of Photons for the Connected Society
- Novel Technologies to Improve Human Health
- Innovative Devices and Architectures for Power Efficiency
- Interacting Efficiently and Reliably with Complex Systems in the Digital World

Finally, I would like to acknowledge our scientists, students and all of our academic and industrial partners for their significant contributions to these achievements.

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(1) Francis H. Cook, The Jewel Net of Indra, Penn State University Press, 2001.


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TECHNOLOGY
RESEARCH
INSTITUTE

Committed to Innovation, Leti Creates Differentiating Solutions for its Industrial Partners.

CEA Tech is the technology research branch of the French Alternative Energies and Atomic Energy Commission (CEA), a key player in research, development and innovation in defense & security, nuclear energy, technological research for industry and fundamental physical and life sciences.

www.cea.fr/english

Leti is a research institute of CEA Tech and a recognized global leader in miniaturization technologies. Leti's teams are focused on developing solutions that will enable future information and communication technologies, health and wellness approaches, clean and safe energy production and recovery, sustainable transport, space exploration and cybersecurity.

For 50 years, the institute has built long-term relationships with its industrial partners, tailoring innovative and differentiating solutions to their needs. Its entrepreneurship programs have sparked the creation of 64 start-ups. Leti and its industrial partners work together through bilateral projects, joint laboratories and collaborative research programs.

Leti maintains an excellent scientific level by working with the best research teams worldwide, establishing partnerships with major research technology organizations and academic institutions. Leti is also a member of the Carnot Institutes network*.

LETI AT A GLANCE

€315
million budget

800
publications per year

ISO 9001
certified since 2000

Founded in
1967

Based in
France (Grenoble)
with offices in the
USA (Silicon Valley) and
Japan (Tokyo)

350
industrial partners

1,900
researchers

2,760
patents in portfolio

91,500
sq. ft. cleanroom space,
8" & 12" wafers

64
startups created

**Carnot Institutes network: French network of 34 institutes serving innovation in industry.*

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Symbiotic Technologies

In the Age of Hyperconnectivity

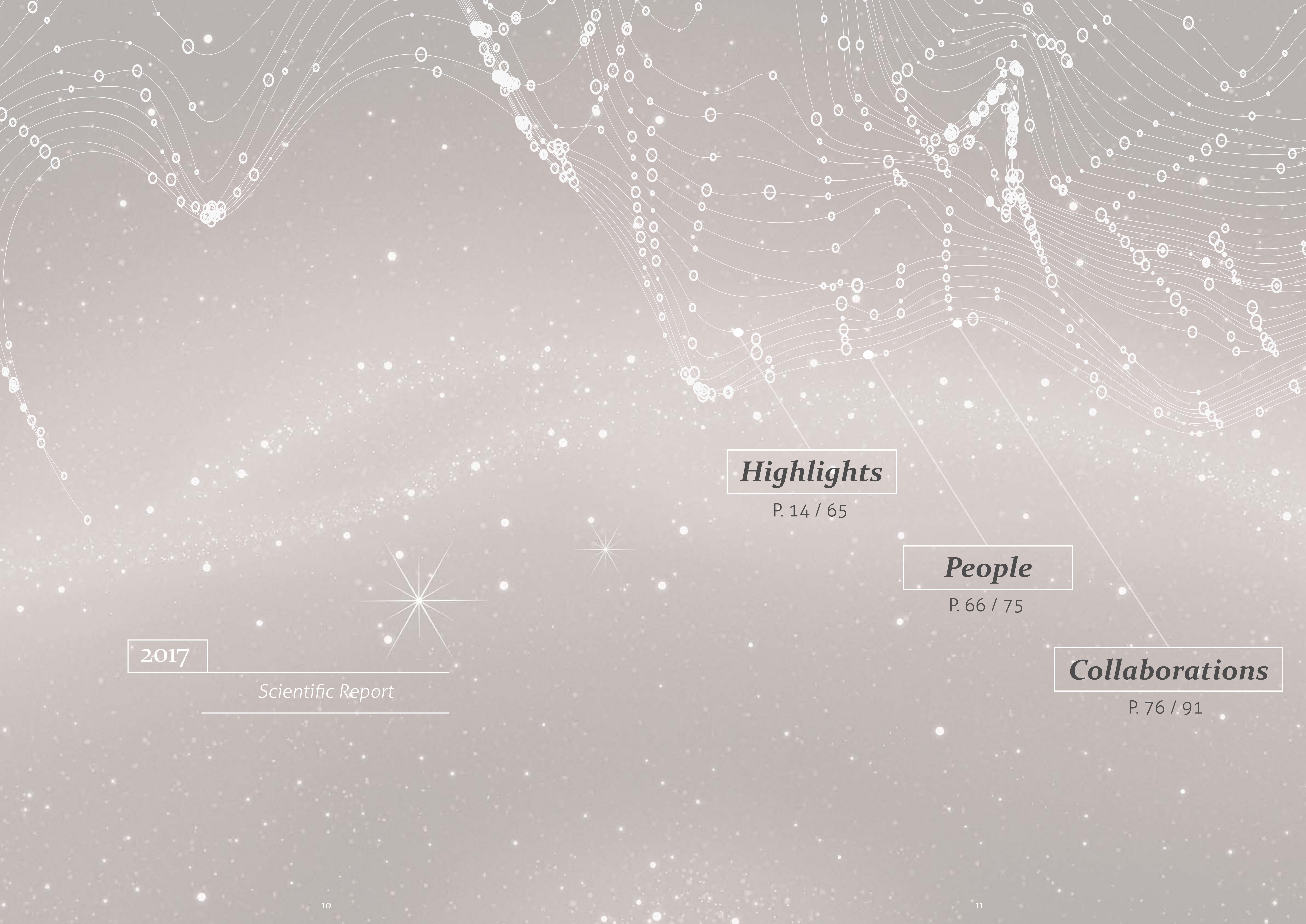
PHOTOGRAPH BY JOHN STANMEYER

African migrants on the shore of Djibouti City at night raising their phones in an attempt to catch an inexpensive signal from neighboring Somalia — a tenuous link to relatives abroad.

In the past few decades, the world has gone through great transformations. Technological progress has led to an age of hyperconnectivity, dramatically changing the way people live, and transforming the world into a truly global village. Hannah Arendt described the modern relational-self's identity as being based on the condition of plurality, a ternary concept made of equality, uniqueness and relationality, harmonizing freedom and responsibility while going beyond the Cartesian and liberal approaches of truth and autonomy.

However, important societal challenges still remain, as the benefits of technological progress and economic growth have not been equally distributed. Environmental issues, dwindling natural resources and harrowing political instabilities are exacerbating the need for new societal guidelines.

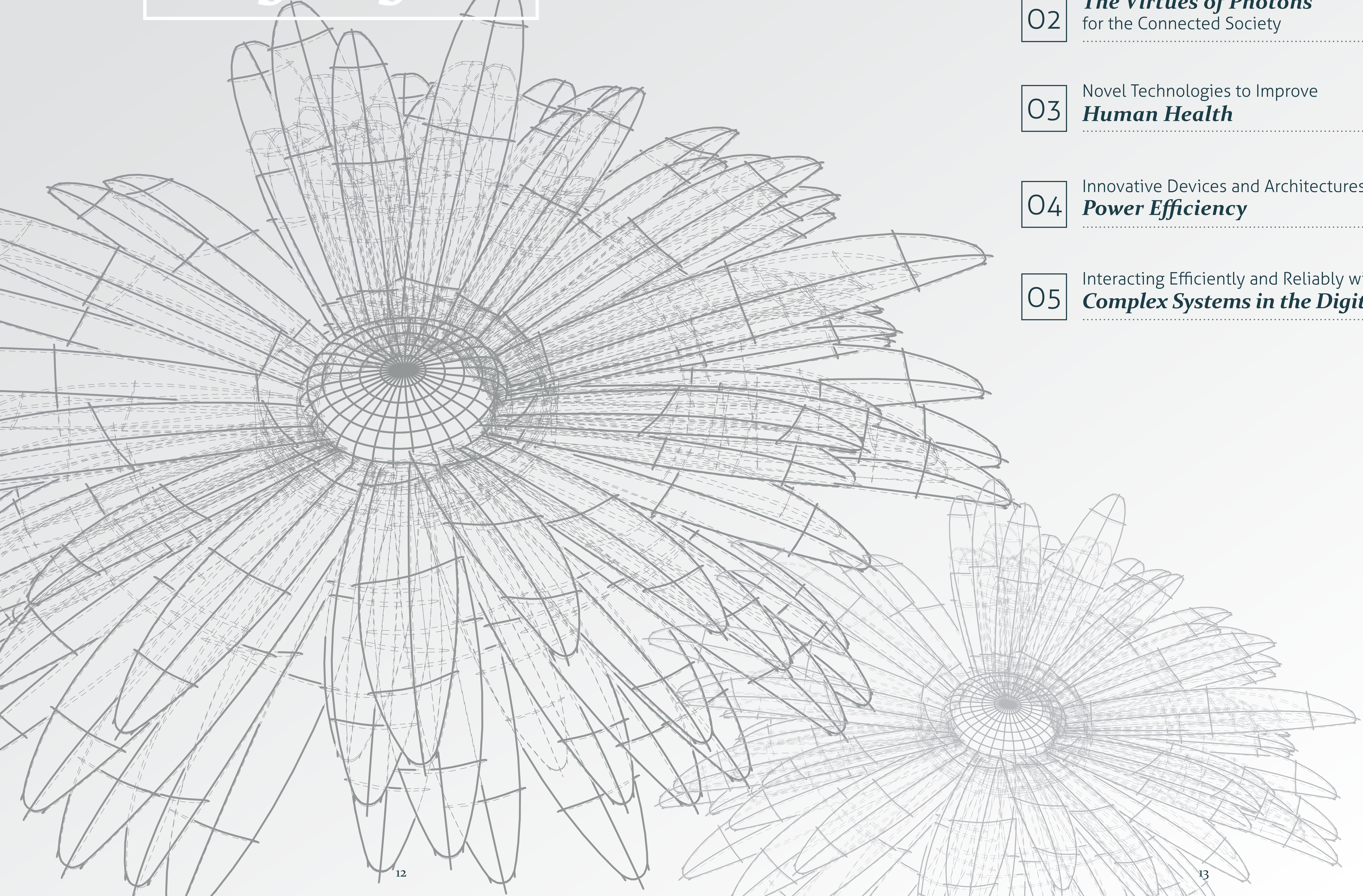
In this era of remarkable changes, the role of Research and Technology Organizations, like Leti, becomes strategic to our society.
As nonprofit organizations, our motivation and raison-d'être are rooted in our long-term commitment to future generations, to develop technologies of freedom able to tackle the main challenges arising from the evolution of society and the economic and industrial landscapes. By taking a wide perspective on technology and science, Leti is leading a new research approach which provides decision makers, including governments, institutions and firms, rigorous, independent and multidisciplinary solutions aimed at reconciling growing individual needs and global societal issues.

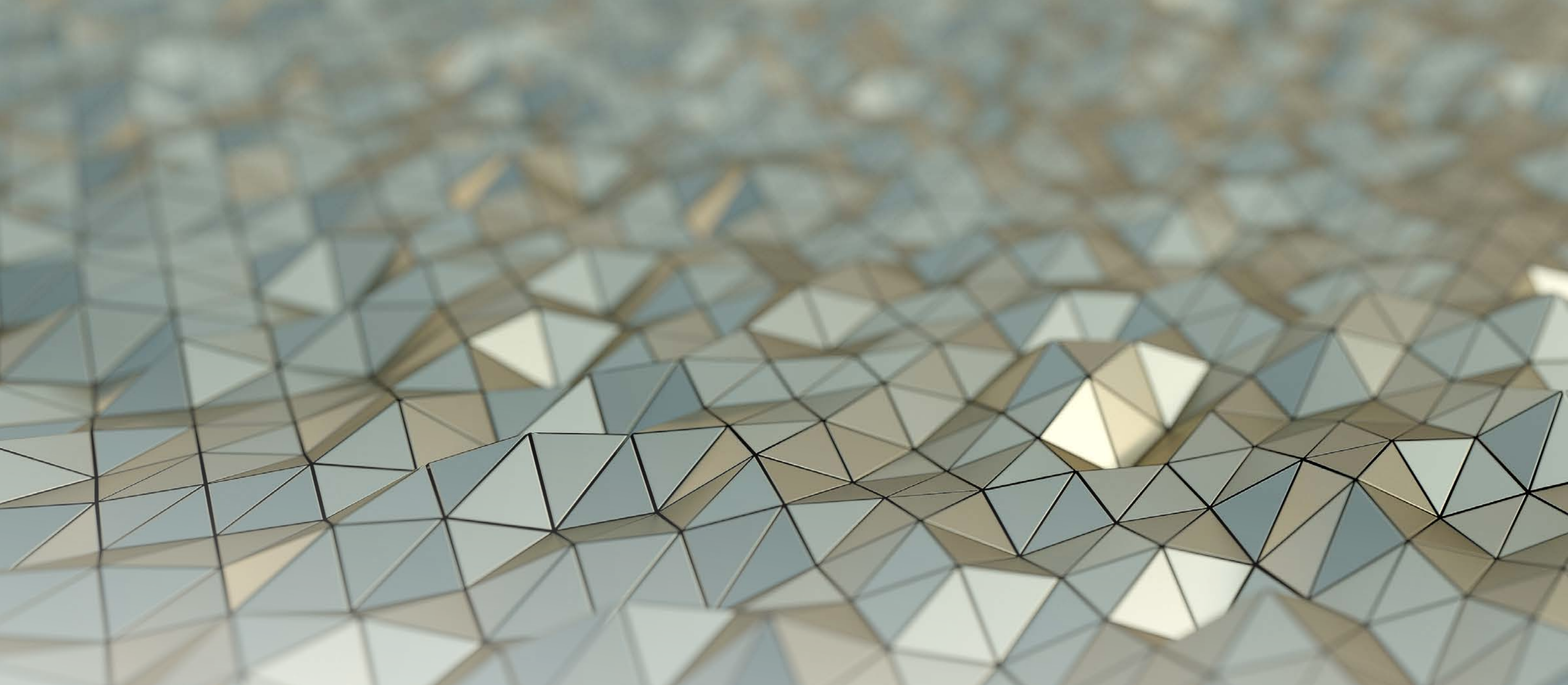


2017

Scientific Report

Highlights





01

New Advanced Materials: The Fuel of Innovation

Advanced materials and processes are at the heart of technological innovation, adding great value to products and systems through new functionalities and improved properties. The following highlights illustrate new processes developed or perfected this past year such as lithographic methods based on DNA origami, new functionalities enabled by innovative materials such as ultrathin membranes of diamond like carbon, and new material growth processes like engineered GaN epitaxy on Silicon to improve power devices. In parallel, novel imaging techniques have been developed to analyze materials at the nano scale, in operando conditions, providing new understanding of emerging devices, such as resistive memories and solar cells.

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***Interview** with Raluca Tiron*
Leti scientist

DNA Origami:

A New Way of Producing High-Resolution, High-Density Chips

Who would have thought that the ancient art of Origami, when applied to DNA strands, might one day play a role in nanotechnology?

By going beyond standard optical lithography, a team of scientists has demonstrated that a bottom-up self-assembly process, exploiting DNA (Deoxyribonucleic acid) properties, could advance a number of fields requiring complex designs with high resolution and low cost.

How do you use DNA properties to overcome the limits of standard lithography?

Standard lithography is limited today in terms of resolution and cost. EUV [extreme ultraviolet lithography] could be the next lithography solution, but technical challenges still need to be overcome, and the overall cost is still very high. In this context, we have to keep investigating new techniques that complement lithography, meet the resolution and density requirements and are suitable for low cost, high throughput manufacturing.

A lot of research has gone into understanding and defining nanometer scale features of DNA. We are particularly interested in a technique called "DNA Origami", which involves folding a long circular strand of DNA into desired shapes using hundreds of "staple strands", which are short DNA molecules. The resulting 2D or 3D structures can then be transferred onto a substrate. The information pre-registered in the DNA will guide the self-assembly process that will create the required shapes.

Our main achievement so far has been to demonstrate very high resolution (sub 10nm), very high density (sub 20nm) patterning using DNA Origami. We also demonstrated pattern transfer onto a SiO2 inorganic hard mask.

This new approach is a real breakthrough with respect to the standard lithography processes used in industrial environments today, which are based on optical lithography—using light to print patterns through a mask onto a wafer. This conventional approach is a top-down approach, in which the initial design registered on the mask is replicated several times on several wafers. By contrast, like other self-assembly based patterning solutions, patterning with DNA is an example of a bottom-up approach.

What new research do you expect will follow your work?

We've achieved a first milestone that demonstrates that these techniques can be used for patterning. But in order to be able to apply them in microelectronics, we will need to show that it is possible to control the exact position of the patterns on a silicon substrate. That means we will have to carefully control alignment and placement of the 2D and 3D Origami structures.

We believe this can be done by combining top down and bottom up approaches—using standard lithography to define the positioning points and DNA self-assembly to provide the required patterning resolution and density.

COLLABORATIONS
CEA-INAC (France)
TILIBIT Nanosystems (Germany)
Emory University (USA)

FOR MORE DETAILS

"DNA Origami Mask for Sub-Ten-Nanometer Lithography"
C.T. Diagne[1], C. Brun[1], D. Gasparutto[2], X.Baillin[1], and R. Tiron[1],
[1]CEA-Leti, [2]CEA-INAC
ACS Nano, vol.10 (7), pp.6458–6463, 2016

Breakthrough

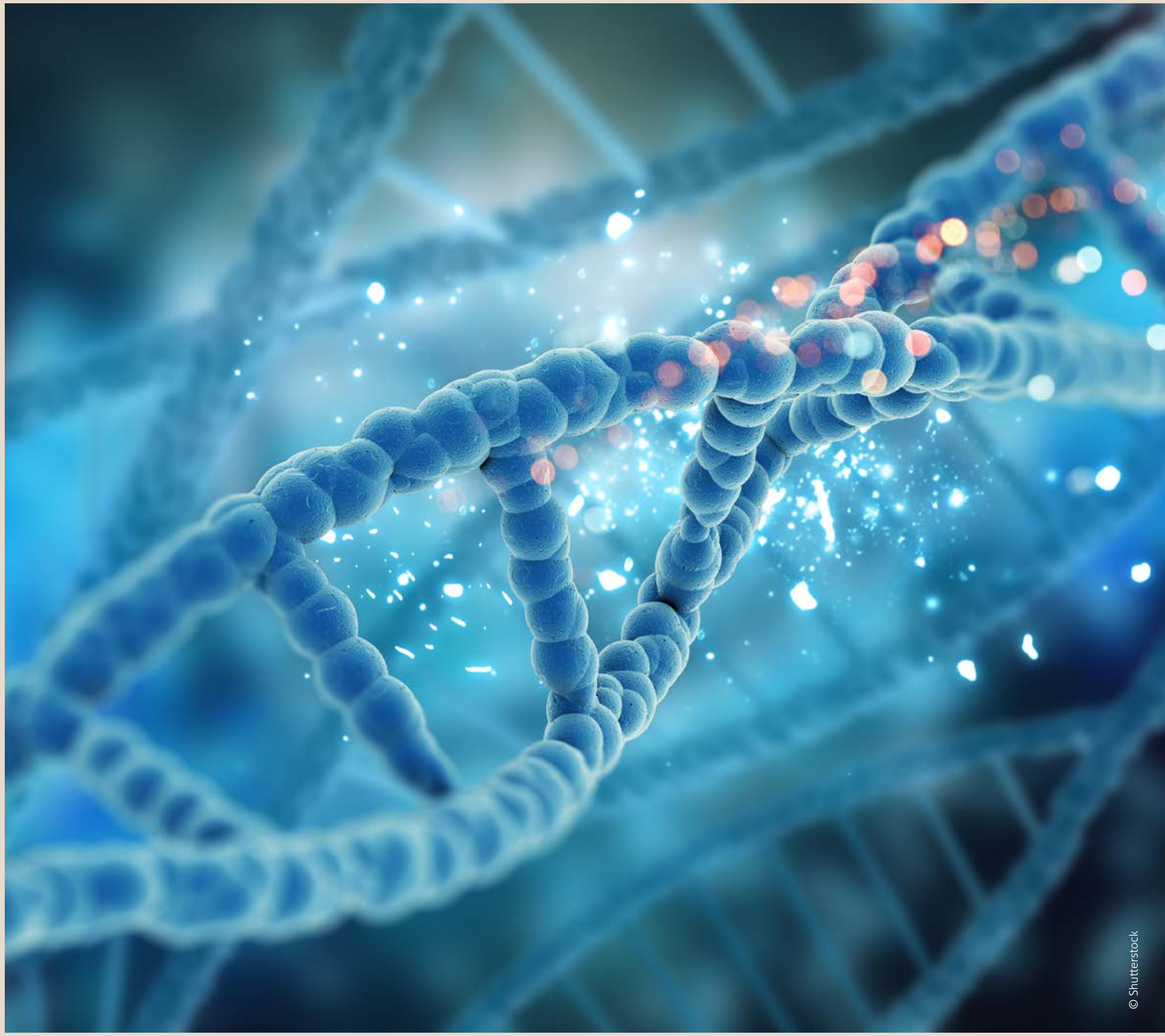
Demonstration of very high resolution (sub 10nm), very high density (sub 20nm) patterning using DNA Origami, with pattern transfer onto a SiO2 inorganic hard mask.

Why it's relevant

DNA Origami overcomes the limitations of standard optical lithography, meeting high resolution, high density and low cost requirements.

Moving forward

We plan to combine standard lithography and bottom-up DNA Origami approaches to control the alignment and placement of the objects.



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***Interview** with David Cooper*
Leti scientist

EXAMINING RESISTIVE MEMORIES IN SITU:

To Improve Memory Devices, We Must First Understand Them

By studying the reversible switching of memory devices in situ in a transmission electron microscope, it's possible to optimize the technology to meet the increasing demand for reliable, fast, and high-density non-volatile data storage.


© CEA-Leti / Chr. Morel

While new types of memory technologies are under development, the precise physical mechanism of their operation is not yet fully understood. But a new method has been developed to improve the understanding of the switching process for a given device—and that understanding will make it possible to adapt the processing steps to provide optimized performance.

How did you improve the understanding of memory devices?

Our work was to show that, by switching a $SrTiO_3$ resistive memory (RRAM) in-situ in a TEM [Transmission Electron Microscope], we can reversibly map the change of oxygen distribution in the device, as it passes from a high resistive state to a low resistive state.

By optimizing the specimen preparation and the in situ technique we are able to control the heating of the specimen such that the device can be reversibly switched. Following this preparation, advanced spectroscopy is performed in the TEM to provide maps of the distribution of oxygen vacancies with 1 nm spatial resolution and reveal how the device changes between a high resistive and a low resistive state.

For some time, we have been hoping to see with nm-scale resolution how nanoscaled materials work, and through in situ operation of these devices, we can now do this. It's also possible to observe specimens being heated, cooled, electrically polarized, under the influence of gas or liquids. As such, these characterization techniques, used in combination with in situ operation, allow unprecedented observations which will lead to improvements in the properties of tomorrow's nanoscaled materials.

Now that it's possible to study memory devices in situ in a controlled manner, what new research areas have opened up?

This work opens a lot of new research paths. Being able to operate semiconductor devices in situ in the TEM means we can examine a range of memory devices, piezoelectric activators, and photovoltaic devices for light emission or absorption. It means we can study doped nanowires and perform a range of different characterization techniques with nm-scale resolution while they are operated in the TEM.

Breakthrough

Switching a resistive memory in situ, inside a TEM, to visualize the movement of oxygen vacancies and understand how the device works.

Why it's relevant

To be able to make better material choices for future nanodevices, it's necessary to know, with atomic resolution, exactly how they work.

Moving forward

We will perform a comprehensive study using different types of memory devices. In parallel, we will use our know-how to study other devices, such as photovoltaic structures for green energy production.

COLLABORATIONS
Forschungszentrum Jülich (Germany)
RWTH Aachen University (Germany)

FOR MORE DETAILS

"Anomalous Resistance Hysteresis in Oxide ReRAM: Oxygen Evolution and Reincorporation Revealed by In Situ TEM"
D. Cooper[1], C. Baeumer[2], N. Bernier[1],
A. Marchewka[3], C. La Torre[3],
R. E. Dunin-Borkowski[2], S. Menzel[2],
R. Waser[2,3], and R. Dittmann[2]
[1]CEA-Leti
[2]Forschungszentrum Jülich
[3]RWTH Aachen University
Advanced Materials, vol.29 (23),
June 2017

***Interview** with Anne Ghis*
Leti scientist

STRONG, ULTRATHIN MEMBRANES,

Based on Amorphous Diamond-Like-Carbon, Enable Large-Band Ultrasonic Transducer Devices


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Breakthrough

Implementation of ultrathin membranes based on amorphous diamond-like-carbon.

Why it's relevant

This breakthrough opens the way to novel MEMS designs and applications, namely ultra-broadband ultrasonic transducers.

Moving forward

The astonishing properties of this material have still to be fully discovered. Innovative applications in biosensors and packaging are foreseen.

New amorphous carbon of nanometric thickness can act as the mobile part of two-dimensional resonators, offering a wide-ranging operating frequency and impacting a very large number of application areas, including ultrasound and chemical sensors.

The behavior of membrane-based micro-electromechanical systems (MEMS), such as micro-machined ultrasonic transducers (MUTs), is determined by the thickness of their self-standing parts. This thickness results in plate-type mechanical behavior, limiting the effective operating frequencies to levels that are close to the fundamental resonance of the vibrating plate.

The development of new materials now makes it possible to use ultrathin membranes as self-standing mobile parts and to achieve high amplitudes of deflection for the whole frequency spectrum on the same device: from zero up to several hundred megahertz.

What breakthroughs did you accomplish on your way to revolutionizing resonators?

The first breakthrough was being able to produce amorphous diamond-like-carbon [DLC] having nanometric thickness. In this range of thickness, DLC exhibits extraordinary mechanical elasticity and tenacity, and is chemically inert.

The second one was the development of an original process in which we used a new combination of stacked nanometer thick Platinum/amorphous carbon to manage the electromechanical properties of the multilayer on the one hand, and to ensure efficient integration of the membrane into operational devices on the other hand.

The third breakthrough was having demonstrated membrane-type mechanical behavior in micrometer-sized devices. Taking advantage of the physical properties of the amorphous carbon-based multilayered membrane, we produced and observed electrostatically induced displacements and vibrations in air of self-standing membranes, from zero up to several hundred megahertz. We measured and mapped both fundamental and high-order modes of resonance, with amplitudes of displacement as high as a hundred nanometers on devices that are only two micrometers large.

These membranes require actuation voltages that are much lower than the actuation voltages required by classical CMUTs [capacitive micro-machined ultrasonic transducers], so they may be compatible with standard microelectronics. In any case, these strong, ultrathin membranes open the way to large band ultrasonic devices, and are likely to impact a large number of application areas, including medical imaging and chemical sensors.

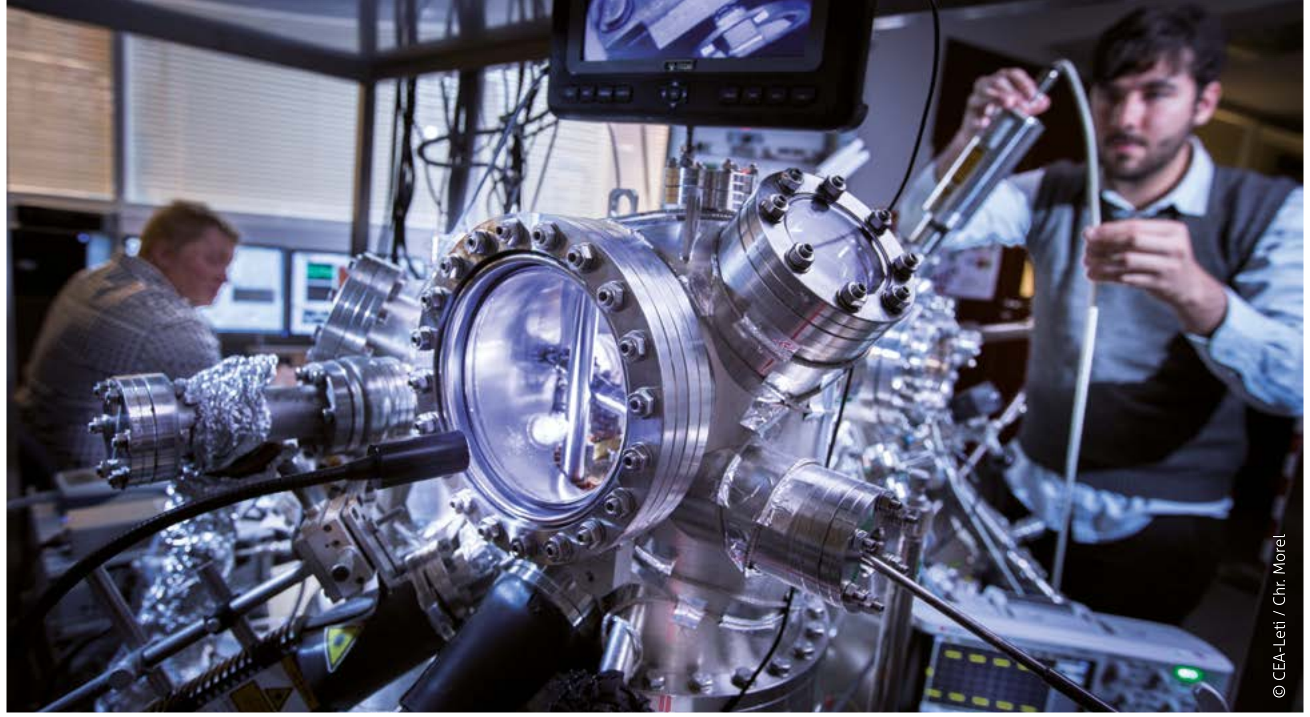
What future research will result from using ultrathin membranes in 2D resonators?

In the short term this technology can be applied to pressure measurements and to ultrasound, both in air and in water. Further research could also focus on the detection of chemicals and on MEMS packaging improvements. Better MEMS packaging will be useful for applications in biology and medicine, and in hostile environments where corrosion is a problem.

COLLABORATIONS
CEA-INAC (France)

FOR MORE DETAILS

"AFM Study of D Resonators Based on Diamond-Like Carbon"
S. Thibert[1], A. Ghis[1], M. Delaunay[2]
[1]CEA-Leti, [2]CEA-INAC
Proc. of the 16th International Conference on Nanotechnology (IEEE Nano), pp.475-478,
Aug. 2016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Interview with
Łukasz Borowik and
Fernández Garrillo
Leti scientists

IMPROVING SOLAR CELLS

through Nanoscale Two-Dimensional Photocarrier Dynamic Imaging

New methods for examining photovoltaic materials on a nanoscale will result in better solar cells.

COLLABORATIONS
Université Grenoble Alpes (France)
CEA-INAC (France)
CNRS (France)

FOR MORE DETAILS

“Photo-Carrier Multi-Dynamical Imaging at the Nanometer Scale in Organic and Inorganic Solar Cells”
P.A. Fernandez Garrillo[1,2,3], L. Borowik[1,2],
F. Caffy[3], R. Demadrille[3], and B. Grévin[3]
[1]CEA-Leti, [2]Université Grenoble Alpes,
[3]CEA-INAC/CNRS
ACS Applied Materials Interfaces, vol.8 (45), pp.31460–31468, Oct. 2016

“Measuring the Lifetime of Silicon Nanocrystal Solar Cell Photo-Carriers by using Kelvin Probe Force Microscopy and X-ray Photoelectron Spectroscopy”
L. Borowik, H. Lepage, N. Chevalier,
D. Mariolle, and O. Renault
CEA-Leti
Nanotechnology, vol.25 (26), July 2014

Discovering phototransport mechanisms and identifying the sources of loss by carrier recombination are key for the development of emerging photovoltaic technologies based on micro- and nanostructured materials. Although it was already possible to examine photocarrier lifetime on a nanoscale at a single point, doing it in one dimension only was not sufficient.

To address this problem, a team of scientists demonstrated new techniques to acquire measurements on the same scale, but in two dimensions. Thanks to this work, photocarrier dynamics can now be studied in nanostructured photoactive materials and devices—a breakthrough that opens the way to great improvements in the development of solar cells.

How were you able to measure photocarrier lifetime with nanometric resolution?

We did this by measuring surface potential using Kelvin probe force microscopy under modulated light. A transfer of photocarriers induces a change in surface potential under continuous light. When fast-modulated light (>100Hz) is used, this change can be averaged over time and this average value can be used to estimate photocarrier lifetime.

Because this is an AFM [atomic-force microscopy] type technique, the characterization of average values can be performed for a matrix of points with nanoscale resolution. These measurements make it possible to distinguish between different photocarrier lifetimes in different timescales, owing to different recombination processes.

What new research will result from your work on photoactive materials?

This groundbreaking technique opens several possibilities for further development in material characterization. For example, using very fast lasers can be advantageous for measuring “fast” recombinations (typically in the order of ns in III-V materials). Very similar methods can be used to measure the diffusion length with high lateral resolution by quantifying the surface potential over several wavelengths of illumination.

Breakthrough

New methods to achieve nanometric resolution in photocarrier lifetime mapping and simultaneous measurement of photocarrier lifetimes over different timescales.

Why it’s relevant

Understanding the role of local heterogeneities in emerging photoactive materials will greatly improve the development of new solar cells.

Moving forward

As the temporal resolution is limited only by the performance of the illumination setup, we expect further improvements to result from using faster illumination chains.


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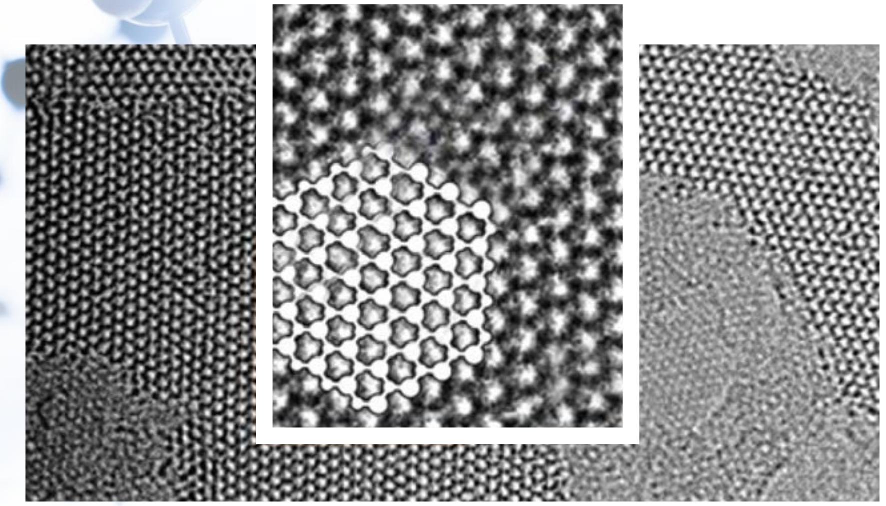
TWO DIMENSIONAL TRANSITION METAL DICHALCOGENIDES:

Enabling Production of Nanoelectronic and Optoelectronic Devices



Interview with
Stéphane Cadot and
François Martin
Leti scientists

A new approach for synthesis of two dimensional (2D) transition metal dichalcogenides (TMDs) on an industrial scale

Layered TMDs have emerged as a new class of 2D materials. Special attention is being given to two such materials behaving as direct gap semiconductors with strong photoluminescence properties when isolated as one single layer: molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2).

Until now, nobody had come up with a convenient method for producing uniform single TMD layers on an industrial scale using atomic layer deposition. But recently a new solution has been developed that will impact a number of applicative areas, including flexible electronics and energy storage.

How did you tackle the problem of making 2D MoS_2 suitable for industry?

We developed a novel approach for the synthesis of 2D MoS_2 layers. Using molybdenum (IV) dimethylamide and 1,2-ethanedithiol as precursors, we first deposited a thin layer of amorphous (and thus uniformly functionalized) molybdenum thiolate using atomic layer deposition (ALD) at low temperature (below 150°C). In a second step, this layer was converted to MoS_2 crystals by rapid thermal annealing. By accurately controlling the thickness of the initial Mo thiolate layer, we were able, after annealing, to obtain 2D MoS_2 layers with perfect uniformity on 300mm silicon wafers.

This process can be considered a generic approach, and is thus potentially extendable to other 2D transition metal disulfides such as semiconducting WS_2, ZrS_2 and HfS_2, or metallic TaS_2. All these 2D materials are inherently well adapted for low-power or transparent electronics and offer a wide panel of properties such as photoluminescence, piezoelectricity or phase change induced by heat or strain. Moreover, their properties can be modulated by chemical doping, making them suitable for numerous functionalities.

What further questions have to be addressed before we see full industrial production of 2D TMDs?

The next step will be to integrate this material into basic devices (probably field effect transistors or phototransistors in a first attempt) to determine which parameters (for example, annealing conditions, chemical treatment and the nature of the metallic contacts) will produce the best performance.

Future challenges will be to extend the process to other 2D transition metal disulfides and to fully explore their potential use in real-life applications.

Breakthrough

A novel and H_2S-free process for the synthesis of 2D MoS_2 layers, fully compatible with a clean room environment.

Why it’s relevant

This is an industrially relevant method that enables the development of nanoelectronic and optoelectronic devices based on 2D transition metal disulfides.

Moving forward

Enhance the performance of the 2D MoS_2 films, study their integration into basic devices, and extend the process to other 2D transition metal disulfides.

COLLABORATIONS
CEA-INAC (France)
C2P2-CPE/CNRS/Université Claude Bernard de Lyon (France)

FOR MORE DETAILS

“A Novel 2-Step ALD Route to Ultra-Thin MoS_2 Films on SiO_2 through a Surface Organometallic Intermediate”
S. Cadot[1],2, O. Renault[1], M. Frégnaux[1],
D. Rouchon[1], E. Nolot[1], K. Szeto[2],
C. Thieuleux[2],
L. Veyre[2], H. Okuno[3], F. Martin[1], and E.A. Quadrelli[2]
[1]CEA-Leti, [2]C2P2-CPE/CNRS/Université Claude Bernard de Lyon,
[3]CEA-INAC
Nanoscale, vol.9, pp.538-546, 2017

Interview *with Matthew Charles*
Leti scientist

GaN Epitaxy:

Understanding the Physics to Enable High Quality 200mm GaN on Silicon

A new understanding of nucleation layers removes a major obstacle to high quality GaN on Silicon.

The demand for high-power electronic components is increasing. Electric vehicles and renewable energy switching require higher voltage and higher current devices, with lower losses and higher efficiency. GaN [gallium nitride] is a very promising candidate to meet those performance requirements, but mass production of wafers based only on GaN isn't an option: pure GaN substrates are not available in large diameters and they are expensive.

Silicon wafers, on the other hand, are of very high quality, with near perfect crystallinity. So to overcome the problems of cost and wafer size, recent developments for power electronics have focused on implementing devices using GaN grown on silicon.

What have you done to understand the physics behind GaN layer growth on silicon for high-power electronics?

Due to the 17% lattice mismatch between GaN and silicon, GaN layers grown directly on silicon substrates typically have a dislocation density of the order of 1x109 dislocations per square centimeter. Although this is high compared to typical semiconductor layers, it is sufficiently low for use in power devices at room temperature. However, the difference in thermal expansion between GaN and silicon is significant, so that an AlN (aluminum nitride) nucleation layer and various buffer layers must be deposited on the silicon substrate before growing the GaN, in order to have a high quality GaN layer, and a flat wafer after growth.

The two most basic properties that characterize high power GaN based switching devices are the breakdown voltage (the voltage at which the device is destroyed) and the electrical resistance (or specific resistance). These are the parameters that define the switching devices' ultimate performance. One of the common problems affecting the breakdown voltage of these devices is the "inverted pyramid" defect in GaN layers. We performed analyses of these inverted pyramid defects in GaN layers, showing as the density of these defects increased the breakdown voltage dropped significantly. We demonstrated that this effect is linked to the geometry of the defect, which causes an increase in the electric field at the point of the defect, and thus premature breakdown.

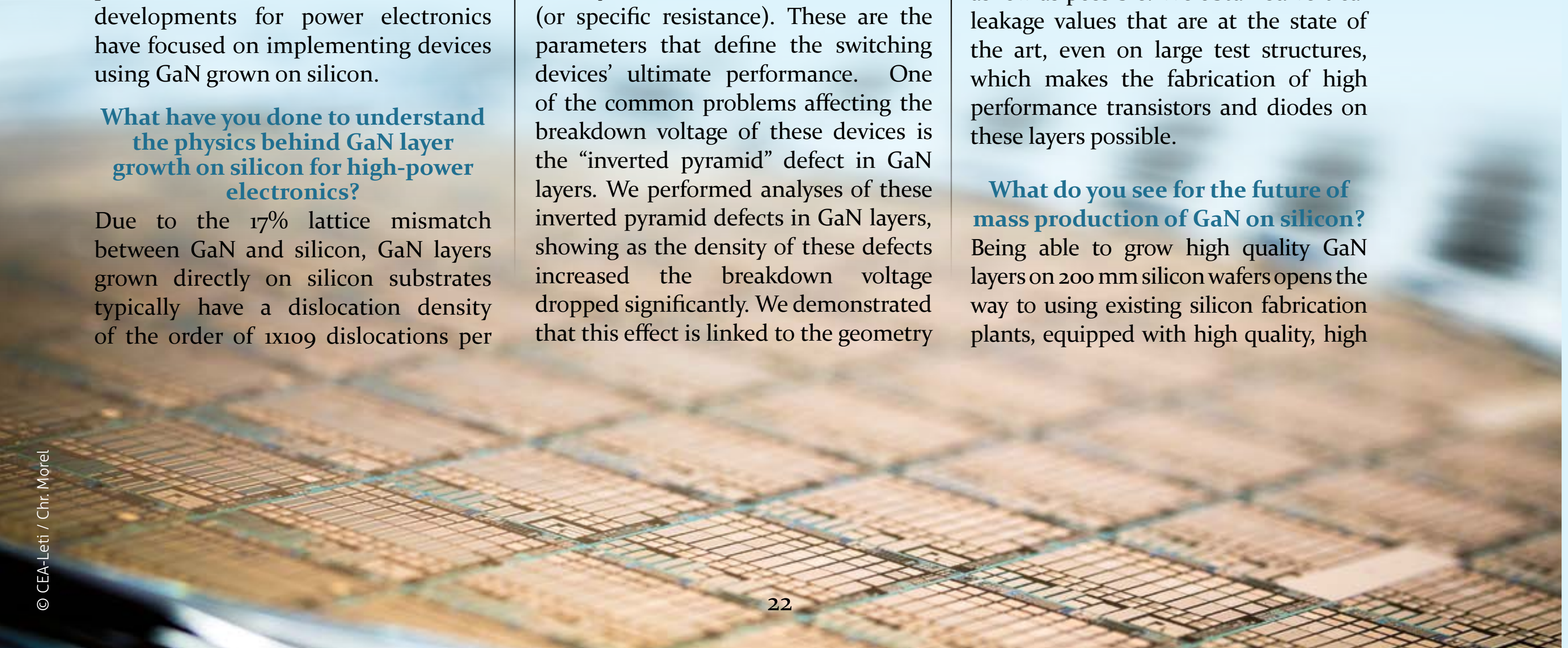
We performed a detailed study of the growth of an AlN nucleation layer on silicon, examining the order in which the different AlN elements were introduced and the amounts of aluminum and nitrogen used. We were able to develop high quality layers that were optimized to reduce the density of the inverted GaN pyramid defects and obtain resulting devices with high breakdown voltages.

In addition, we performed further research to develop the buffer layers which are implemented between the AlN nucleation layer and the GaN layers. These buffer layers should ensure that the wafer remains unbowed after GaN layer growth, and that the leakage current through the different layers is as low as possible. We obtained vertical leakage values that are at the state of the art, even on large test structures, which makes the fabrication of high performance transistors and diodes on these layers possible.

What do you see for the future of mass production of GaN on silicon?

Being able to grow high quality GaN layers on 200 mm silicon wafers opens the way to using existing silicon fabrication plants, equipped with high quality, high throughput equipment, to integrate new advanced materials and obtain higher performance devices. And using existing silicon infrastructures is key in producing competitively priced components that can truly compete with silicon.

Other reductions in all types of defects, macro-, micro- and nano-scale, will further improve device performance. Future work will focus in this direction and on reducing vertical leakage while increasing breakdown voltage. By understanding the physics behind these improvements, we are able to make fast progress towards even higher performance transistors and diodes.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Breakthrough

Optimization of AlN nucleation layers and AlGaN buffer layers to significantly reduce the density of macro-defects of GaN on silicon devices and their vertical leakage current.

Why it's relevant

Leakage current and defect density should be reduced to very low levels to allow the fabrication of high performance efficient power transistors based on GaN for renewable energy switching and electrical vehicles.

Moving forward

Further reductions in leakage current with thicker structures, along with reduced point defect density, will result in even higher performance of high power electrical devices.

COLLABORATIONS
Exagan (France)
Université Grenoble Alpes (France)

FOR MORE DETAILS

"The Effect of AlN Nucleation Temperature on Inverted Pyramid Defects in GaN Layers Grown on 200mm Silicon Wafers"
M. Charles[1,2], Y. Baines[1,2], S. Bos[1,2], R. Escoffier[1,2], G. Garnier[1,2], J. Kanyandekwe[1,2], J. Lebreton[1,2], and W. Vandendaele[2]
[1]CEA-Leti, [2]Université Grenoble Alpes
Journal of Crystal Growth, vol.464, pp.164-167, April 2017

"Developments in Understanding the Nucleation of AlN on Silicon by MOCVD and its Effects on Defects"
M. Charles[1], A. Bavard[1,2], R. Bouis[1], Y. Baines[1], and R. Escoffier[1]
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Physica Status Solidi (A) Applications and Materials, vol.214 (4), Nov. 2016

02

The Virtues of Photons for the Connected Society

Photonics underpins technologies of daily life. Innovations in this field are pushing the performance limits of existing techniques in communications, imaging and displays. In the following highlights, we will show how highly sensitive HgCdTe APD detectors enable higher data rate communication of light signals over very long distances, thus facilitating inter-satellite communications. We will explain how sub-electron noise performance of CMOS image sensors achieved through circuit optimization will impact any application involving low-light illumination, e.g. in automotive or scientific applications and how the use of InGaN LEDs and pixels will improve hi-fidelity reproduction of colors in museum paintings and high-quality multi-color imaging in smart glasses. Moreover, we will present developments in silicon photonics compatible platforms that will also bring miniaturization and cost reduction to sensors and optical interconnections, key figures of the IoT market. The use of Germanium based materials for optical functions, like laser sources, will be described as well as their mass deployment in photonics-based IoT systems. We will also show that millimetric and micrometric scales are achievable for gas sensors thanks to miniaturized photoacoustic cells.

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***Interview** with Johan Rothman*
Leti scientist

Detecting a Handful of Photons at High Bandwidth:

Deep Space Communications Improved

A demonstration of key capabilities of photon detectors for space applications.

The more you increase the gain of Avalanche Photodiodes (APDs) without adding more than a negligible amount of noise, the better the sensitivity of photon detectors. In the early 2000s, it was shown that HgCdTe (mercury cadmium telluride) APDs perform far better in this regard than those based on other semi-conductor materials, making it possible to greatly improve their sensitivity, while maintaining a nearly constant signal-to-noise ratio (SNR).

More recently, there has been a special focus on developing detectors with high temporal resolution that can detect a very small number of photons operating under the hazardous conditions of deep space. Leti and partners have demonstrated that many space applications can be addressed using single element HgCdTe APDs.

What capabilities have you demonstrated with HgCdTe APDs designed to operate in space?

In 2016, Leti conducted the first space qualification tests of its HgCdTe APD technology, in collaboration with the CNES. The results were positive: the large area HgCdTe APD remained stable under high operating temperatures and gain, while undergoing photon irradiation followed by a long-term endurance test. The results showed that this APD can indeed be used for a number of space applications.

More recently, in another set of tests, we demonstrated that our HgCdTe APDs could achieve 4 GHz bandwidth. This result confirms our earlier estimations on the response time limitations in HgCdTe APDs, and provides evidence that bandwidths in the order of 10 GHz can be achieved with such devices.

Where will HgCdTe APDs operating in space have the biggest impact?

The HgCdTe APD is an enabling technology for inter-satellite communications in global Internet networks, where their high sensitivity can be used to reduce the complexity of the terminals, increase bandwidth, and/or reduce emitted laser power. Access to Internet everywhere will have a strong societal impact and is the application where we expect the largest number of detectors to be used—as many as a hundred thousand— and the highest revenues to be made once industry is able to manufacture the detectors.

HgCdTe APDs are sure to make a significant contribution in a number of other fields. Their use for deep space optical telecommunications will allow space vehicles exploring the far reaches of our solar system to send more data back to earth. The higher the data collection capacities of these explorers, the bigger the data rate they will need.

Another field of application is environmental science, in which the detectors can be used to study our atmosphere from space, to keep an eye on things like the exchange and storage of greenhouse gases. This will result in a better understanding of the dynamics of greenhouse gases, thereby helping us to improve our climate models.

Finally, the ability of HgCdTe APDs to detect single photons at very high rates will improve both the data rate and the level of security in the transfer of cryptographic keys, and will open new scientific perspectives in the field of quantum optics.

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Breakthrough

HgCdTe Avalanche Photodiodes can operate reliably at high bandwidth, in space conditions.

Why it's relevant

Highly sensitive detectors allow higher data rate communication of light signals over very long distances.

Moving forward

Detectors need to operate at even higher bandwidths (6 to 10 GHz) to support Internet everywhere and more advanced deep-space applications.

COLLABORATIONS
Institut Pierre Simon Laplace/LMD (France)
Centre National d'Études Spatiales (France)
Institut de Planétologie et d'Astrophysique de Grenoble (France)
CEA-IRFU (France)

FOR MORE DETAILS

"HgCdTe APDs for Time Resolved Space Applications"
J. Rothman[1], G. Lasfargues[1], B. Delacourt[1], A. Dumas[2], F. Gibert[2], A. Bardoux[3], and M. Boutillier[3]
[1]CEA-LETI, [2]Institut Pierre Simon Laplace/LMD, [3]Centre National d'Études Spatiales
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J. Rothman, CEA-Leti
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"MCT APD Focal Plane Arrays for Astronomy at CEA-Leti"
J. Rothman[1], E. de Borniol[1], O. Gravrand[1], P. Kern[2], P. Feautrier[2], J-B. Le Bouquin[2], and O. Boulade[3]
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Interview *with Arnaud Peizerat*
Leti scientist

SUB-ELECTRON NOISE ON CMOS IMAGE SENSORS:

More than Just Better Night Time Selfies

A new technique to squeeze readout noise on CMOS image sensors down to well below one electron


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One way to improve the performance of CMOS-compatible image sensors is to reduce the noise level in situations where noise is particularly intolerable—for example, when there is little light. Any such improvements will impact a number of applications, ranging from defense and security all the way to taking selfies with a smartphone at night.

How were you able to get sub-electron noise levels?

To boost performance under low light conditions, the noise of the whole readout chain has to be minimized, starting with thermal noise, using conventional circuit techniques, such as bandwidth control, in-pixel or column-level amplification, and correlated multiple sampling (CMS). Once you reduce the thermal noise, the 1/f noise originating from the pixels becomes the primary contributor to overall noise.

At the circuit level, correlated double sampling (CDS) and CMS significantly reduce that 1/f noise—but not enough to reach sub-electron noise performance. To further reduce the 1/f noise, pixel-level optimization is required. The purpose of our work was to exploit the very few degrees of freedom left to the designer, in a standard process—to get the input-referred TRN (temporal readout noise) below one electron, which is the state-of-the-art noise performance.

We achieved the low noise performance exclusively through circuit optimization, without any process refinements. What's more, our techniques can be combined with any known additional noise reduction techniques to further reduce the TRN.

We expect this breakthrough to impact all applications involving low-light illumination, enhancing image sensors for automotive or scientific use, and improving high-end cameras in general.

What more needs to be done to benefit even further from your work?

The next step is to adapt our methods to industrial specifications, and make them work in a real industrial context.

COLLABORATIONS
École Polytechnique Fédérale de Lausanne (Switzerland)
Pyxalis (France)

FOR MORE DETAILS

“Temporal Readout Noise Analysis and Reduction Techniques for Low Light CMOS Image Sensors”
A. Boukhayma[1,2], A. Peizerat[2], and C. Enz[1]
[1]École Polytechnique Fédérale de Lausanne,
[2]CEA-Leti
IEEE Transaction on Electron Devices,
Jan. 2016

“A Sub-0.5 Electron Read Noise VGA Image Sensor in a Standard CMOS Process”
A. Boukhayma[1,2], A. Peizerat[2], and C. Enz[2]
[1]École Polytechnique Fédérale de Lausanne,
[2]CEA-Leti
IEEE Journal of Solid-State Circuits,
Sept. 2016

Breakthrough

Demonstration that sub-electron readout noise can be achieved in low–light situations.

Why it's relevant

Sub-electron noise levels on CMOS-based image sensors will enhance a number of applications areas, including medical, security, industrial, vision, defense, and scientific imaging.

Moving forward

Further research should exploit the fact that these noise reduction techniques can be combined with any known additional noise reduction technique to further reduce the temporal readout noise.

USING InGaN AS THE SINGLE MATERIAL FOR LIGHT EMITTING DIODES

Interview *with Amélie Dussaigne*
Leti scientist

On how to increase the Indium content in InGaN, while preserving high material quality

Using a single material for all colors is the ideal approach to LEDs, because it simplifies color control, impacting a variety of applications that require high-quality color rendering—from high-fidelity reproduction of colors in museum paintings to high-quality multi-color imaging in smart glasses. An InGaN alloy can theoretically cover the whole visible range, and is therefore a good candidate for being that single material. However, the main drawback is that, in general, as the indium content in the InGaN alloy increases, the material quality decreases.

How were you able to raise the indium content without losing material quality?

The issues to overcome are the low miscibility of indium in gallium nitride, and the high lattice mismatch between the GaN buffer layer and the InGaN quantum wells. We have tackled the latter by reducing the indium compositional pulling effect in InGaN based quantum wells, making it possible to increase the indium incorporation rate and thus to easily reach long wavelength emissions, from blue to red, using the same material.

Our solution could enable three- or four-color LEDs (RGB or RGBY) for high quality lighting—smart lighting reproducing solar spectrum as a function of the time of day, lighting in museums with high color rendering index, and so on. It can also be used in multi-color micro displays, for which three colored pixels (RGB) are needed.

What new possibilities has your work with InGaN opened?

The first application we'll see using this approach will probably be a multi-color micro display, which won't require a lot of efficiency in the near term. In the long run, our work may lead the way to closing the green gap—that is, to produce green LEDs with high efficiency, and to reach red emission using InGaN based material with much better efficiency than the actual state of the art.

We will also continue to evaluate substrates for long wavelength emissions with a special focus on the red emission.

Breakthrough

A full InGaN structure grown on a novel substrate technology that allows InGaN quantum wells to combine a high Indium content with great material quality.

Why it's relevant

Higher Indium content will raise the color-rendering index for high quality lighting; and using the same material for all pixels in three-pixel RGB will enhance multi-color micro displays.

Moving forward

Bridge the green gap and explore ways of using InGaN-based material for red emission.

COLLABORATIONS Soitec (France)

FOR MORE DETAILS

“Enhanced Indium Incorporation in full InGaN Heterostructure Grown on Relaxed InGaN Pseudo-Substrate”
A. Even[1], G. Laval[1], O. Ledoux[1], P. Ferret[1],
D. Sotta[2], E. Guiot[2], F. Lévy[1], I.C. Robin[1],
and A. Dussaigne[1]
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“Bridging the Green Gap with a New Foundation”
A. Dussaigne[1] and D. Sotta[2]
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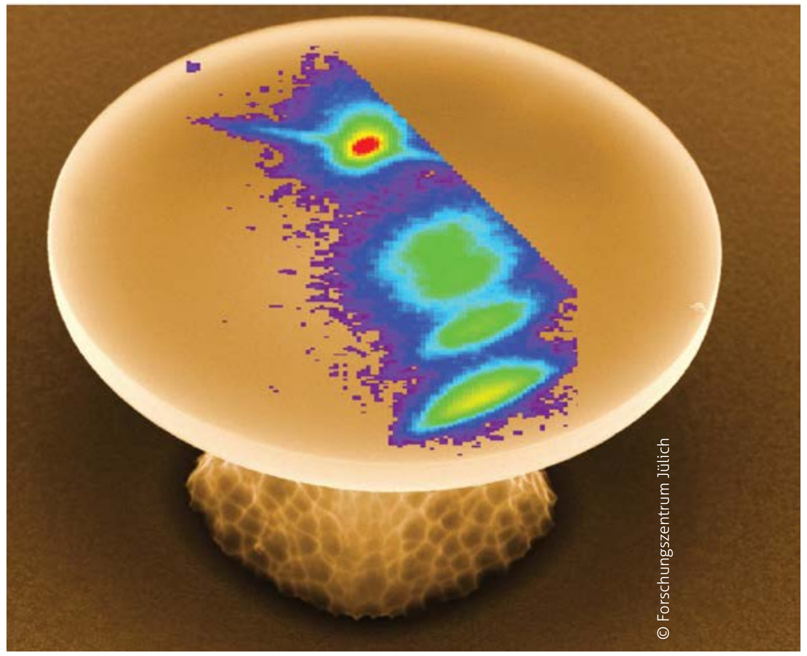
Compound Semiconductor, July 2017

***Interview** with Vincent Reboud*
Leti scientist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GeSn GROWN ON Si

Providing Better Optical Functions for Large Scale CMOS Compatible Photonic Applications

A new approach for growing high crystalline quality GeSn on wafers will result in improved optical functions that impact a variety of application areas, ranging from process control to optical data communications.

While silicon (Si) photonics has the advantage of being fully compatible with the current massively produced Si complementary metal-oxide semiconductor (CMOS) technology, Si is a poor choice for efficiently emitting light. Germanium (Ge) based materials, such as germanium-tin alloys (GeSn, SiGeSn) or tensile-strained Ge, are also fully CMOS compatible, and are an alternative to III-V lasers, whose integration on Si is rather complex. But one big challenge remains: transforming the indirect group-IV semiconductor bandgap into a direct bandgap using high tensile strains and/or by alloying germanium with tin.

How have you paved the way for optical platforms based on GeSn?

We demonstrated that the use of step-graded GeSn buffers enables the growth of high crystalline quality GeSn layers with high Sn content on the full surface of 200mm wafers with no significant Sn segregation. We also showed that lasing operates from 25K to 180K with 16% of Sn content in GeSn layers at a wavelength of 3.1 µm.

Finally, we verified that lasing in GeSn layers up to 180 K can be attributed to three factors. The first is a stronger band offset between the L- (indirect) and the Γ- (direct) valleys stemming from a higher Sn content. The second is a better crystalline quality of the GeSn layers grown on top of step-graded GeSn buffers. And the third is that carrier confinement inside the lowest bandgap top layer prevents recombination in the more defective GeSn bottom layers.

What further work needs to be carried out to get GeSn to the point where it can be used by industry as an optical platform?

Our aim is to demonstrate room temperature electrically pumped Ge-based lasers. One next step is to reduce the threshold of our lasers, using surface passivation and carrier confinement layers, for example. We also plan to increase the temperature of the lasing operation by controlling larger energy splitting between Γ- and L- valleys in high Sn-content layers using tensile strain; and we intend to inject efficient carriers in heterostructures by electrical pumping. Finally we aim to integrate electrically pumped Ge-based lasers on a full silicon/germanium photonic platform on GeOI substrates.

COLLABORATIONS
Paul Scherrer Institute (Switzerland)
Forschungszentrum Jülich (Germany)
CEA-INAC (France)

FOR MORE DETAILS

“Optically Pumped GeSn Micro-Disks with 16 % Sn Lasing at 3.1 µm up to 180K”
V. Reboud[1], A. Gassenq[2], N. Pauc[2], J. Aubin[1], L. Milord[1], Q. M. Thai[2], M. Bertrand[1], K.Guilloy[2], D. Rouchon[1], J. Rothman[1], T. Zabel[3], F. Armand Pilon[3], H. Sigg, A. Chelnokov[3], J.M. Hartmann[1], and V. Calvo[2]
[1]CEA-LETI, [2]CEA-INAC, [3]Paul Scherrer Institute
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"Germanium Based Photonic Components Toward a Full Silicon/Germanium Photonic Platform"
V. Reboud[1], A. Gassenq[2], J.M. Hartmann[1], J. Widiez[1], L. Virot[1], J. Aubin[1], K. Guilloy[2], S. Tardif[2], J.M. Fédéli[1], N. Pauc[2], A. Chelnokov[1], and V. Calvo[2]
[1]CEA-Leti, [2]CEA-INAC
Progress in Crystal Growth and Characterization of Materials, vol. 63 (2), pp. 1-24, May 2017

Breakthrough

Demonstration of techniques to grow high crystalline quality GeSn on a 200mm wafers, with no significant Sn segregation, and validation of the lasing characteristics and direct bandgap behavior of the resulting GeSn.

Why it’s relevant

These results pave the way for fully integrating group IV laser sources in short-wave infrared and mid-infrared Si photonic systems, both for sensing applications and on-chip/chip-to-chip short range optical interconnects.

Moving forward

Further research should be directed towards increased lasing temperature operation using surface passivation and carrier confinement layers.

***Interview** with Jean-Guillaume Coutard*
Leti scientist

MINIATURIZED PHOTOACOUSTIC CELLS:

Towards Mass Deployment of Sensors that Detect Trace Gases

These low-cost, miniaturized photoacoustic (PA) cells open up opportunities to detect trace gases over wide areas.

A PA cell is an extremely sensitive optical sensor that can be used to detect gases. When light is emitted at wavelengths that target the molecules of interest, these generate acoustic waves that the optical sensor can detect.
The problem is, PA cells are cumbersome and expensive—and this inhibits mass deployment for a variety of applications, including monitoring greenhouse gases and detecting pollutants inside houses and buildings.

What have you done to miniaturize PA cells and bring down their cost?

We designed, built, and characterized two miniaturized PA cells, based on the differential Helmholtz resonator (DHR) principle. We then used commercial MEMS (micro-electro-mechanical system) microphones to detect the differential PA signal.
We built the first cell by stacking several laser-cut stainless steel sheets and obtained a cell constant at resonance frequency of 1,710 Pa/(W.cm-1). Using a 2.2 mW optical power DFB-ICL laser, we obtained a gas detection limit of 650 ppbv of methane at 2,979 cm-1. The manufacturing technique, based on metal sheet stacking, is not expensive but some issues with gas leakage must be managed carefully.

The second cell, made by DMLS (direct metal laser sintering), is highly airtight, easier to build and remains a low cost solution. With this second cell we achieved a nearly two-fold improvement of the cell constant 3,840 Pa/(W.cm-1) using the same laser and microphones, and a detection limit of 92 ppbv for methane.

What more research needs to be carried out to move miniaturized PA cells closer to industrialization?

Our work served to demonstrate the DHR principle at the centimeter scale. Ongoing work should aim to bring this design to millimetric and micrometric scales on a silicon platform.

Breakthrough

The design, implementation, and characterization of two low-cost, miniaturized photoacoustic cells, based on the differential Helmholtz resonator principle.

Why it’s relevant

Miniaturizing photoacoustic cells and reducing their cost, will enable mass deployment for large IoT applications.

Moving forward

The photoacoustic cell design will be brought to millimetric and micrometric scales and will be integrated onto silicon.


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COLLABORATIONS
mirSense (France)
GSMA-CNRS, Université de Reims Champagne-Ardenne (France)

FOR MORE DETAILS

“Development of a High Performance Miniaturized Photoacoustic Gas Sensor”
J.G. Coutard[1], J. Rouxel[1], M. Brun[2], O. Lartigue[1], S. Nicoletti[1], F. Badets[1], M. Carras[2], and A. Gliere[1]
[1]CEA-Leti, [2]mirSense
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“Miniaturized Differential Helmholtz Resonators for Photoacoustic Trace Gas Detection”
J. Rouxel[1,2], J.-G. Coutard[1], S. Gidon[1], O. Lartigue[1], S. Nicoletti[1], B. Parvitte[2], R. Vallon[2], V. Zéninari[2], and A. Glière[1]
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[2]GSMA-CNRS, Université Reims Champagne-Ardenne
Sensors and Actuators B: Chemical, vol.236 (29), pp.1104-111, Nov. 2016

03

Novel Technologies to Improve *Human Health*

Life expectancy has increased steadily throughout history and has brought with it new challenges in biomedical research. Micro and nanotechnologies are expected to play a central role in developing new preventive, diagnosis and therapeutic tools to allow us to live longer and in greater health.

One of neuroscience's priorities today is to develop innovative implantable stimulation methods that can treat and even prevent age related neurodegenerative diseases. In advanced medicine, the focus is on developing smart drug delivery and monitoring systems to reduce severe side-effects and dosage. Research and development of safe and personal health monitoring systems that minimally disturb everyday life are expected to improve patient compliance and well-being, and non-invasive lab on chip methods and connected Point of Care tools will increase patient autonomy.

All of these devices will be able to connect to medical service centers and will generate massive amounts of data. The digital patient era is well on its way.

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***Interview** with Cécile Moro*
Leti scientist

Delivering Near-Infrared Radiation Intra-Cranially:

Fighting Root Causes of Parkinson’s Disease

A new intracranial optical fiber device can deliver near-infrared radiation (NIR) at close enough range to have a protective impact on neurons.

Currently the only treatment for Parkinson’s disease is to relieve the symptoms. But, as soon as treatment is stopped, the symptoms come back and the disease continues to advance. Now, for the first time, scientists have demonstrated a strikingly neuro-protective therapy to fight root causes.

How was Leti able to demonstrate that NIR might be an effective therapy against Parkinson’s disease?

Parkinson disease manifests itself after the progressive death of dopaminergic cells in an area of the midbrain called sustantia nigra pars compacta (or SNc). There is in vitro evidence suggesting that NIR mitigates or prevents the degeneration of the dopaminergic cells in the midbrain, and NIR has been viewed, for some time now, as a promising therapy against Parkinson’s disease.

But to find out whether NIR is really neuro-protective, you have to first overcome the challenge of getting the signal all the way to the targeted tissue. The problem is that when NIR is delivered from outside the cranium, the relatively long distance the light has to travel is such that its energy is reduced to a negligible, or even non-existent, quantity.

So, we developed an intracranial optical fiber device that is minimally invasive to deliver NIR near the SNc, ensuring that the targeted cells receive sufficient energy. We implanted a device that delivered NIR (670nm) to the midbrain of macaque monkeys, close to the substantia nigra of both sides of the brain. MPTP, a neurotoxin that causes symptoms of Parkinson’s disease, was injected (in doses of 1.5–2.1mg/kg) over a 5- to 7-day period, during which time the NIR device was turned on. This was then followed by a 3-week survival period. Monkeys were evaluated clinically (for example, for posture and bradykinesia), and their brains were processed for immunohistochemistry and stereology.

During the period when the MPTP generated severe clinical signs and considerable cell loss, NIR offset these signs and reduced the death of cells. These findings suggest that NIR has a neuro-protective effect, and might therefore serve as a therapeutic agent to fight against the root causes of Parkinson’s disease.

What more needs to be done to start using your intracranial optical fiber device to fight Parkinson’s disease?

The next step is to perform clinical trials. We think this will happen soon. In developing the device we took special care to make sure it conforms to regulatory requirements, so that when the time comes to perform trials on humans, it’s ready to go.

COLLABORATIONS
The University of Sydney (Australia)

FOR MORE DETAILS

“Near-Infrared Light is Neuroprotective in a Monkey Model of Parkinson’s Disease”
F. Darlot[1], C. Moro[1], N. El Massri[2], C. Chabrol[1], D.M. Johnstone[2], F. Reinhart[1], D. Agay[1], N. Torres[1], D. Bekha[1], V. Auboiroux[1], T. Costecalde[1], C.L. Peoples[2], H.D. Anastascio[2], V.E. Shaw[2], J. Stone[2], J. Mitrofanis[2], and A.L. Benabid[1]
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[2]University of Sydney
Annals of Neurology, vol.79 (1), pp.59-75, Jan. 2016

“Turning On Lights to Stop Neurodegeneration: The Potential of Near Infrared Light Therapy in Alzheimer’s and Parkinson’s Disease”
D.M. Johnstone[2], C. Moro[1], J. Stone[2], A.L. Benabid[1], and J. Mitrofanis[1]
[1]CEA-Leti
[2]University of Sydney
Front Neuroscience, vol.9, Jan. 2016

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Breakthrough

The first optical fiber device was implanted into a midbrain site in monkeys, 5 to 10 mm from the substantia nigra, delivering near-infrared radiation to the affected tissue.

Why it’s relevant

Our findings suggest that NIR is neuro-protective in a non-human primate model of Parkinson’s disease; and our work serves as a template for what can be done in clinical trials on human patients.

Moving forward

Clinical trials will be run in the near future.

***Interview** with Cédric Allier*
Leti scientist


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LENS-FREE MICROSCOPY:
A New Tool for Fast and Convenient Diagnosis of Meningitis

Small, rapid, and automatic, this new method for diagnosing meningitis is perfectly suited for point-of-care testing

Until now, diagnosing meningitis has required an operator using an optical microscope to count leukocytes and erythrocytes in cerebrospinal fluid (CSF). Unfortunately, bulky equipment and excessive human intervention make this approach inappropriate for point-of-care (POC) testing, which means meningitis cannot be diagnosed in a number of cases, including emergency service, surgery room analysis, and routine medical care in developing countries.

Recognizing this need, Leti developed a miniaturized system and an accompanying methodology for diagnosing meningitis in a POC device.

What was your approach for POC diagnosis of meningitis and how did you demonstrate its efficacy?

We set out to develop an operator-free method that takes less than 10 microliters of CSF to find leukocytes and erythrocytes in a POC environment, using very small equipment capable of connecting to the lab's information systems.

We considered lens-free microscopy to be most appropriate for our purposes. Based on in-line holography, this emerging microscopy technique starts by illuminating objects with a plane light wave. Then, a CMOS sensor records the holographic pattern resulting from the interference between the light diffracted by the micrometric structures and the incident wave. A large field-of-view (around 30 square millimeters) can be instantaneously acquired; and, thanks to a phase retrieval algorithm, the image of every single cell present in the sample can be recreated.

We ran a proof-of-concept to demonstrate the performance of these techniques and compare it to the traditional approach involving operators and optical microscopy. We found that the lens-free technology has the same level of reliability as optical microscopy, but that the lens-free technology operates much quicker, requires much less human intervention and is far easier to reproduce and disseminate.

What further research do you expect will result from this breakthrough?

We chose the diagnosis of meningitis as our starting point to develop these methods. But given their high potential, we believe that in the future this same approach could be used to address other pathologies that might be diagnosed by analyzing CSF using a POC device. Furthermore, similar methods can be developed to analyze bodily fluids other than CSF.

COLLABORATIONS
Université Aix Marseille/INSERM, CNRS, IRD, URMITE (France)

FOR MORE DETAILS

"Cerebrospinal Fluid Lens-Free Microscopy: a New Tool for the Laboratory Diagnosis of Meningitis"
R. Delacroix[1], S.N.A. Morel[2], L. Hervé[2], T. Bordy[2], J.M. Dinten[2], M. Drancourt[1], and C. Allier[2]
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Nature Scientific Reports, vol.7, Jan. 2017

Breakthrough

A digital solution, using lens-free microscopy and algorithms specifically designed to provide rapid diagnosis of meningitis.

Why it's relevant

The small size and automated nature of this new system make it perfectly suited for point-of-care diagnostics.

Moving forward

Other pathologies will be addressed, and other bodily fluids tested.

***Interview** with*
Vincent Agache
Leti scientist

SERIAL SUSPENDED MICROCHANNEL RESONATOR ARRAYS:
Measuring Single-Cell Growth Quickly

Highly accurate, high-throughput technology for measuring cell growth enables personalized drug therapies.

A suspended microchannel resonator (SMR) determines the mass of a cell in aqueous environments. It does this by measuring the changes in the resonance frequency of a vibrating hollow cantilever as a cell flows through the U-shaped channel buried in the resonator. By using an SMR cantilever to repeatedly flow a cell back and forth, you can plot a cell's growth by observing the change in mass over time.

But the problem is that until now, it had been impossible to simultaneously study more than one cell because only a single SMR had been implemented per chip—and this throughput limitation had severely constrained the applicability of SMRs.

How have you made SMRs practical for widespread use?

By serially connecting SMRs in an array, with ten to twelve cantilevers per array, we've allowed many cells to traverse the device simultaneously. With this configuration, our collaborators from MIT demonstrated the capacity to observe the full distribution of growth behaviors among a population of cells. What's more, all this can be done very quickly—serial SMR arrays can measure single-cell mass accumulation rates for up to 60 mammalian (or 150 bacterial) cells, per hour, with a mass resolution of 0.2 pg per hour for mammalian cells and 0.02 pg per hour for bacteria.

This work paves the way for many applications that measure the sensitivity of cells and bacteria to drugs, so that, for example, antibiotics can be tested. The microchip not only tracks the dynamic growth of cells reacting to environmental changes, but it also enables tests to determine susceptibility to antibiotics of a very small number of bacteria, with results being available within one hour. By comparison, traditional techniques would require growing a culture of bacteria for at least a day prior to running tests.

The ability to take cells from a patient biopsy, put those cells in a complex mixture, and detect unusual growth behavior from a subset of the cell population suggests that growth patterns can be correlated with disease states. We can also assess how those rare cells react to drugs.

What more can be done to reap the benefits of high-throughput SMR?

As this breakthrough enables clinical in vitro testing of the effects of drugs on cells, it's sure to impact personalized cancer therapy. By observing weight changes in tumor cells as they react to anticancer drugs, this device can be used to predict a patient's response to a given therapy. Outside of medical applications, the serial SMR system could be used to quantify cellular heterogeneity to determine how cell growth is intrinsically tied to a broad array of molecular-scale phenomena.

COLLABORATIONS
Dana-Farber Cancer Institute (USA)
Massachusetts Institute of Technology (USA)
Harvard Medical School (USA)
Innovative Micro Technology (USA)
Broad Institute, Cambridge (USA)

FOR MORE DETAILS

"High-Throughput Single-Cell Growth Measurements via Serial Microfluidic Mass Sensor Arrays"
N. Cermak[1], S. Olcum[1], F.F. Delgado[1], S.C. Wasserman[1], K.R. Payer[1], M. Murakami[2], S.M. Knudsen[1], R.J. Kimmerling[1], M.M. Stevens[1], Y. Kikuchi[1], A. Sandikci[1], M. Ogawa[3], V. Agache[4], F. Baléras[4], D.M. Weinstock[1,5], and S.R. Manalis[1]
[1]Massachusetts Institute of Technology, [2]Harvard Medical School, [3]Innovative Micro Technology, [4]CEA-Leti, [5]Broad Institute, Cambridge
Nature Biotechnology, vol.34 (10), pp.1052-1059, Oct. 2016

Breakthrough

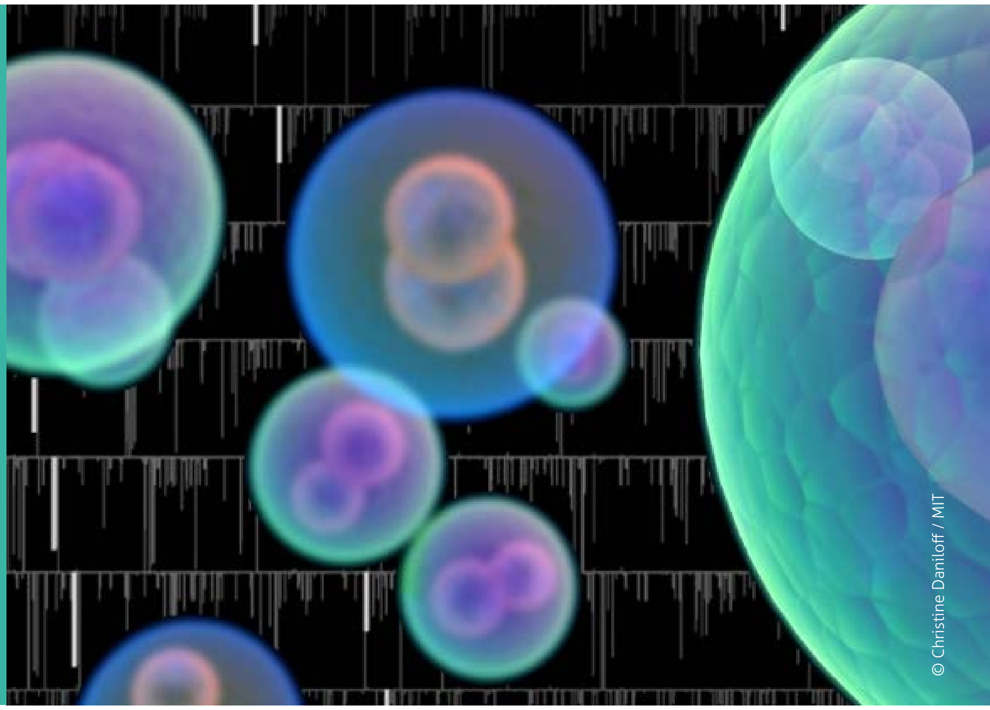
Serial suspended microchannel resonator arrays that provide a high-throughput method for weighing cells.

Why it's relevant

Measuring the growth of individual cells within a large population makes it possible to determine the reaction variability to a given substance, such as drugs or antibiotics.

Moving forward

Personalized cancer therapy, and an improved understanding of the link between cell growth and a wide range of microscopic phenomena.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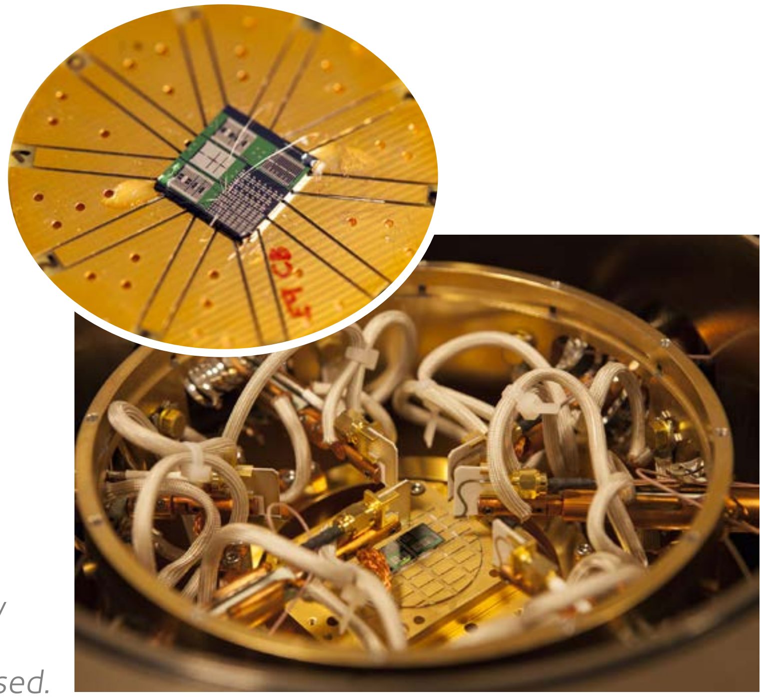
***Interview** with Sébastien Hentz*
Leti scientist



SOLVING THE MYSTERY OF UNKNOWN NOISE IN NANORESONATORS

to Identify Infinitesimal Traces of Biological Species or Gases

Nanoresonators could never get close to their theoretical minimum frequency fluctuations. By understanding why, the accuracy of nanoscale mass and force measurements has been increased.

Nanoresonators detect minute variations in frequency, which makes them well suited for measuring mass (for example, to identify and quantify traces of gases or help diagnostics by precisely weighing viruses) and force (for example, to study how DNA interacts with proteins). But accuracy has been limited by background noise that scientists have always assumed to be of thermal origin.

Now, a team of scientists has overturned that assumption, identifying the source to be in the mechanics of the device itself—a breakthrough that will help improve sensor accuracy by several orders of magnitude.

What did you do to figure out the real source of noise in nanoresonators?

We reviewed the vast majority of frequency stability measurements reported from experiments in the scientific literature, and we noticed that the experimental observations differed widely from what was predicted by theory. So we decided to eliminate all the possible causes one by one, through a combination of brainstorming and experimentation.

In the process, we developed an experimental technique that allows researchers to assess the loss of resolution and quantify how much the measurement system (the technique used for resonance frequency readout is noisy and introduces uncertainty) and the device itself (fluctuations of resonance frequency, so far always disregarded) contribute to that loss. Using this technique, we eliminated several other possible sources of noise.

In the end, fluctuations of the device's resonance frequency, the so-called mechanical noise, was the only cause we couldn't rule out, so we knew that had to be the source.

We then tested our hypothesis by running an experiment. Normally you would perform measurements right at resonance frequency. But we closely studied the signal on either side of the resonant frequency. Noise in the measurement system would have no reason to be identical at two different frequencies, but still we observed the same noise. This finding identified the mechanical noise as the source.

Now that you've identified the source of noise to be mechanical, what more should be done?

We need to figure out exactly what mechanical processes are causing the noise and then find a way of mitigating them. Our main suspicion is that the cause is related to defects in the crystalline lattice that may move over time. Depending on the exact source of the mechanical noise, it may be possible to raise the frequency of resonators from the megahertz to the gigahertz range, which would lead to increased resonator sensitivity.

COLLABORATIONS
California Institute of Technology (CalTech) (USA)
Indian Institute of Science, Bangalore (India)
École Polytechnique Fédérale de Lausanne (Switzerland)

FOR MORE DETAILS

"Frequency Fluctuations in Silicon Nanoresonators"
M. Sansa[1], E. Sage[1], E.C. Bullard[2], M. Gély[1], T. Alava[1], E. Colinet[1], A.K. Naik[3], L.G. Villanueva[4], L. Duraffourg[1], M.L. Roukes[2], G. Jourdan[1], and S. Hentz[1]
[1]CEA-Leti, [2]California Institute of Technology (CalTech), [3]Indian Institute of Science, Bangalore
[4]EPFL
Nature Nanotechnology, vol.11, pp.552–558, Feb. 2016

Breakthrough

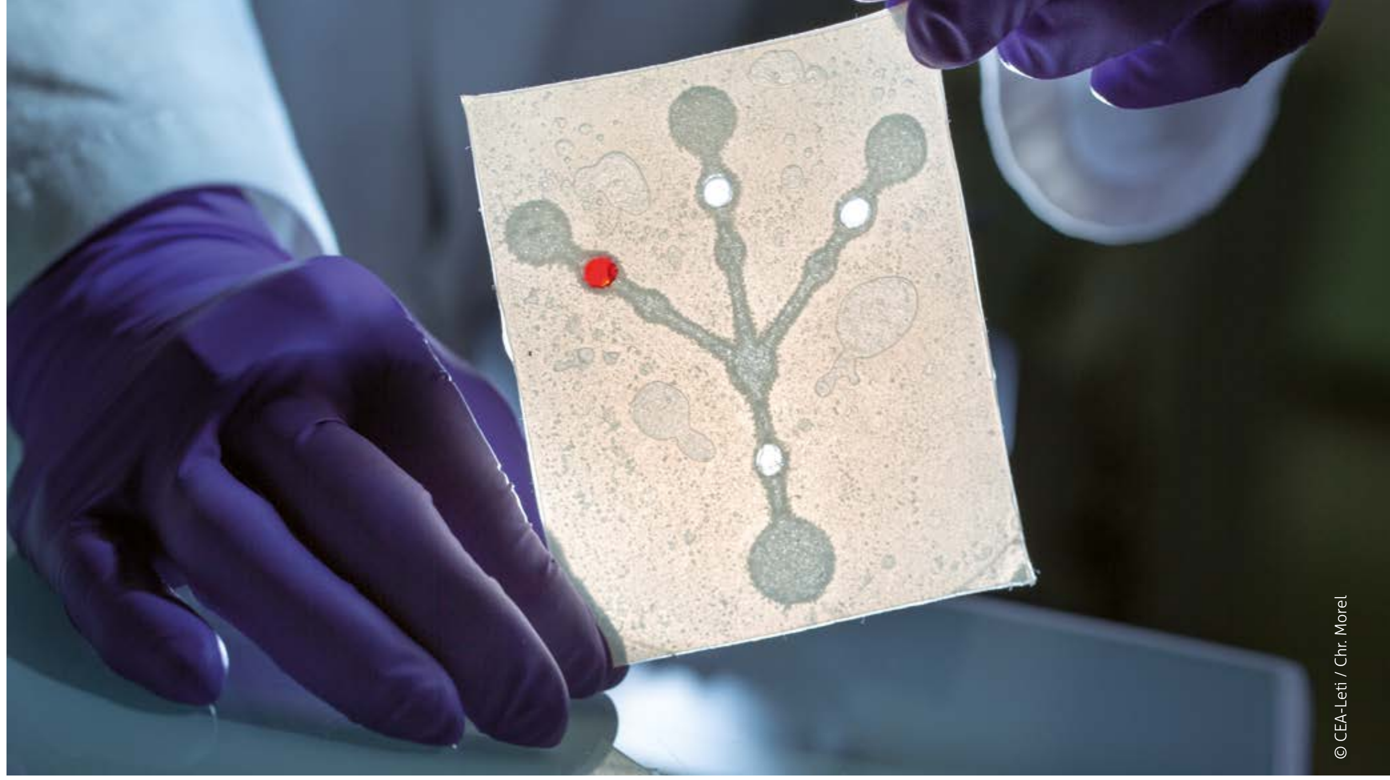
Identifying mechanical noise as the source of inaccuracy in nanoresonators.

Why it's relevant

Having identified the source of the noise we can now work towards improving sensor accuracy by several orders of magnitude to be able to detect infinitesimal traces of gases or viruses.

Moving forward

New integration schemes will be used to analyze physico-chemical interface phenomena.



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Interview
with Yves Fouillet
Leti scientist

FOAM BASED MICROFLUIDIC DEVICES:

A User-Friendly Lab-On-A-Chip

A new class of low-cost, user-friendly microfluidic devices enable lab-on-a-chip applications, and much more.

A team of scientists developed a new method for producing low-cost microfluidic devices based on the combination of open-cell polyurethane foam and a hyper-elastic silicon rubber. The resulting devices are highly flexible, and can be handled in a user-friendly manner – for example, the user can just apply pressure with his or her hand.

How do the materials you use revolutionize the production of microfluidic devices?

Open-cell polyurethane foams are already used in bandages because they have a number of interesting properties — elasticity, porosity, and high fluid retention, to name a few. What's more, they are already mass-produced at a low cost. By combining those foams with a hyper-elastic polymer we have obtained fluidic channels that are highly elastic and can be mass-produced.

To test this new material in a real application, we developed a foam device that performs blood type testing. We then used this prototype to demonstrate the capabilities of our new microfluidics device to handle blood and store liquids and dried reagents without compromising data accessibility in cases where, for example, electronic images need to be made.

Now that you've introduced this new class of microfluidic devices, what lies ahead?

Near-term research will focus on optimizing mass production – for example, reducing scale, using other types of foam, and using roll-to-roll production techniques that are similar to those used for bandages.

Other research will aim at applying this technology to areas that can benefit from the deformability of the material and the simplicity of the technology—applications such as point-of-care medical diagnostics, in vitro cultivation of cells, and value-added bandages that provide wound therapy.

Breakthrough

A new method for producing low-cost microfluidic devices using an original composite made of polyurethane foam and hyper-elastic silicon rubber.

Why it's relevant

The unique mechanical and structural features of polymeric foam offer a number of advantages over materials currently used to make microfluidic devices, for example, the use of either manual compression or external actuation for contamination-free monitoring of microfluidic flows.

Moving forward

This new technology will be optimized for mass production, and a variety of medical applications will be developed.

COLLABORATIONS
SIMaP (Grenoble-INP/Université Grenoble-Alpes/CNRS) (France)

FOR MORE DETAILS

"Foam-Based Microfluidics: Experiments and Modeling with Lumped Elements"
G. Gropplero[1,2], L. Davoust[2], S. Arnoux[1], Y. Fouillet[1], and F. Revol-Cavalier[1]
[1]CEA-Leti, [2]SIMaP (Grenoble-INP/Université Grenoble-Alpes/CNRS)
Microfluid Nanofluid, vol.20, Dec. 2016


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***Interview** with Myriam Cubizolles*
Leti scientist

Automatic Measurement of Agglutination:

A Fast and Reliable Method of Detecting Proteins and Viruses

A new protocol and image-processing algorithms automatically measure agglutination.

When specific reagents are introduced into a blood sample, the cells containing the proteins that are targeted by the reagents react by clumping—a response known as agglutination. An experienced operator can detect the presence of the targeted cells by spotting that clumping through a microscope.

While this protocol is widely used today, it has a number of drawbacks. First, it requires the presence of an experienced operator to perform a number of relatively slow manual steps (which makes these procedures inappropriate for Point-Of-Care or POC testing, where the operator is usually the patient and where speed is of the essence). The protocol is also prone to human error both in the handling of the samples and in the detection of agglutination. Finally, the protocol and the equipment do not facilitate data exchange with laboratory information systems.

How did you come up with a quick and automatic method to measure agglutination that can be used in POC devices?

We designed a microfluidic chip that incorporates a reagent and in which the movement of liquid samples occurs through capillary flow. Because the reagent is already in the device, the experimental protocol is simple. The capillary flow moves the fluid through the device, preventing accidental fluid projections induced by forced flow actuation, thereby reducing the risk of contamination for the human operator.

As the sample passes through the device, digital images are captured by an optical microscope—and those images are analyzed by two algorithms we developed that use correlation and variance of gray levels to monitor the kinetics of agglutination in real-time.

This microfluidic device quantifies agglutination in real-time, is simple to use, all but eliminates human error and is compatible with laboratory information systems. What's more, to facilitate industrialization of the device, we designed it in such a way that it requires no assembly steps and is compatible with rapid, low-cost industrial manufacturing through injection molding.

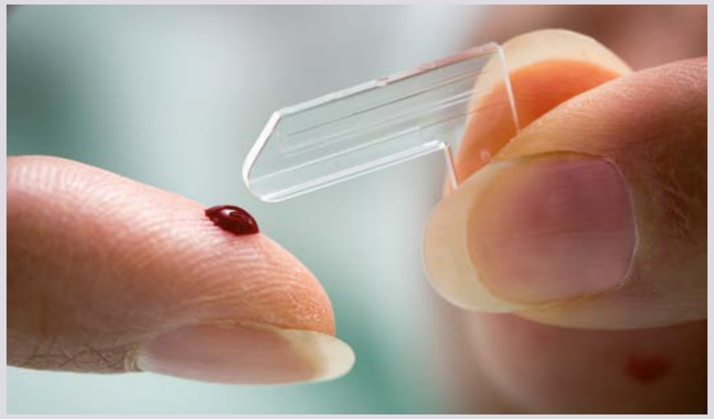
How did you demonstrate your technology and protocol?

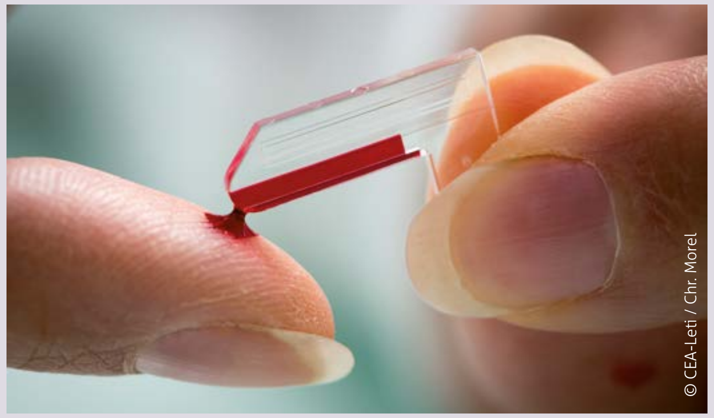
We developed a proof-of-concept around ABO forward blood typing by hemagglutination. Our proof-of-concept consisted of two biochips with embedded reagents—one had an anti-A reagent, the other an anti-B reagent. The blood flowed through the microfluidic device thanks to capillary flow and a video recording was made of the blood through a microscope.

The algorithms were used to process the image sequence to see if agglutination took place in one biochip but not the other, in both biochips, or in neither biochip. Accordingly, the blood was identified as A, B, AB, or O. The results of our test were one hundred percent correct, discrimination between positive and negative agglutinations taking place within less than two minutes.

Now that you've demonstrated this approach using ABO blood typing, what further research do you expect will result from your work?

This work opens up possibilities of new research around a large set of potential POC applications beyond ABO blood typing, which could lead to the detection and quantification of efficient biomarkers through hemagglutination techniques or even latex agglutination assays.

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Breakthrough
An integrated biological protocol and two image-processing algorithms suitable for automatic analysis in Point-Of-Care systems.

Why it's relevant
Suitable for Point-Of-Care, this technology will simplify disease detection and dramatically reduce human error.

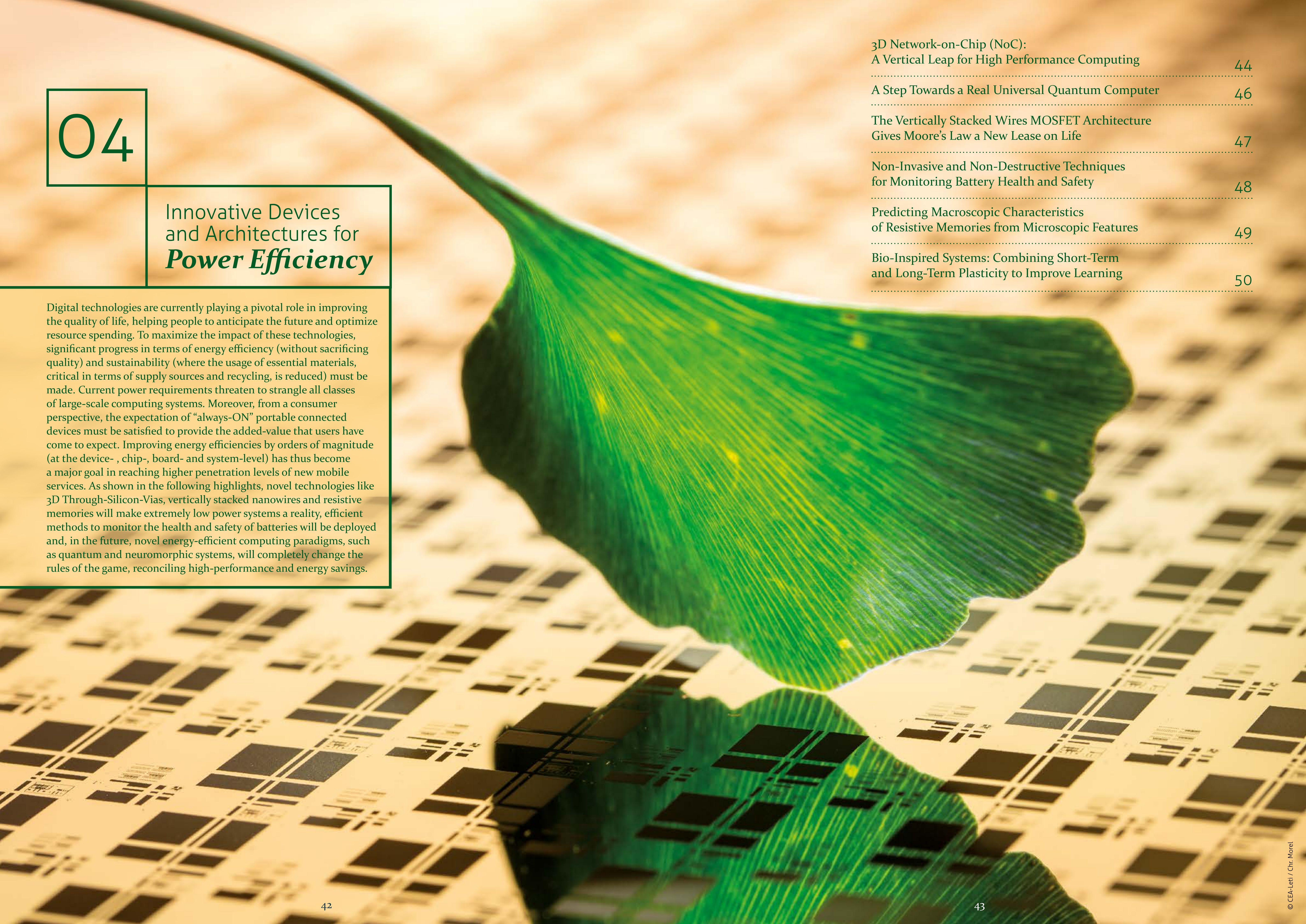
Moving forward
Further research will focus on efficient detection and quantification of cancer biomarkers, cardiovascular diseases and metabolic diseases by hemagglutination assays or latex agglutination assays.

COLLABORATIONS
CEA-INAC (France)
Avalun (France)

FOR MORE DETAILS

"Real Time Observation and Automated Measurement of Red Blood Cell Agglutination inside a Passive Microfluidic Biochip Containing Embedded Reagents"
M. Huet[1], M. Cubizolles[1], and A. Buhot[2]
[1]CEA-Leti, [2]CEA-INAC
Biosensors and Bioelectronics, pp.110-117,
July 2017

"Method for Determining the Particle Agglutination Level in a Sample"
Inventors: M. Huet and J.-G. Coutard, CEA
Patent published in 2016 - EP3076156



04

Innovative Devices and Architectures for ***Power Efficiency***

Digital technologies are currently playing a pivotal role in improving the quality of life, helping people to anticipate the future and optimize resource spending. To maximize the impact of these technologies, significant progress in terms of energy efficiency (without sacrificing quality) and sustainability (where the usage of essential materials, critical in terms of supply sources and recycling, is reduced) must be made. Current power requirements threaten to strangle all classes of large-scale computing systems. Moreover, from a consumer perspective, the expectation of "always-ON" portable connected devices must be satisfied to provide the added-value that users have come to expect. Improving energy efficiencies by orders of magnitude (at the device- , chip-, board- and system-level) has thus become a major goal in reaching higher penetration levels of new mobile services. As shown in the following highlights, novel technologies like 3D Through-Silicon-Vias, vertically stacked nanowires and resistive memories will make extremely low power systems a reality, efficient methods to monitor the health and safety of batteries will be deployed and, in the future, novel energy-efficient computing paradigms, such as quantum and neuromorphic systems, will completely change the rules of the game, reconciling high-performance and energy savings.

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Innovative Devices and Architectures for
Power Efficiency

Interview *with Pascal Vivet*
Leti scientist

3D Network-on-Chip (NoC):

A Vertical Leap for High-Performance Computing

The implementation of the world's first power-efficient, silicon-based 3D communication infrastructure marks a significant milestone in the evolution of computing architectures.

Thanks to this breakthrough, it's now more likely than ever that you will get high-definition video streaming on your smartphone. Not only will this work result in performance improvements on mobile devices connecting to 5G networks, the same model can also be applied to large servers to provide noticeable improvements in any application of high-performance computing (HPC). Scientists might find new exoplanets faster, or they might discover large prime numbers in less time than they could before; enterprises will spot trends in their markets more quickly by applying Big Data techniques to large unstructured data sets; and meteorologists will be able to provide more accurate weather forecasts.

What was the driving force behind this achievement?

Big jumps in processing power are no surprise to those of us who have been observing the results of Moore's Law over several decades. Long before Moore's law began to approach the inevitable physical limits of miniaturization, researchers had started coming up with other ways of enhancing overall performance. Sometimes collectively referred to as "More than Moore", these techniques have already provided orders of magnitude improvements in processing power without relying on increased transistor density.

One such approach is to use a three-dimensional (3D) architecture to stacks dies vertically so they are physically closer to one another, resulting in reduced latency. But viable 3D architectures require certain features that, until now, had not been proven to work in concert.

To serve as a viable backbone for a computing architecture, 3D Networks on Chip (NoC) must allow for asynchronous communication among heterogeneous components—some dies are large, others are small; some are special purposed, others are for more general use; some serve as volatile memory, others as processors. The ideal system should enable heterogeneous 3D technologies to be assembled in various configurations, similarly to Legos, to be able to serve different application areas. Moreover, it would be great as it could also provide fault tolerance through component redundancy.

Finally, with so much processing occurring in such close proximity, the architecture must manage power consumption and heat dissipation.

How does Leti's 3D technology advance the state of the art?

Leti validated several innovations with a proof-of-concept, demonstrating that the implementation of the 3D NoC using asynchronous logic provides robust communication in the context of Process Voltage Temperature (PVT) variations, and in the context of the high temperatures inherent to 3D architectures. It was also shown, and measured on silicon, that it is the lowest energy consumption yet seen for 3D communication. Finally, the fault tolerance mechanisms and testability of the 3D NoC infrastructure was shown to work by using additional spare through-silicon-vias (TSVs), and by employing a two-step test-and-repair mechanism.

Is the future of computing architectures still what it used to be?

Not at all. The 3D scheme will allow designers to rethink computing architectures in ways that weren't possible before. This technology will offer better memory latency access, and it will improve inter-die communications. Because 3D technology allows for a much tighter integration between processing and memory, the classical opposition between computing and memory will certainly be re-visited.

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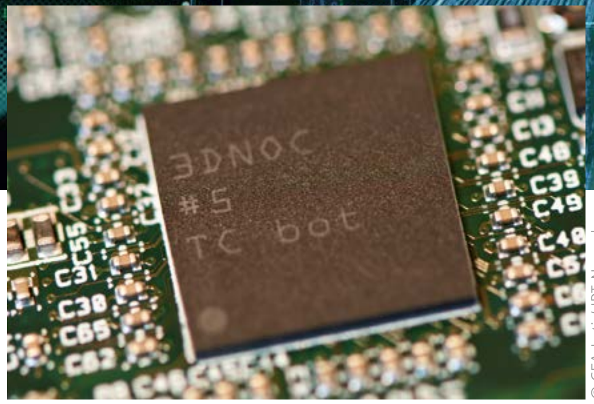

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Breakthrough

The world's first in-silicon implementation of a power-efficient 3D communication infrastructure, providing scalability and modularity for large-scale circuits.

Why it's relevant

It enables fundamental improvements in computing architectures—heterogeneous components can communicate asynchronously in the vertical direction.

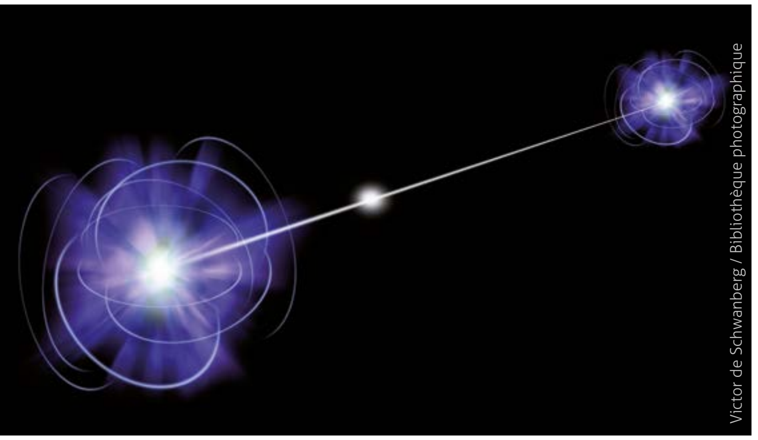
Moving forward

The 3D scheme will allow designers to rethink computer architectures, revisiting the classical opposition between computing and memory—and to facilitate modularity, 3D communications should be standardized.

COLLABORATIONS
STMicroelectronics (France)
Mentor Graphics (France)
TIMA Laboratory/UGA/INPG (France)

FOR MORE DETAILS

"A 4 × 4 × 2 Homogeneous Scalable 3D Network-on-Chip Circuit with 326 MFlit/s 0.66 pJ/b Robust and Fault Tolerant Asynchronous 3D Links"
P. Vivet[1], Y. Thonnart[1], R. Lemaire[1], C. Santos[1], E. Beigné[1], C. Bernard[1], F. Darve[1], D. Lattard[1], I. Miro-Panades[1], D. Dutoit[1], F. Clermidy[1], S. Cheramy[1], H. Sheibanyrad[1], F. Pétrot[2], E. Flamand[3], J. Michailos[3], A. Arriordaz[4], L. Wang[4], and J. Schloeffel[4]
[1]CEA-Leti, [2]TIMA Laboratory/UGA/INPG,
[3]STMicrolelectronics, [4]Mentor Graphics
IEEE Journal of Solid-State Circuits, vol.21 (1), pp.33-49, Jan. 2017


Victor de Schwanberg / Bibliothèque photographique

***Interview** with Maud Vinet*
Leti scientist

A Step Towards a Real Universal QUANTUM COMPUTER

A team of scientists in Grenoble demonstrated for the first time that qubits can be implemented on a silicon chip with foundry-compatible processing

This breakthrough opens perspectives in terms of fabricating a real universal quantum computer. Up to billions of qubits are required and so far the only industry capable of making billions of similar objects is the semi-conductor industry.

How does this breakthrough open new potential for quantum computing?

Each of the small number of algorithms capable of taking advantage of quantum computing requires billions of physical qubits to produce worthwhile results. However, none of the current approaches can integrate more than a few tens of qubits today. And looking forward, mainstream approaches (ions and superconductors) will face intrinsic challenges in terms of volume when it comes to such a big number of qubits. That's where Silicon spin qubits are serious contenders: our results support the hope of being able to build a universal quantum computer. One key asset of Silicon is also that its material properties are very favorable to quantum coherence preservation and as such should ease the computer design. It's not the first time qubits have been implemented on Silicon. But it's the first time it has been done with an object derived directly from an industrial CMOS process, with all the materials and dimensions that are compatible with what you find in commercial chips nowadays. This should speed up the development towards industrialization.

We believe that the "VLSI Si CMOS" could leverage the robustness of the semiconductor industry's technological processes for high-density integration, and could be of particular relevance to scaling quantum circuits up to levels matching the specifications of future quantum supercomputers.

What steps need to be taken to further advance your approach to quantum computing?

So far, we've only implemented a system with one qubit. There's a lot of work still needed to integrate a billion qubits with all the circuitry and the fault tolerance algorithms that correct errors faster than they occur. There are also challenges in terms of integration density and power dissipation. Remember that Si spin qubits typically operate at temperatures below 1 Kelvin.

The next step towards feasibility will be to demonstrate that we are able to control a large assembly of quantum dots. Lots of questions are still open regarding the variability and the tunability of the dots because the regime of operation (single or few charges) is quite different than the MOS strong inversion regime (lots of carriers).

To address those challenges we will scan several designs of qubits and optimize materials and integration. In parallel, it will also be of prime interest to demonstrate all-electrical control of electron spins in silicon (a task far from trivial) and show that we can scale up to two-qubit gates with tunable quantum coupling between qubits. These are just a few of the things we need to work on in the near term.

COLLABORATIONS
CNRS/Institut Néel (France)
CEA-INAC (France)
Université Grenoble Alpes (France)

FOR MORE DETAILS

"Towards Quantum Computing in Si MOS Technology: Single-Shot Readout of Spin States in a FDSOI Split-Gate Device with Built-in Charge Detector"
M. Urdampilleta[1], L. Hutin[2], B. Jadot[1], B. Bertrand[2], H. Bohuslavskyi[2,3], R. Maurand[3], S. Barraud[2], C. Bäuerle[1], M. Sanquer[3], X. Jehl[3], S. De Franceschi[3], T. Meunier[1], and M. Vinet[2]
[1]CNRS/Institut Néel, [2]CEA-Leti, [3]CEA-INAC
Proc. of the Symposium on VLSI Technology, pp.T172-T173, June 2017

"SOI CMOS Technology for Quantum Information Processing"
L. Hutin[1], B. Bertrand[1], R. Maurand[2], M. Urdampilleta[3], B. Jadot[3], R. Bohuslavskyi[1,2], L. Bourdet[2], Y.-M. Niquet[2], X. Jeh[2], S. Barraud[1], C. Bäuerle[3], T. Meunier[3], M. Sanquer[2], S. De Franceschi[2], and M. Vinet[1]
[1]CEA-Leti, [2]CEA-INAC, [3]CNRS/Institut Néel
Proc. of the IEEE International Conference on IC Design and Technology (ICICDT), May 2017

Breakthrough

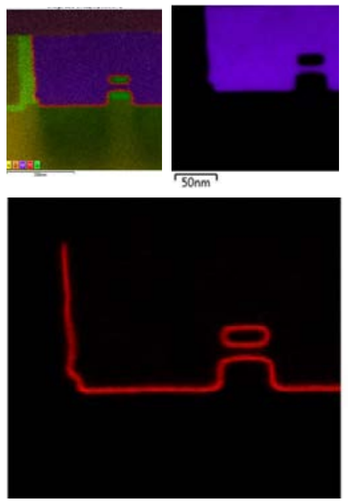
We've performed the first demonstration of an electrically-driven hole spin qubit in a Silicon On Insulator CMOS-derived device.

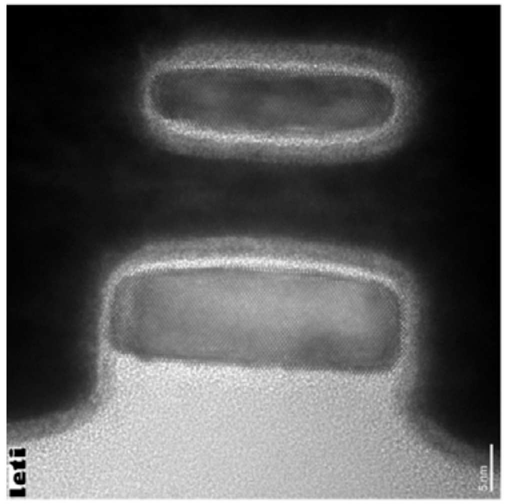
Why it's relevant

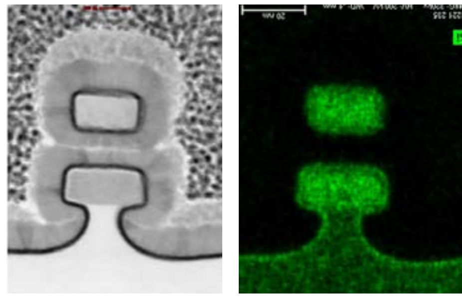
The Si MOS approach could be of particular interest both in terms of scaling quantum circuits up to billions of integrated qubits and because Si benefits from unique quantum coherence properties.

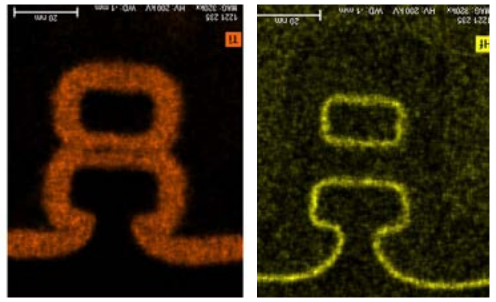
Moving forward

In the short term we want to quantify the variability of the qubits to show that the tunability makes controlling a large assembly of quantum bits possible.









***Interview** with Sylvain Barraud and Olivier Rozeau*
Leti scientists

THE VERTICALLY STACKED WIRES MOSFET ARCHITECTURE

Gives Moore's Law a New Lease on Life

Demonstrating the viability of vertically stacked wires MOSFET architecture, researchers have opened the door to further scaling of CMOS technologies.

As the laws of physics began imposing limits that prevent continued scaling of traditional CMOS technologies, researchers came up with new device architectures, such as Fully-Depleted Silicon-On-Insulator (FDSOI) and Fin Field-Effect Transistors (FinFET). To build the next generation of smartphones and connected devices, we now have a more advanced architecture with a new path towards more performance and less power consumption: the metal-oxide-semiconductor field-effect transistor (MOSFET) architecture based on vertically stacked silicon nanowires.

While several IC companies have already started including the vertically stacked wires MOSFET architecture in their roadmaps for sub-5 nanometer nodes, a handful of remaining obstacles have to be overcome before industrialization.

What have you done to move the vertically stacked wires MOSFET architecture further down the path to industrialization?

In addition to fabricating vertically stacked-nanowires MOSFETs in a replacement metal gate process, we developed a physically compact model for these new devices—a requirement for the design of integrated circuits. Based on a novel methodology for the calculation of the surface potential, this model is able to handle arbitrary nanowire cross-section shapes of vertically stacked-nanowires MOSFETs. Our model accounts for quantization effects induced by small nanowire cross-sections as well as additional physical features, such as electrical field dependence on mobility, short-channel effects and drain-induced barrier lowering, channel length modulation, access resistance with bias dependence, velocity saturation, gate current, gate-induced drain leakage and gate-induced source leakage, self-heating effects, and parasitic capacitances.

We validated our model, developed for both horizontal and vertical nanowire MOSFETs, with both numerical simulations and experimental data, demonstrating its high efficiency in all operation regimes. The agreement between the model and experimental data highlights the credibility of our quantitative estimate of nanowire gate-all-around [GAA] MOSFETs operation. Through this work, we demonstrate that vertically stacked wires MOSFET architecture is a viable solution in term of process integration, performance, and power consumption, meeting the requirements for the sub-5 nanometer CMOS technology nodes.

Our model is now ready to be used to design the first circuits based on nanowire GAA MOSFETs.

COLLABORATIONS
CEA-INAC (France)
STMicroelectronics (France)
IBM Research (USA)

FOR MORE DETAILS

"Vertically Stacked-Nanowires MOSFETs in a Replacement Metal Gate Process with Inner Spacer and SiGe Source/Drain"
S. Barraud[1], V. Lapras[1], M.P. Samson[2], L. Gaben[1,2], L. Grenouillet[1], V. Maffini-Alvaro[1], Y. Morand[2], J. Daranlot[1],N. Rambal[1], B. Previtalli[1], S. Reboh[1], C. Tabone[1], R. Coquand[1], E. Augendre[1], O. Rozeau[1], J. M. Hartmann[1], C. Vizioz[1], C. Arvet[2], P. Pimenta-Barros[1], N. Posseme[1], V. Loup[1], C. Comboroure[2], C. Euvrard[1], V. Balan[1], I. Tinti[1], G. Audoit[1], N. Bernier[1], D. Cooper[1], Z. Saghi[1], F. Allain[1], A. Toffoli[1], O. Faynot[1], and M. Vinet[1]
[1]CEA-Leti, [2]STMicroelectronics
Proc. of the IEEE International Electron Devices Meeting (IEDM), Dec. 2016

"NSP: Physical Compact Model for Stacked-Planar and Vertical Gate-All-Around MOSFETs"
O. Rozeau[1], S. Martinie[1], T.Poiroux[1], F. Triozon[1], S. Barraud[1], J. Lacord[1], Y. M. Niquet[2], C. Tabone[1], R. Coquand[1], E. Augendre[1], M. Vinet[1], O. Faynot[1], and J.-Ch. Barbé[1]
[1]CEA-Leti, [2]CEA-INAC
Proc. of the IEEE International Electron Devices Meeting (IEDM), Dec. 2016

Breakthrough

The first demonstration of the viability of the vertically stacked wires MOSFET architecture.

Why it's relevant

This MOSFET architecture extends the scaling limits of CMOS technologies, and is seen as a possible extension beyond FDSOI and FinFET.

Moving forward

Continued research will aim to improve process integration and model predictability.

***Interview** with Viviane Cattin*
Leti scientist

NON-INVASIVE AND NON-DESTRUCTIVE TECHNIQUES

for Monitoring Battery Health and Safety

*A new method for tracking electrochemical impedance of a battery will enable performance improvements in **electric vehicles and mobile devices.***

Several innovative industrial applications call for increasingly efficient Battery Management Systems (BMS) that continuously determine the state of a battery—and that do so in a non-invasive and non-destructive way. Now there's a new method for monitoring battery state that should bring significant improvements in electric vehicles, mobile devices, and many other fields.

What did you do to improve the measurement of the state of a battery?

We developed an algorithm that estimates the electrical impedance of a battery in real time. The proposed method not only allows for an accurate frequency impedance estimation, but also tracks its temporal evolution, a real advantage when compared to classical impedance spectroscopy methods.

With inexpensive modifications to the battery electronics (by superposing a current modulation on the cell), battery management systems are now able to access impedance and thermal information. They can provide finer indicators of the health and safety of batteries.

What new areas of research will open up thanks to your work?

In the short term, the integration of the management system with the microprocessor and the battery cell still needs to be improved. Further work is required to improve precision and robustness when estimating the battery's thermal profile.

Additionally, two new application areas should be developed. Firstly, precise impedance estimations could be used to predict thermal runaway in a battery. Secondly, statistical learning algorithms could be developed to exploit data coming from a large set of batteries, increasing in this way the robustness of the impedance estimation of each battery, for example, in a fleet of electric vehicles.

Breakthrough

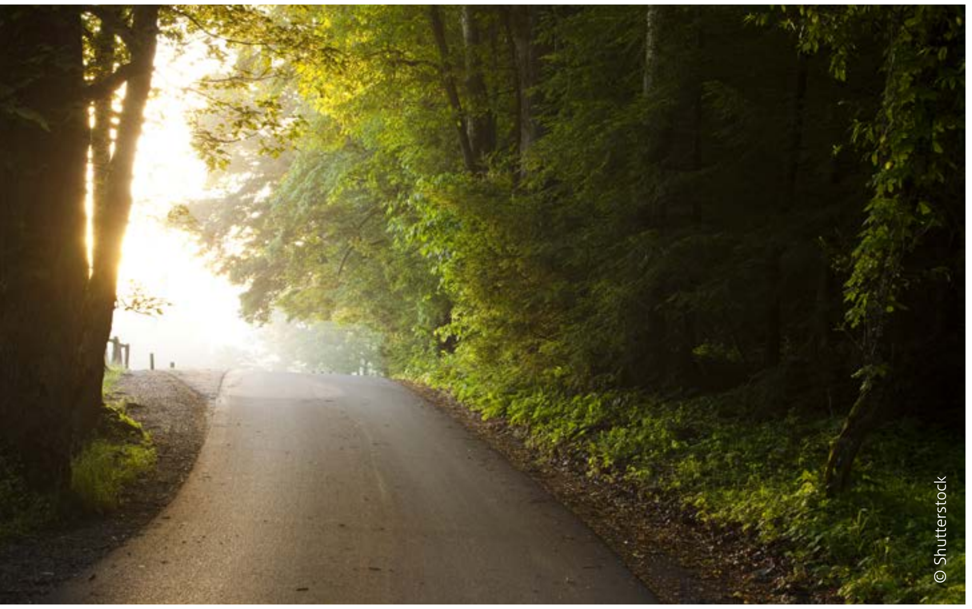
A time-varying algorithm that estimates the internal temperature of a cell by tracking the evolution of the electrochemical impedance.

Why it's relevant

With a few modifications to the battery electronics, the battery management systems will provide finer indicators of the health and safety of a battery, to enable perfomance improvements in electric vehicle.

Moving forward

The management system needs to be more tightly integrated with the battery cell. Impedance estimation need to be further improved to increase precision and robustness.



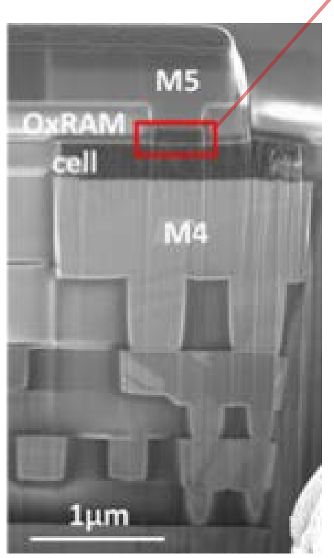
COLLABORATIONS
Université Grenoble Alpes/
Gipsa-Lab (France)
INES (France)
CEA-LITEN (France)

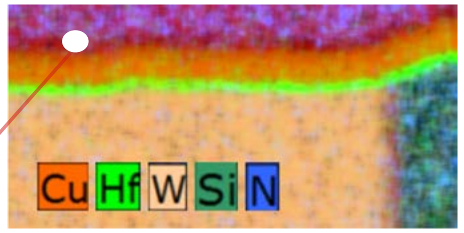
FOR MORE DETAILS

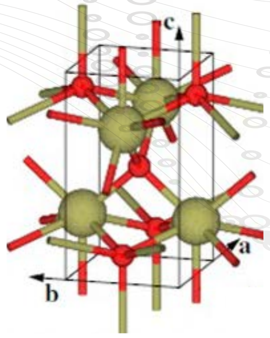
"Tracking of Electrochemical Impedance of Batteries"
H. Piret[1], P. Granjon[2], N. Guillet[3], and V. Cattin[4]
[1]CEA-Leti, [2]Université Grenoble Alpes/Gipsa-Lab, [3]INES, [4]CEA-LITEN
Journal of Power Sources, Vol.312, pp.60-69, April 2016

"Electronic Module for the Thermal Monitoring of a Li-ion Battery Cell through the Electrochemical Impedance Estimation"
M. Ranieri[1], D. Alberto[2], H. Piret[2], and V. Cattin[2],
[1]CEA-LITEN, [2]CEA-Leti
Proc. of the 22nd International Workshop on Thermal Investigations of ICs and Systems (THERMINIC), Sept. 2016

***Interview** with Gabriel Molas*
Leti scientist







PREDICTING MACROSCOPIC CHARACTERISTICS OF RESISTIVE MEMORIES

from Microscopic Features

Thanks to a new understanding of the relationship between the material properties of emerging memory technologies and the memory's performance, it's now possible to tailor memory design to a specific application.

Resistive RAM (RRAM) will have a major impact on a number of applications, including mass storage in cloud servers and embedded systems in consumer or automotive markets. But each application has a specific set of requirements, and designers need to be able to customize the technology for the application.

How has your work made it possible to design RRAM performance for specific applications?

We clarified for the first time the strict correlation between endurance, window margin and data retention of RRAM. We did this by investigating various classes of RRAM with high window margins or high data retention—for example, OXRAM [Oxide-based RAM] and CBRAM [Conductive Bridge RAM]. Using experimental data and modeling, we analyzed the conductive filament composition of the various RRAM technologies, and extracted their properties. This allowed us to define an analytical model linking material parameters and memory characteristics.

Now that we have understood the link between microscopic features and macroscopic behavior in RRAM, it becomes possible to design memory stacks that are optimized for a given application. For example, we now know that RRAM used in embedded automotive applications that require high thermal stability should be designed to include a high-ion migration barrier to ensure a low diffusion coefficient of the atoms constituting the filament. So, in that specific case, we would use OXRAM technology composed of HfO2/Ti instead of CBRAM.

In addition to embedded applications, we also focused on storage class memories for computing systems. We evaluated, at the system level, which emerging memory technologies would be the most efficient when used as DRAM [Dynamic RAM] for computing, and which for data storage in a solid-state drive or SSD. We found that for high endurance applications, RRAM based on Hfo2/CuTex should be used.

What more can be done to further improve RRAM technologies?

Our next focus will be on energy consumption—a critical concern for most of the applications using emerging memory technology. We are developing atomistic equations that model the causal relationship between the composition of conductive filaments and power efficiency. Additionally, we would like to perform characterizations at the array level, with new memories integrated in various configurations. We'd also like to discover smart programming techniques and performance tradeoffs that reduce energy expenditure. Finally, bringing all of these pieces together, we will be able to precisely predict gains in energy consumption.

Breakthrough

Modeling of the physical relationship between the resistive random access memory (RRAM) filament properties, the material composition and the memory behavior (endurance, window margin, and retention).

Why it's relevant

Given this new understanding, it is now possible to build optimized memory stacks to address specific applications, such as storage class memory for computing, data storage for servers, and automotive microcontrollers.

Moving forward

The next major challenge will be to find the atomistic equations which describe energy consumption in emerging memories.

COLLABORATIONS
IMEP/LAHC/CNRS (France)
CNRS/LTM (France)
WD San Jose Research Center (US)

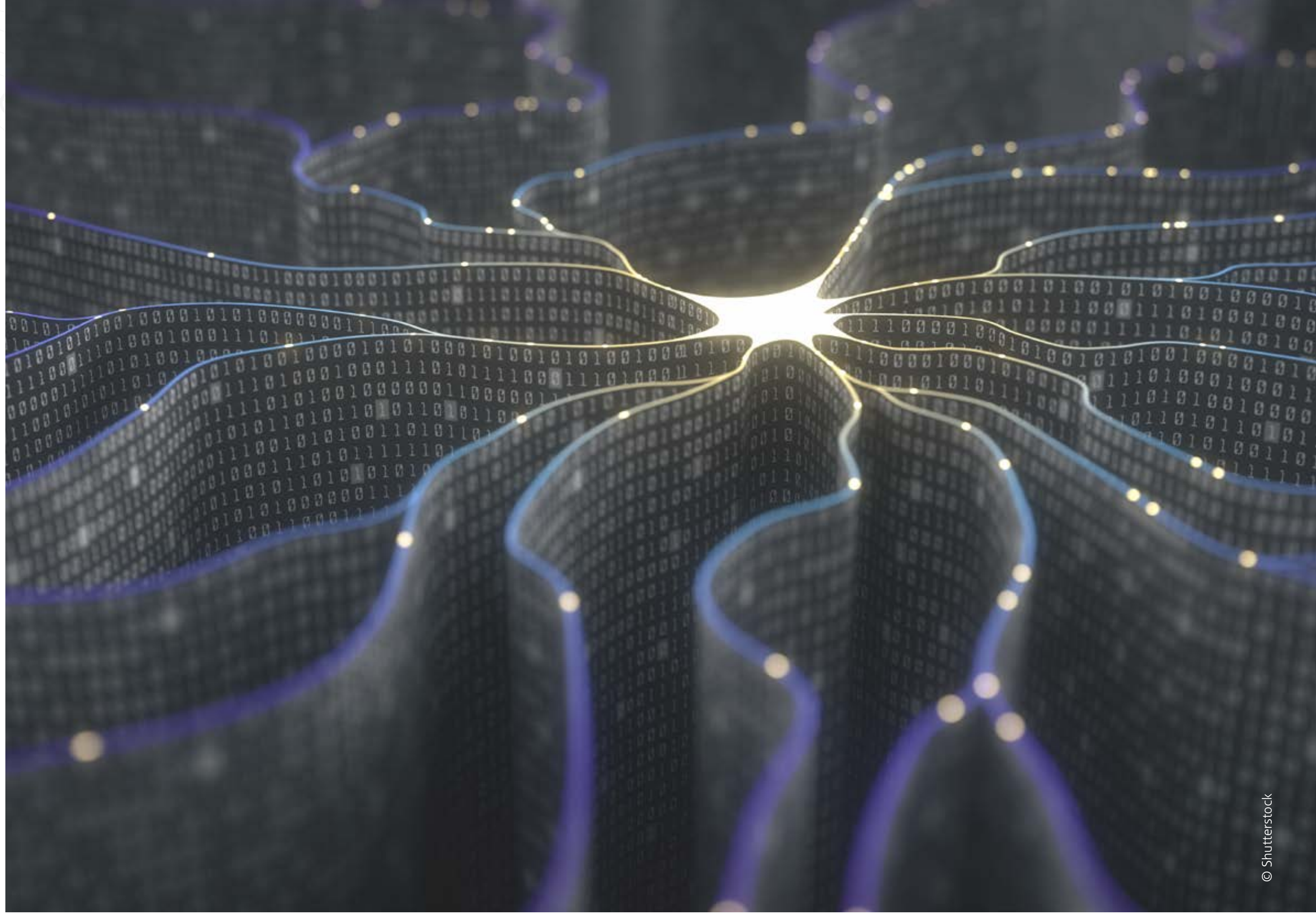
FOR MORE DETAILS

"Understanding RRAM Endurance, Retention and Window Margin Trade-off Using Experimental Results and Simulations"
C. Nail[1], G. Molas[1], P. Blaise[1], G. Piccolboni[1], B. Sklenard[1], C. Cagli[1], M. Bernard[1], A. Roule[1], M. Azzaz[1], E. Vianello[1], C. Carabasse[1], R. Berthier[1], D. Cooper[1], C. Pelissier[1], T. Magis[1], G. Ghibaudo[2], C. Vallée[3], D. Bedeau[4], O. Mosendz[4], B. De Salvo[1], and L. Perniola[1],
[1]CEA-Leti, [2]IMEP/LAHC/CNRS, [3]CNRS/LTM
[4]WD San Jose Research Center
Proc. of the IEEE International Electron Devices Meeting (IEDM), Dec. 2016

Interview *with Elisa Vianello*
Leti scientist

Bio-Inspired Circuits:
Combining Short-Term and Long-Term Plasticity to Improve Learning

Unsupervised learning in resistive memory neuromorphic circuits can be improved by simultaneously applying short-term and long-term plasticity, just like synapses operate in our brains.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Embedding learning into low-power neuromorphic devices could enable the design of autonomous systems, such as brain-machine interfaces that make decisions based on real-time, on-line processing of in-vivo recorded biological signals. While such systems may one day enable the design of autonomous implantable devices for rehabilitation, biological data are intrinsically noisy. Any such system must filter out bad input, learning only from the right data.

How are you using what we know about the brain's learning process to improve unsupervised learning in situations where input is particularly noisy?

Synaptic plasticity is the capability of synapses to enhance or diminish the connectivity between neurons, thereby providing the basis for learning and memory. Two forms of plasticity that co-exist in a biological synapse inspired us in our approach to unsupervised learning.

The first form of plasticity is "Hebbian Learning", whereby synaptic weight increases as both pre- and post- neuron activities increase. An example of synaptic learning is the spike timing dependent plasticity (STDP).

The second form of synaptic plasticity can be referred to as synaptic adaptation. In this case, synaptic weight modification depends on the pre-neuron activity only. What's more, in this second case, the weight modification is temporary, relaxing to its initial state with a characteristic time constant, which ranges from milliseconds to hours. Consequently, we refer to the synaptic adaptation as short-term plasticity (STP).

We developed an architecture and a programming strategy that implement both STDP and STP using two resistive memory (RRAM) devices. STDP allows our artificial neural networks to learn patterns in an unsupervised manner; STP makes the learning process very robust against environmental noise.

Why is minimizing noise essential to unsupervised learning?

Despite tremendous advances in machine learning, which has enabled functions like speech and image recognition in embedded systems, there are still fundamental deficits. For instance, most machine learning algorithms need to be trained with huge labeled data sets, a process we call supervised learning. For a machine to learn in an unsupervised setting, algorithms must filter out bad data, or noise. This is particularly important in the case of noisy and incomplete real-life sensor data analysis, as is the case with video, audio, or biological data.

RRAM devices are well suited to emulate synaptic plasticity, which makes them good platforms to support unsupervised learning. Thanks to spike time dependent plasticity, the system is capable of learning by using an unsupervised paradigm. The short-term plasticity makes it possible to improve accuracy in the presence of significant background noise in the input data.

Given what you've already accomplished, what more can be done to improve unsupervised learning?

Neuronal networks in the brain serve as proof that there does exist a computing paradigm that serves as a universal problem solver, adapting to diverse learning tasks, learning new things without complete regression. So a future scientific challenge is to set up a true interdisciplinary core team. The team should first gain an analytical understanding of the principles that allow biological neuronal networks to progressively learn new tasks while making use of the previously learned knowledge. Then the team should translate these basic principles to a new set of brain-inspired algorithms and associated neuromorphic hardware to create low-power autonomous intelligent systems capable of progressive learning.

Extracting principles from the way the brain works might well be a game-changer for the development and application of smart neuromorphic devices that are able to solve a large variety of real-world tasks in real time.

Breakthrough

A neuromorphic circuit architecture that implements both short-term and long-term plasticity rules using resistive random access memory (RRAM) arrays.

Why it's relevant

It enables efficient unsupervised learning in neuromorphic circuits in noisy environments.

Moving forward

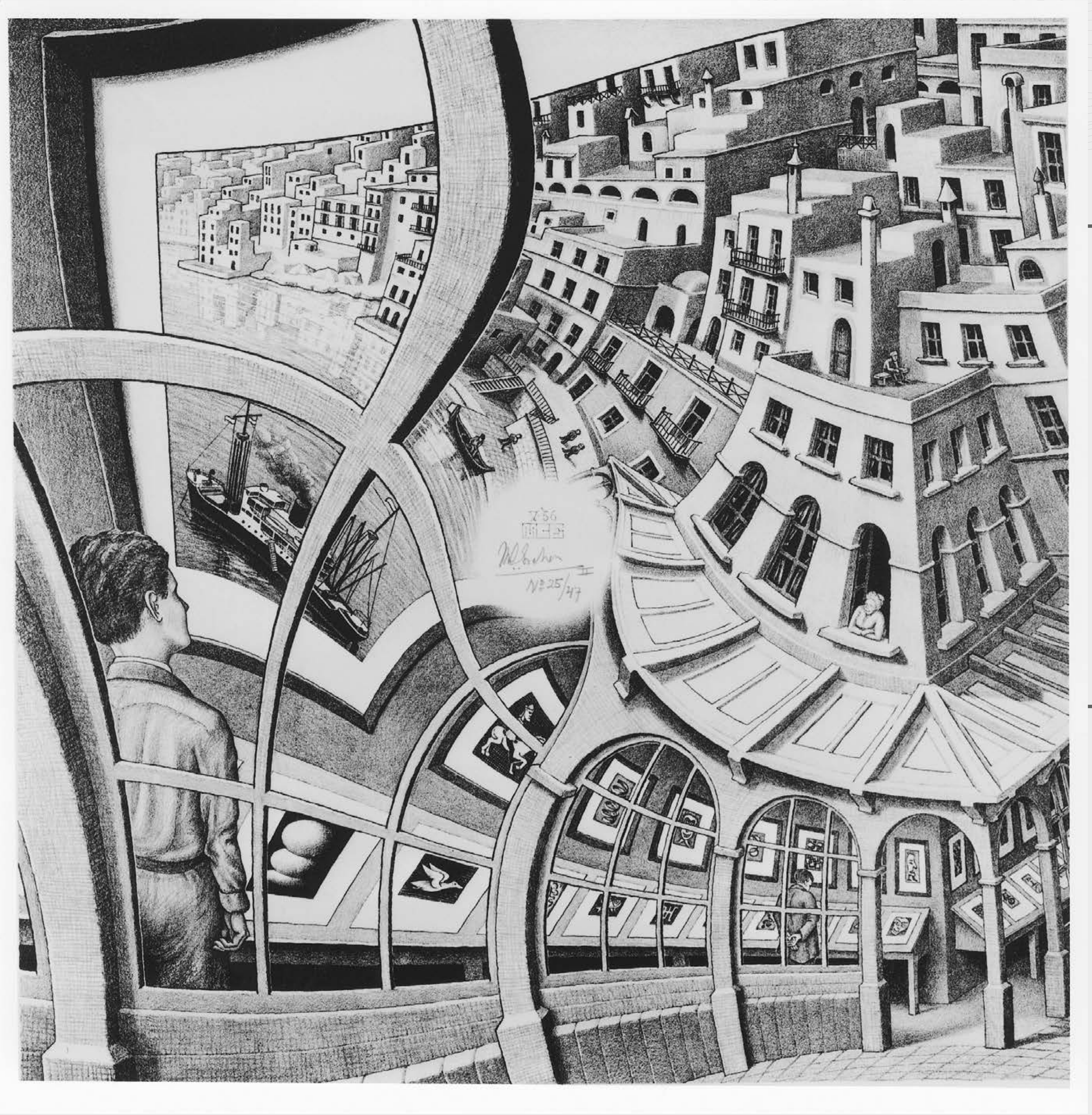
Reproducing the ability of intelligent biological systems to act as problem solvers and make use of previous knowledge for life-long learning.

COLLABORATIONS
CEA-List (France)
INSERM-Clinatec (France)

FOR MORE DETAILS

"Experimental Demonstration of Short and Long Term Synaptic Plasticity Using OxRAM Multi K-Bit Arrays for Reliable Detection in Highly Noisy Input Data"
T. Werner[1], E. Vianello[1], O. Bichler[2], A. Grossi[1], E. Nowak[1],
J.-F. Nodin[1], B. Yvert[3], B. DeSalvo[1], and L.Perniola[1]
[1]CEA-Leti, [2]CEA-LIST, [3]INSERM-Clinatec
Proc. of the IEEE International Electron Devices Meeting (IEDM), Dec. 2016

"Resistive Memories for Spike-Based Neuromorphic Circuits"
E. Vianello[1], T. Werner[1], O. Bichler[2], A. Valentian[1], G. Molas[1],
B. Yvert[3], B. De Salvo[1], and L. Perniola[1]
[1]CEA-Leti, [2]CEA-LIST, [3]INSERM-Clinatec
Proc. of the IEEE International Memory Workshop (IMW), May 2017



05

Interacting Efficiently and Reliably with ***Complex Systems in the Digital World***

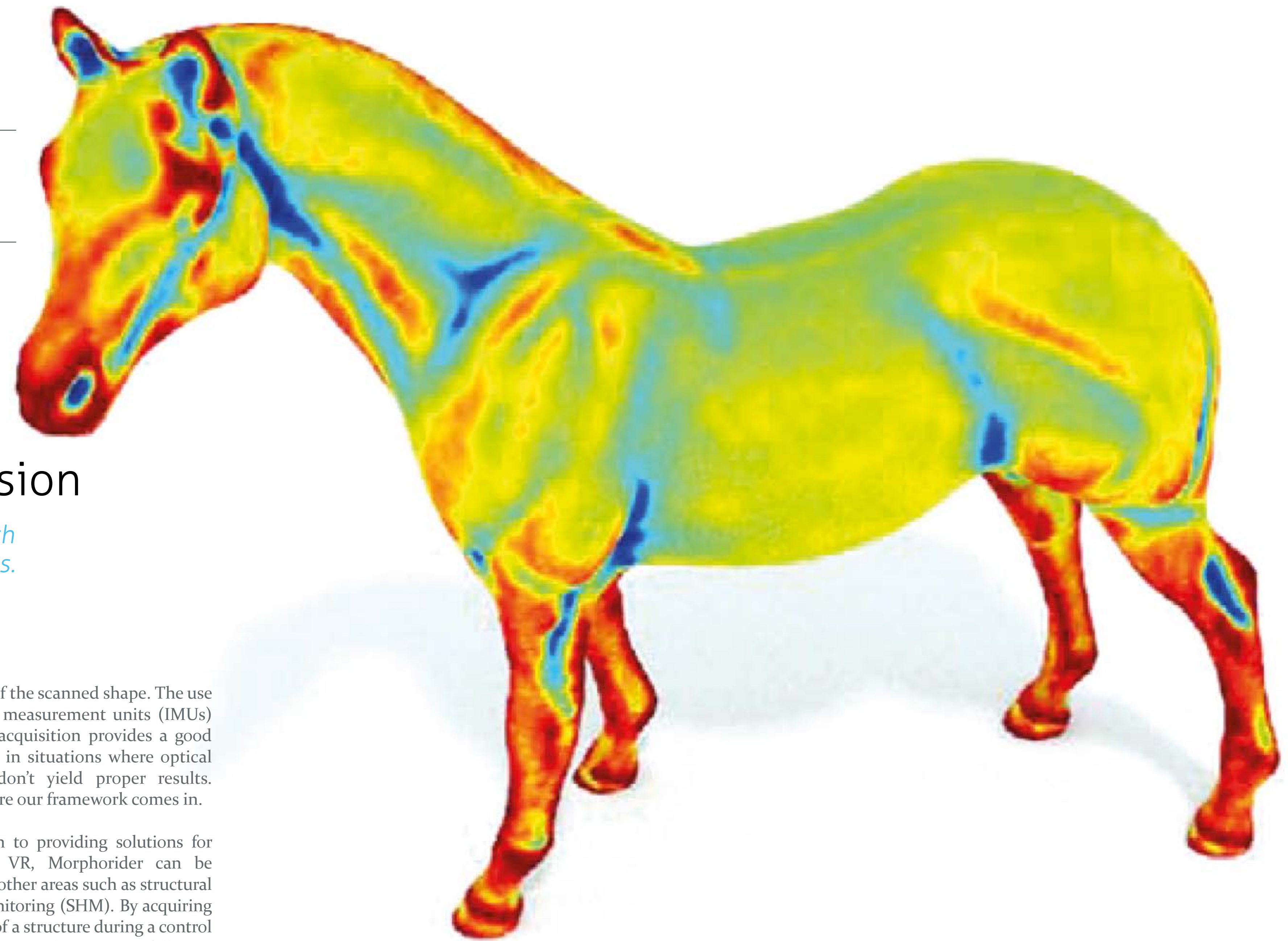
The digitalization of the real world, by way of the IoT, generates a high volume of environmental information, enabling context-aware smart applications that provide personalized real-time services both cheaply and non-intrusively. Complex adaptive systems are characterized by a very high level of autonomy in deciding when to perform certain tasks. In these systems, smartness is directly proportional to awareness, where various types of data sources such as miniaturized sensors, IoT devices, mobile applications, social networks and other web data act as the "senses" of the systems. In the following highlights, we will show devices that capture data to reconstruct 3D object shapes, a key advance for applications like virtual reality and structural health monitoring. A new occupancy grid computation framework that helps make autonomous vehicles a reality by fusing raw data from heterogeneous sensors in real time on resource-constrained computers is presented. Accurate and resilient localization frameworks for cooperative intelligent transport systems are described, as well as algorithms that reduce latency and optimize precious computational resources in 5G networks. New energy-efficient sub-GHz transceivers for mobile applications are explained and, at the hardware level, an architecture for continuous time Analog-To-Digital converters that is as efficient and more compact than classical ones is demonstrated. Scientists show that synchrotron-based X-ray nanobeams can perturb the security at digital circuits. Finally, we present Q-learning methodologies which allow for intuitive and self-power management in IoT and data-center applications.

***Interview** with Viviane Cattin*
and Nathalie Saguin-Sprynski
Leti scientists

Morphorider:

Capturing Shapes with Precision

A team of scientists developed a novel approach for accurately capturing the shape of 3D objects.



A new device and a set of accompanying algorithms provide a revolutionary framework for acquisition and reconstruction of 3D curves. All a user has to do is roll the device, Morphorider, along the surface of an object, and the algorithms figure out the shape.

What are the specific advantages of Morphorider over existing systems that capture real-world shapes?

While the idea of sensor shape reconstruction is not new, ours is the first method for creating well-connected networks of curves on surfaces using only orientation and distance measurements and a small set of user-defined constraints.

To do this, we addressed three main challenges. The first was unknown positions. While sensors can measure local orientations of the surface, they have never been made to pinpoint absolute positions in world space, nor even positions relative to adjacent sensors.

The second challenge was inconsistent data. Intersecting curves often provides conflicting data—for instance two different normals might be reported for the same point in the world space.

The third challenge was sensor noise. Raw data from inertial sensors is naturally noisy and it needs to be pre-processed prior to reconstruction.

Our approach differs from standard curve acquisition and reconstruction methods in that we formulate all the algorithms in terms of orientations. This way, we can leverage consistency of reconstructed curves with respect to user-defined topological constraints. By working directly with orientations, our framework robustly resolves all three of the challenges mentioned.

What fields will benefit the most from Morphorider?

Using a traditional computer aided design (CAD) approach, designers sketch curves directly, either on a flat screen or via a 3D interface. These traditional methods are well suited for designing new shapes, but they don't work when you have to reconstruct an existing, real-word shape. Similarly, virtual reality (VR) systems run into problems when they try to accurately capture and model existing shapes.

Curve networks are often used to convey designs—and 3D scanners are typically used to capture the curves. But these optical tools tend to ignore the intrinsic structure of the scanned shape. The use of inertial measurement units (IMUs) for shape acquisition provides a good alternative in situations where optical methods don't yield proper results. That's where our framework comes in.

In addition to providing solutions for CAD and VR, Morphorider can be applied to other areas such as structural health monitoring (SHM). By acquiring the shape of a structure during a control or a maintenance phase, you can follow its possible deformations, and raise alarms if abnormal geometries are detected, or critical thresholds are exceeded. You could also follow shape fluctuations resulting from environmental pressures, and then improve models based on this kind of feedback.

What more needs to be done to further improve shape capture?

The process of shape acquisition requires well-trained users, and those users have to provide critical input—for instance, the user has to provide feedback for the system to know when the device passes through a node (a curve intersection). We are therefore working to provide a more intuitive interface, using heuristics to minimize the need for user input.

Breakthrough

Morphorider, a device equipped with inertial sensors that can be rolled onto a surface, and a set of innovative algorithms to capture the shape of the object via curves acquisition.

Why it's relevant

By accurately capturing shapes, Morphorider opens up new possibilities in a number of fields (for example, Computer Aided Design, Virtual Reality, and Structural Health Monitoring) where real-world shapes need to be modeled.

Moving forward

While Morphorider is already easy to use, an even more intuitive interface will be developed, using heuristics to minimize the need for user input.

COLLABORATIONS
Université Grenoble Alpes/LJK (France)

FOR MORE DETAILS

"Smooth Interpolation of Curve Networks with Surface Normals"
T. Stanko[1,2], S. Hahmann[1], G.-P. Bonneau[1],
and N. Saguin-Sprynski[2]
[1]Inria/LJK/INPG, [2]CEA-Leti
Proc. of the 37th Annual Conference
of the European Association for Computer Graphics,
pp.21-24, May 2016

"Surfacing Curve Networks with Normal Control»
T. Stanko[1,2], S. Hahmann[2], G.-P. Bonneau[2],
and N. Saguin-Sprynski[1]
[1]CEA-Leti, [2]Université Grenoble Alpes/CNRS-LJK/Inria
Computers & Graphics, vol.60, pp.1-8

***Interview** with Julien Mottin and Diego Puschini*
Leti scientists

SIGMAFUSION:
Reliable Vehicle Perception Using Constrained Computing Platforms

Given the limited computing power at their disposal, how can autonomous vehicles be counted on to sense danger?

Leti has solved this problem by developing a novel occupancy grid computation framework, perfectly suited for industrial automative-grade applications. Using only integer arithmetic, SigmaFusion fuses raw data from heterogeneous sensors in real time, and builds high-resolution 2D or 3D occupancy grids.

What is unique about SigmaFusion?

Knowing precisely the state of "the ego vehicle" (the vehicle I'm in) and its environment is crucial for comprehensive scene analysis. Is the vehicle in the correct lane? Where are other vehicles? Are they at a safe distance? Based on the answers to these kinds of questions, the central system decides how to operate the vehicle.

Occupancy grids model the environment as a grid composed of a finite number of cells. A cell has a binary state: either occupied or empty. An occupancy grid is computed from multiple sensor measurements, and measurement uncertainties are modeled by a probability distribution.

Modeling a driving environment that extends over hundreds of meters around a car requires thousands to millions of cells. Occupancy probabilities are calculated with floating-point arithmetic; and performing real-time computations using data from multiple sensors requires a processing hardware with a dozen Giga-floating points per second (GFLOPS).

The problem is, in the automotive domain, safe processing platforms are mainly based on low-cost and low-power embedded CPUs and microcontrollers. Since these platforms offer little or no support for floating-point arithmetic, we had to develop a new digital representation of probabilities.

What new work do you expect will result from SigmaFusion?

In the not-so-distant future, SigmaFusion's potential will drive the development of innovative sensor architectures in optics, radar, ultrasound and other technologies.

COLLABORATIONS
Inria (France)

FOR MORE DETAILS

"Integration of multi-sensor occupancy grids into automotive ECUs"
T. Rakotovao[1], J. Mottin[1],
D. Puschini[1], and C. Laugier[2]
[1]CEA-Leti, [2]Inria
Proc. of the Design Automation Conference (DAC), June 2016

"Multi-sensor fusion occupancy grids based on integer arithmetic"
T. Rakotovao[1], J. Mottin[1],
D. Puschini[1], and C. Laugier[2]
[1]CEA-Leti, [2]Inria
Proc. of the IEEE International Conference on Robotics and Automation (ICRA), 2016

Breakthrough

SigmaFusion, fusing raw data from heterogeneous sensors on resource-constrained computers to generate occupancy grids.

Why it's relevant

By simultaneously addressing cost and safety constraints, SigmaFusion will help make autonomous driving a reality.

Moving forward

SigmaFusion will inspire novel sensor development with distributed perception.

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***Interview** with Benoît Denis*
Leti scientist

HYBRID LOCALIZATION PAVES
the Way for Autonomous Vehicles

A team of scientists designed a hybrid data fusion framework that provides positioning accurate to within 20 centimeters, an enabling feature for autonomous transportation.

The lack of affordable systems that consistently determine vehicle position to within 25 centimeters has long stood in the way of highly autonomous driving (HAD). Standalone GPS-based navigation systems could provide the required accuracy, but they cost too much and don't perform well enough under sub-optimal operating conditions. Alternative solutions, based on cooperative intelligent transport systems (C-ITS), deliver resilient and accurate enough positioning. But they present a new set of challenges, including communication footprint and error propagation.

How has your work made it possible to design RRAM performance for specific applications?

We developed a global data fusion framework based on both cooperative particle filtering and V2x [vehicle-to-everything] communications using the ITS-G5 protocol currently under standardization at the European level.

To stay within the constraints of CAM [cooperative awareness message] payloads currently under standardization, we drastically reduced the amount of data communicated by applying various message approximation methods, and we designed transmission control strategies to convey only the most informative positional data in a timely manner.

We also developed robust ways of combatting error propagation among cooperative vehicles at both signal processing and operations scheduling levels. Finally, our proposal is flexible enough to include a variety of new data sources, including more accurate V2x ranging technologies, onboard sensors, and RSUs [roadside units].

What next steps will further enhance your data fusion framework?

Within the context of the European high precision positioning for cooperative-ITS (HIGHTS) project, several field data logging campaigns are scheduled over the next eighteen months, involving cooperating vehicles under real driving conditions. Another key challenge to address in the future is providing truly secure end-to-end transactions, not only between cooperating vehicles, but also with elements of infrastructure such as RSUs.

Finally, we need to further exploit the wide and unprecedented potential of accurate and resilient positioning in emerging automotive domains—beyond the most trivial navigation and beyond autonomous driving—opening new research perspectives in related fields, such as simultaneous localization and mapping.

Breakthrough

A data fusion framework that operates in the context of cooperative vehicle-to-everything communications, and improves the accuracy to within less than 20 centimeters.

Why it's relevant

Accurate and resilient localization and wireless connectivity are key enablers to both autonomous vehicles and assisted driving.

Moving forward

Transactions between vehicles, and with roadside units, need to be fully secured; and research should be conducted to apply this potential to other fields, such as automotive IoT, crowd sensing, and environment monitoring.

COLLABORATIONS
EURECOM (France)

FOR MORE DETAILS

"Breaking the Gridlock of Spatial Correlation in GPS-aided IEEE 802.11p-based Cooperative Positioning"
G.M. Hoang[1], B. Denis[1], J. Härri[2], and D. Slock[2]
[1]CEA-Leti, [2]EURECOM
IEEE Transactions on Vehicular Technology, vol.65 (12), Dec. 2016

"Cooperative Localization in GNSS-aided VANETs with Accurate IR-UWB Range Measurements"
G.M. Hoang[1], B. Denis[1], J. Härri[2], and D. Slock[1]
[1]CEA-Leti, [2]EURECOM
Proc. of the IEEE Workshop on Positioning, Navigation and Communications, Oct. 2016

***Interview** with Dominique morche*
Leti scientist


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TUNABLE CONTINUOUS-TIME ANALOG-TO-DIGITAL CONVERSION:

Enabling Smarter IoT Applications

A new architecture renders event-driven analog-to-digital conversion far more efficient.

With traditional analog-to-digital converters (ADC) you define a sampling frequency, which is the rate at which data is sampled on input—and therefore the rate at which the building blocks operate and consume power. The sampling frequency also influences the rate at which data is updated on output (even when no change occurs on input, the output is updated).

By contrast, a continuous time (CT) ADC works not by sampling the input at regular intervals, but by modifying the output only when it detects a change in the input signal. Because it requires less processing, this event-driven approach would naturally be a useful approach to digitize data in IoT sensors. However, until now, one major drawback has been that, when compared to classical ADC, CT ADC consumed more power—a precious resource in IoT sensors.

What have you done to make CT ADC practical for Internet of Things (IoT) solutions?

Nowadays sensors need to extract more and more data from their environment. Normally, the data is filtered after it is digitized. But the conversion to digital consumes energy—and most of the time, what is converted gets thrown out. We've developed a solution that involves filtering the data before it is converted, thereby consuming less power. This makes a lot of sense for IoT, because the key challenge is to reduce power consumption. It relies on the implementation of a low-pass filter in the feedback path of the converter. The filter attenuates the unwanted signals and reduces the ADC requirements, thereby reducing its power consumption. Since the filter is in the feedback loop, it takes benefit of the digital implementation to inherit a strong tenability.

Usually when people develop tunable components, they make them tunable in terms of performance. But power consumption remains stable. We've enabled the development of components whose performance and power consumption can be adapted to the application.

What more needs to be done to fully exploit this new architecture for event-driven ADC?

In the near term we intend to further reduce power consumption by adapting the CT quantization procedure to the characteristics of the input. In the longer term, these techniques could also be applied to analog neuromorphic processing to exploit the output characteristics.

COLLABORATIONS
Columbia University (USA)
Université Claude Bernard Lyon (France)
INSA Lyon (France)

FOR MORE DETAILS

"A 3-10fJ/conv-step 0.0032mm2 Error-Shaping Alias-Free Asynchronous ADC"
S. Patil[1], A. Ratiu[2,3], D. Morche[2], and Yannis Tsividis[1]
[1]Columbia University, [2]CEA-Leti
[3]Université Claude Bernard Lyon
Symposium on VLSI Circuits Digest of Technical Papers, pp.C160-C161, June 2015

"Continuous-Time Digital Filtering Analogue-To-Digital Converter"
A. Ratiu[1], D. Morche[1], B. Allard[2], X. Lin-Shi[2], and J. Verdier[2]
[1]CEA-Leti, [2]INSA Lyon
Electronics Letters, Vol.52 (6), pp.432-433, March 2016

Breakthrough

Demonstration of an architecture for continuous time Analog-To-Digital converters that is as efficient as that of classical ADCs, but more compact.

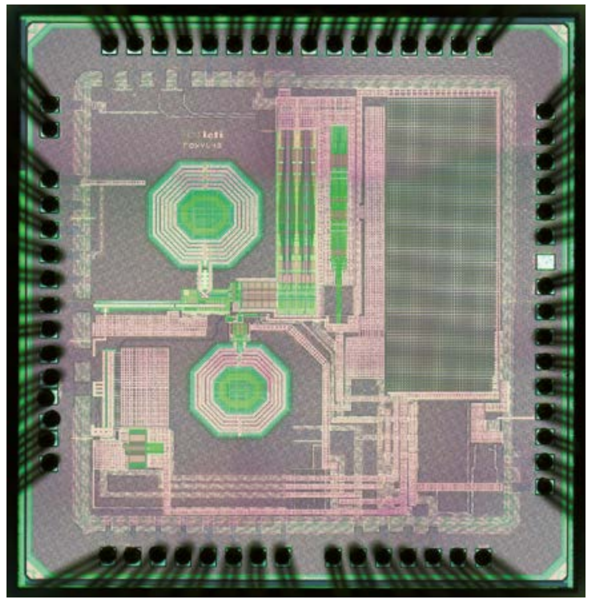
Why it's relevant

By reducing power consumption, continuous time Analog-To-Digital will enable the development and deployment of the small, autonomous smart systems that make up larger IoT solutions.

Moving forward

Power consumption could be reduced even further by adapting the continuous time quantization procedure to the characteristics of the input.

***Interview** with Carolynn Bernier*
Leti scientist



MAKING MASSIVE EVENT-DRIVEN IoT APPLICATIONS AFFORDABLE

A sub-GigaHertz transceiver demonstrates that inexpensive "things" can communicate on low power wide area network— and the batteries on those "things" can last up to seven years.

Ultra-narrow band (UNB) signaling is an enabling technology for the low power wide area (LPWA) networks that make up the "Internet-of-Things." Based on spectrally efficient modulations, such as differential binary phase shift keying (DBPSK) or Gaussian frequency shift keying (GFSK), UNB signaling maximizes the communication link budget while optimizing network capacity. But until now, for very small devices to communicate on UNB, a trade-off had to be made between using components that were too expensive or components that consumed too much power.

A group of researchers designed a new transceiver to overcome this obstacle, which has been standing in the way of massive, event-driven IoT applications, such as smart city or smart grid. This transceiver, called FOXY, operates within ultra-narrow bandwidths of 100 Hz without requiring expensive temperature compensated crystal oscillators (TCXOs).

What challenges had to be overcome to develop FOXY?

UNB signaling poses many technical challenges. In the receiver, CFO [carrier frequency offsets] can shift the desired signal from the expected channel. In the transmitter, the difficulty resides in generating the modulated signal with the required spectral purity.

We designed an 850-920 megahertz RF transceiver to overcome these challenges, thus advancing the state of the art. The transceiver is dedicated to UNB communication systems employing the DBPSK/GFSK modulations. The receiver resists to CFO offsets of plus or minus 75 hertz (in other words, 150% of the 100 Hz channel) and drifts of 35 Hz per second. It does so with only 1 dB sensitivity loss.

Thanks to these unique capabilities, unprecedented bandwidths of 100 Hz can be achieved, even in the downlink, without a costly TCXO, taking the UNB paradigm to its limits. In addition, the circuit can be used in a standalone uplink-only mode thanks to its embedded Sigfox MAC [media access control], enabling ultra-low cost solutions.

How is FOXY's architecture opening up new R&D opportunities in IoT?

To increase the coverage of the Sigfox network, an evolution of the transceiver is being designed for the bi-mode, terrestrial and satellite extension planned by Airbus Defense & Space.

In addition, the architecture developed for FOXY opens up new opportunities for developing multi-standard IoT transceivers. The inherently wide-band nature of the analog to digital converters in the receiver can be exploited to simultaneously address a large number of competing IoT technologies.

Such a solution would have considerable value, reducing the costs of developing new products, while simultaneously lowering the costs of fixing hardware bugs. What's more, our architecture could address tomorrow's IoT landscape, which is expected to be a multi-vendor, multi-standard environment.

Breakthrough

An 850-920 MHz RF transceiver with the unique capability of addressing ultra-narrow bandwidths of 100 Hz without a temperature compensated crystal oscillator.

Why it's relevant

It enables marginal cost, event-based, massive IoT applications.

Moving forward

A multi-standard version, which may have considerable importance in tomorrow's IoT landscape, is currently being researched.

COLLABORATIONS
Sigfox (France)

FOR MORE DETAILS

"A TCXO-Less 100Hz-Minimum-Bandwidth Transceiver for Ultra-Narrow-Band Sub-GHz IoT Cellular Networks"
D. Lachartre[1], F. Dehmas[1], C. Bernier[1], C. Fourtet[2], L. Ouvry[1], F. Lepin[1], E. Mercier[1], S. Hamard[2], L. Zirphile[2], S. Thuries[1], and F. Chaix[1]
[1]CEA-Leti, [2]Sigfox
Proc. of the IEEE International Solid-State Circuits Conference, pp.134-136, Feb. 2017

Interacting Efficiently and Reliably with
Complex Systems in the Digital World

***Interview** with Emilio Calvanese*
Leti scientist

Minimizing Redundant Processing
in 5G Networks

Will 5G networks be able to reduce latency and optimize precious computational resources by reusing processing results from one user to another?

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Yes they will, thanks to a new set of algorithms that cache the results of computations and match those results to subsequent requests.

How does caching computational results help make 5G networks a reality?

Micro-cells on the edge of a network have limited computing and storage capabilities compared to centralized cloud farms. So our idea was that, when local requests for computation exceed the computing power of a single small cell, instead of requesting support from the central cloud, the small cells federate in ad-hoc clusters to serve local requests.

We've observed that most operations needed for service provisioning and network optimization are recurrent, context-dependent and too often re-executed. So we developed a novel paradigm, which involves caching computational results.

Our approach and algorithms change the way mobile edge clouds work today by avoiding redundant execution of popular computation requests, making mobile edge cloud more energy efficient, and reducing delay in most cases. Major vertical industries will benefit from mobile edge cloud support—especially in cases where high local computational loads depend on heavy cloud infrastructure, or where power consumption is a limiting factor on battery-operated mobile devices.

What steps need to be taken to further advance Mobile Edge Computing?

One of the next steps is to devise good methods for maintaining consistency in the distributed databases, which are essential to the caching mechanism. We also have to work on ways of freeing memory as computational results become less popular. The idea is to employ machine learning to help make predictions and decide what needs to be in the cache and for how long.

Communication technology also needs to be improved. (We see communication as one of three resources that we can optimize through our algorithms, the other two being computation and storage.) Fast communication is very important, but fast communication consumes more energy.

Finally, work needs to be done to predict blocking of backhauling technologies and to provide redundant communication links as appropriate. We are already starting to get promising results in working with millimeter waves.

Breakthrough

A set of algorithms to cache computational results that can be reused on subsequent requests, thereby minimizing redundant processing.

Why it's relevant

Requiring very low latency, 5G networks must move computing power to the edge. But computing resources on the edge will always be sparse—and therefore limited—so they must be used efficiently. Minimizing redundant processing will address this issue.

Moving forward

A distributed cache of processing results is needed; and more work must be done to combine these algorithms with new radio access and backhauling technologies, such as millimeter waves and visible light communication.

COLLABORATIONS
Sapienza University of Rome (Italy)

FOR MORE DETAILS

"Computation Caching for Local Cloud Computing"
J. Oueis and E. Calvanese Strinati, CEA-Leti
Proc. of the IEEE Wireless Communications and Networking Conference (WCNC), March 2017

"Distributed Mobile Cloud Computing: A Multi-user Clustering Solution"
J. Oueis[1], E. Calvanese Strinati[1], and S. Barbarossa[2]
[1]CEA-Leti, [2]Sapienza University of Rome
Proc. of the IEEE International Conference on Communications (ICC), pp.1-6, May 2016.

***Interview** with Jacques Fournier*
Leti scientist

Enhancing Digital Security Testing
with Nanofocused X-Ray Beams

A team of scientists identify synchrotron-based X-ray nanobeams as a new dangerous technique able to perturb the security of integrated circuits

In the era of the digital economy and identities, the deployed systems must be secure and trustworthy to prevent fraud and malicious activity. To assess the security of commercial devices (such as credit cards, passports and smartphones), scientists in Leti's security evaluation laboratory investigate the future cyber and physical attacks which hackers can use to threaten the security of integrated circuits. This will lead to future development of specific protection shields and counter measures for secure state of the art integrated circuits.

What made you think of using x-rays to corrupt individual transistors?

To maintain a high level of digital security standards, scientists in the domain of security evaluation are constantly investigating new techniques to perturb electronic circuits. Currently, white light and lasers are used during security evaluations of smart cards to induce faults in protected electronic circuits. The possibility of using electromagnetic radiation with different wavelengths, and the proximity of the ESRF, led us to explore X-ray nanofocused beams as an alternative form of attack.

In this experiment, one of the ESRF's intense hard X-ray beam was focused down to a few tens of nanometers and used to change the information in a single Flash, EEPROM and RAM memory cell. The fault effects remained after the X-ray radiation was turned off. Being able to directly modify the NVM (non-volatile memory) program state demonstrates that nanofocused X-rays represent a threat to circuit security. The memory cell was then restored to its original state by heating the cell at 150°C for one hour, proving that the modification was reversible.

Compared to laser beam induced perturbations, nanofocused X-ray radiation modifications are semi-permanent: normal operation can be restored. Furthermore, nanofocused X-rays can be focused down to target a single transistor, which means that individual functions or part of a device can be modified. For example, attack detection mechanisms and security countermeasures could be deactivated.

Additionally, nanofocused X-rays can be used to modify transistors without prior sample preparation, that is, without removing the packaging around the circuits. This, and the reversibility of the induced perturbations means attacks can be carried out without damaging the chip and without leaving any traces.

How will this new discovery impact future circuit security certification?

Leti validated several innovations with a proof-of-concept, demonstrating that the implementation of the 3D NoC using asynchronous logic provides robust communication in the context of Process Voltage Temperature (PVT) variations, and in the context of the high temperatures inherent to 3D architectures. It was also shown, and measured on silicon, that it is the lowest energy consumption yet seen for 3D communication. Finally, the fault tolerance mechanisms and testability of the 3D NoC infrastructure was shown to work by using additional spare through-silicon-vias (TSVs), and by employing a two-step test-and-repair mechanism.

Is the future of computing architectures still what it used to be?

We have developed a new way to attack electronic circuits by modifying the state of single transistors and reprogramming single memory cells. Up until now, there was little experience with technological nodes below 90nm. This work shows that it's possible to modify transistors at or below the 45nm node. Being able to perturb individual memory cells and transistors means that, for example, permanent faults can be introduced in cryptographic algorithms, security mechanisms can be deactivated and memories can be reprogrammed. New counter measures will need to be developed to prevent future successful cyberattacks using this technique.

In the same way that laser techniques have become standard equipment in security evaluation centers in the last 20 years, we can imagine that these techniques will become part of security certification processes in the future. However, synchrotron availability being very limited, research should now focus on developing ways to reproduce the same effects using more accessible means.


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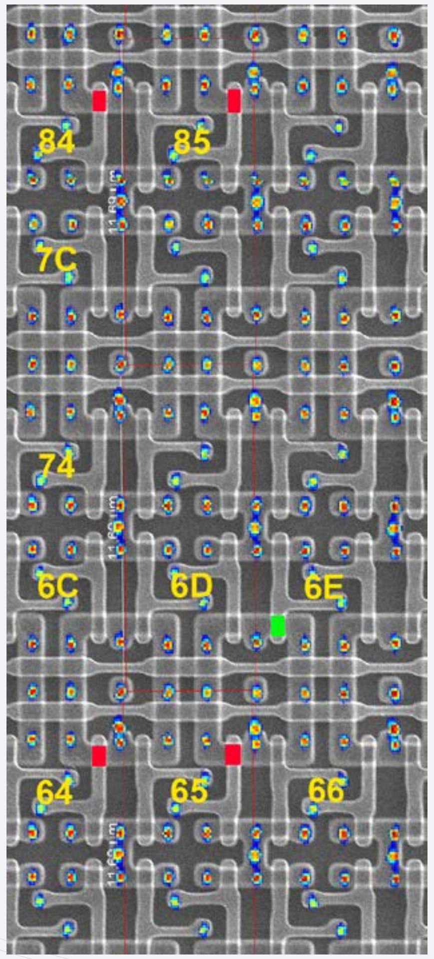

Breakthrough

Nano-focused X-ray beams were identified as a semi-permanent threat able to change the information of a single 45nm RAM cell.

Why it's relevant

At the highly secure circuit level, the recognition of this new risk to corrupt integrated circuits will help develop efficient new counter measures to improve the cybersecurity of secure smart cards.

Moving forward

Develop test equipment that can recreate results similar to the synchrotron X-ray beams using techniques that are more accessible to current security evaluation and certification centers.

COLLABORATIONS
European Synchrotron Research Facility
(Grenoble, France)

FOR MORE DETAILS

"Nanofocused X-Ray Beam to Reprogram Secure Circuits"
S. Anceau[1], P.Bleuet[1], J.Clédière[1], L. Maingault[1], J.-L. Rainard[1], and R. Tucoulou[2]
[1]CEA-Leti, [2]European Synchrotron Research Facility (ESRF)
Conference on Cryptographic Hardware and Embedded Systems 2017. Lecture Notes in Computer Science, vol.10529, Springer, 2017

Interview *with Anca Molnos*
Leti scientist

Q-Learning May Revolutionize Resource Management

in IoT and Data-Center Applications

Learning algorithms makes it possible to optimize energy consumption for a specific application, without requiring extra steps from developers.


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Energy efficiency is more crucial than ever in many computing fields. But traditional approaches to manage chips' power require specific on-chip hardware and advanced software strategies. The designer has to add dedicated logic and develop an accurate model of the dynamics of the given application to be used by the energy management software during run time. Today, learning algorithms, make it possible to have a platform learn the behavior of a specific application and manage power according to the behavior of the application.

What drove research efforts towards applying learning algorithms to energy management?

IoT application developers and data-center users don't always have the knowledge and budget to manually perform power and performance optimizations required before deployment to enable their applications (e.g., object recognition, image and text processing) to utilize rapidly-changing heterogeneous hardware, such as field programmable gate arrays [FPGAs] or graphical processing units [GPUs].

So, learning methods are now being used to allow energy management sub-systems to optimize power use for an application. The application doesn't have to be designed specifically with built-in assumptions about energy use on a given platform. However, a drawback is that before deployment, the sub-system goes through a training phase using data to learn about application behavior in order to be able to make decisions during run time.

How does Q-learning advance the state of the art of energy management?

We've taken the learning approach one step further, by employing indirect adaptive control, also referred to as reinforcement learning [RL]. The idea of this method is that, as the application executes, the manager gradually learns which operating points yield the largest energy savings given a performance constraint. Neither accurate modeling, nor training data are necessary—and the programmer doesn't have to write special code for a given platform.

We use Q-learning, a rather simple, low cost, reinforcement learning approach well suited to manage IoT systems. We tested a device made up of an ARM host processor and a system on chip [SoC] with sixteen processor elements, using an object recognition application. With a time overhead of only point six percent, the Q-learning reduced energy consumption by up to forty-four percent compared to state-of-the-art methods.

Our work is a first step towards shifting the burden of platform-dependent optimization away from the application developer. This will result in a drastic reduction in application development time—and time spent performing optimizations manually. Consequently, it will lead to quicker deployment of new applications.

What new opportunities does this work on Q-learning create for the future?

The energy manager should take upon a more general functionality of a self-tuning resource manager, responsible for administering the entire system, including heterogeneous compute cores, accelerators, memory hierarchies, and adaptive radio bands.

In the IoT sensing nodes, which could depend on harvested energy only, the challenge is to make the Q-learning method ultra-low power consuming. Hence the energy manager should have a minimal resource footprint. The manager could follow an always-on/on-demand functionality split, as the IoT sensing nodes do themselves.

An entirely different use case is in the data center, where hardware is currently undergoing a holistic redesign by fusing memory and storage, flattening complex data hierarchies, and bringing processing closer to the data. In this context, the main responsibility for the efficient utilization of the compute ensemble goes to the resource management software. State-of-the-art data-center schedulers and compilers are too rigid to be able to dynamically identify application requirements, and select the most suitable hardware from a pool of heterogeneous computing resources. Our method represents a good start towards an auto-adaptive, efficient platform for resource management.

Breakthrough

The application of Q-learning, a simple reinforcement learning approach, to optimize energy management in computing systems.

Why it's relevant

Energy management systems learn optimal use of resources for a given application on the fly, relieving application developers from the task of platform-dependent energy optimization.

Moving forward

A complex heterogeneous resource model should be considered in the future.

COLLABORATIONS
Université Grenoble Alpes (France)

FOR MORE DETAILS

"Investigation of Q-Learning Applied to DVFS Management of a System-on-Chip"
A. Molnos, S. Lesecq, J. Mottin, and D. Puschini, CEA-Leti
IFAC-PapersOnLine, vol.49 (5), pp.278-284, 2016

People

Awards

Leti's Research Directors and International Experts

Leti's Organization

Awards

European Inventor Award 2016 for High-Frequency Deep Brain Stimulation to Combat Parkinson's Disease

Alim Louis Benabid, a neurosurgeon and physicist, was honored at the European Inventor Award 2016 ceremony in Lisbon for his invention of high-frequency deep brain stimulation (DBS), which has become a standard treatment worldwide to combat Parkinson's disease and other neurological conditions.

Over 150,000 patients have undergone DBS and many of those who were previously immobilized by Parkinson's disease have been able, as a result, to resume functional, self-directed lifestyles.

E-MRS Best Presentation Award for First Demonstration of III-V MOS Capacitors on Si Substrates

E-MRS honored Mathilde Billaud with the Best Presentation Award for her talk about GaAs and InGaAs metal-oxide-semiconductor capacitors elaborated by metalorganic chemical vapor deposition. Her presentation was based on the first demonstration of III-V MOS capacitors made on 300mm Si substrates with very thin buffer layers.

A description of her work can be found in the publication titled "GaAs and InGaAs metal-oxide-semiconductor capacitor elaborated by MOCVD on 300mm Si substrate" which she co-authored with Z. Chalupa, M. Cassé, C. Leroux and H. Boutry of CEA-Leti and M. Martin and T. Baron of CNRS-LTM.

E-MRS Graduate Student Award for Work on Dual Strain CMOS Integration

The E-MRS Graduate Student Award was given to Aurore Bonnevialle at the 2016 E-MRS Spring Meeting, which was held in Lille, France. The award was for her outstanding PhD work, which significantly contributed to understanding the physical mechanisms underlying CMOS layout dimension and ion implantation dependencies.

A. Bonnevialle's work is detailed in the publication "Localized STRASS Technique on an Advanced FDSOI Platform: Highly Tensile Si Demonstration for Dual Strain CMOS Integration" which was co-authored by S. Reboh, C. Le Royer, J.M. Hartmann, D. Rouchon, C. Tabone, N. Rambal and M. Vivet of CEA-Leti, J.M. Pedini and M. Haond of ST Microelectronics, and A. Claverie of CNRS-CEMES.

ESTC Best Paper Award for Packaging Techniques for High-Speed Silicon Photonic Photoreceiver Modules

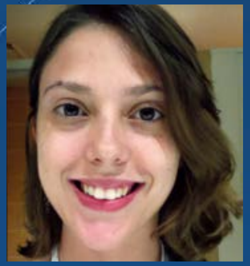
Olivier Castany received the Best Paper Award at the 6th IEEE Electronics System-Integration Technology Conference (ESTC), held in Grenoble in September, 2016. The award was for the development of compact multichannel photoreceiver modules based on silicon photonic integrated circuits (PIC) and designed for 100 Gbps aggregated bandwidth transmission.

The work is described in the paper titled "Packaging of High Speed 100 Gbps Silicon Photonic Photoreceiver Module Using a 50-µm-Pitch Micro-Bump Flip-Chip and Chip-On-Board Approach" which was co-authored by B. Blampey, B. Charbonnier, G. Pares, M. Germain, I. Borel, S. Malhoutre, C. Kopp, and S. Bernabé of the CEA-Leti and E. Temoriti of STMicroelectronics.

WPNC'16 Best Student Paper Award for Work on Hybrid Cooperative Localization

Gia-Minh Hoang was granted the Best Student Paper Award at the WPNC'16 IEEE Workshop on Positioning, Navigation and Communication in Bremen Germany for his paper entitled "Cooperative Localization in GNSS-Aided VANETs with Accurate IR-UWB Range Measurements."

Co-authored by Benoît Denis of CEA-Leti, and Jérôme Härri and Dirk T.M. Slock of EURECOM Sophia Antipolis, the paper describes new techniques to improve hybrid Cooperative Localization (CLoc) by applying Bayesian filtering to position values from a variety of sources. These sources include an embedded Global Navigation Satellite System (GNSS) in the vehicle and neighboring mobile vehicles (seen as "virtual anchors"), which transmit information over ITS-G5 vehicle-to-vehicle communication channels.



"Prix Roger Fourme" for Discovering the Influence of Polarization in CBRAM Memory

Munique Kazar Mendes received the "Roger Fourme Prize" at the 12th SUM "SOLEIL Users' Meeting" 2017, France, for the best student poster entitled "Electrochemistry of Resistivity Changes in TaN/TiTe/Al2O3/Ta Conducting Bridge Random Access Memories." The poster was co-authored by E. Martinez, O. Renault, R. Gassilloud, M. Bernard of CEA-Leti, N. Barrett of CEA-IRAMIS and J. Ablett of Synchrotron Soleil.

The work described made use of hard X-ray photoelectron spectroscopy to study, with sufficient depth sensitivity, electrochemical reactions involved in the memory's switching mechanism. Munique's research contributes to advancing our understanding of conductive-bridging resistive random access memories (CBRAMs), strong candidates for the next generation of non-volatile memories (NVM).

ECS Prime 2016 Best Paper Award for Measuring Wave Velocity and Adhesion Energy

Vincent Larrey received the Best Paper Award at the ECS Prime 2016, in Honolulu, USA for developing a method to accurately measure bonding wave velocity and adhesion energy, experimentally confirming Rieutord's theoretical relation between these two quantities. Using this method, a fluidic cut-off distance of 55nm (very close to the molecular mean free path) was found to accurately depict the bonding wave propagation for hydrophilic bonding. The same method was also used to characterize hydrophobic direct bonding and to better understand slipping effects at the surfaces.

This work is presented in the paper entitled "Adhesion Energy and Bonding Wave Velocity Measurements", which was co-authored by G. Mauguen, F. Fournel, D. Radisson, C. Morales, C. Bridoux, and H. Moriceau of CEA-Leti and F. Rieutord of CEA-INAC.

Awards

Best Project Prize for "Smart City"

Leti's scientist Sylvie Mayrargue received the "Celtic Plus Award of Excellence – Smart Cities" at the Celtic-Plus event held in Stockholm. The prize rewarded the TILAS European project, which was carried out with partners TST, Spain; TTI, Spain; Bankoi, Spain; Université de Paris-Est (UPEC), France; Webdyn, France; Turk Telekom Argela, Turkey; Pangea, South Korea and Paragon Europe, Malta.

The project involved developing a variety of technologies for smart cities, enabling the deployment of sensors and providing methods for making use of the data generated by those sensors. Results from the project have been validated in several experimental settings in Santander, Paris, Grenoble and Seoul. Leti's main contributions were in the areas of secure communications and algorithm design to connect sensors to a network.

For more information about the TILAS project please go to https://www.celticplus.eu/project-tilas/

European SEMI Award 2016 for Outstanding Contributions in the Field of 3D Integration

Gilles Poupon, CEA-Leti fellow on advanced packaging and 3D integration, was one of the three recipients of the 2016 European SEMI Award at the SEMI Industry Strategy Symposium in Munich, Germany.

This award recognizes his outstanding contributions in the field of 3D integration during his long and distinguished career.

E-MRS Best Poster Award for Demonstrating the Relationship between Size and Performance in Light Emitting Diodes

François Olivier won the Best Poster Award at the European Materials Society (E-MRS) Spring 2016 meeting in Lille for having demonstrated that LED performance strongly depends on size. Efficiency drop for micro-sized LEDs was investigated using current-voltage-luminance characterization and luminescence measurements (electroluminescence, photoluminescence and cathodoluminescence).

The work is detailed in the paper entitled "Influence of Size Reduction on the Performance of GaN-based Micro-LEDs for Display Applications" which was co-authored by S. Tirano, L. Dupré, B. Aventurier, and F. Templier of CEA-Leti.

CHES Best Paper Award for Reprogramming Secure Circuits with Nanofocused X-Rays

Stephanie Anceau received the Best Paper Award at the Conference on Cryptographic Hardware and Embedded Systems (CHES 2017) which was held in Taipei in September, 2017. The award recognized the revolutionary achievement in digital security achieved by Leti's ITSEF laboratory, acknowledging the team's scientific and technical excellence.

A nanofocused synchrotron X-ray beam was used to corrupt electronics circuits, modifying the behavior of memory cells and the state of a single 45nm transistor reversibly. The work is detailed in the publication "Nanofocused X-Ray Beam to Reprogram Secure Circuits" which was co-authored by P.Bleuet, J.Clédière, L. Maingault, and J.-L. Rainard of CEA-Leti, and R. Tucoulou of ESRF.

IDW'16 Best Paper Award for GaN LED Microdisplays with High Resolution and Very Small Pixel-Pitch

François Templier received the Best Paper Award at the 23rd International Display Workshops 2016 (IDW'16) in Fukuoka, Japan. The paper describes a new approach for manufacturing GaN microdisplays, using direct bonding technology which eliminates the need for an alignment step and provides a way to produce very small pixel-pitches. By using this approach to demonstrate a 3 µm LED pixel-pitch, the CEA-Leti team set a new world record.

The paper is titled "New Approach for Fabricating High-Brightness GaN LED Microdisplays with High Resolution and Very Small Pixel-Pitch" and is co-authored by L. Benaïssa, I. Degirmencioglu, M. Charles, S. Tirano, and A. Daami, from CEA-Leti and the III-V Lab, France.

NANO 2016 Best Paper Award for the Study of 2D Resonators Based on Diamond-Like-Carbon

The Best Paper Award at the IEEE NANO 2016 International Conference in Japan was conferred to Sébastien Thibert for his paper entitled "AFM Study of 2D Resonators Based on Diamond-Like-Carbon", co-authored with Anne Ghis of CEA-Leti and Marc Delaunay of CEA-INAC.

The paper presented a new process to manufacture 2D resonators based on Diamond-Like-Carbon (DLC), demonstrating that an ultrathin DLC layer can effectively be used as the mobile membrane of microresonators.

MBE Outstanding Student Award for Revealing Dirac Fermions in Strained HgTe

Candice Thomas received the Outstanding Student Award at the 19th International Conference on Molecular Beam Epitaxy (MBE 2016), which was held in September, 2016 in Montpellier, France.

The award recognizes her contributions to the world's first clear and evident demonstration of electronic transport via topological Dirac surface states in MBE-grown strained HgTe/CdTe thin films at the topological insulator 2D to 3D cross-over.

LETI'S RESEARCH DIRECTORS AND INTERNATIONAL EXPERTS


Marc Belleville
Research Director

IC design
and microsystems


Barbara De Salvo
Research Director

Memory technologies,
neuromorphic devices


Lea Di Cioccio
Research Director

Bonding techniques,
hetero-integration
and power devices


Jean-Marc Dinten
International Expert

Data, image and signal
processing for biomedical
devices


Laurent Dussopt
Research Director

Millimeter-wave wireless
communication systems, millimeter-wave circuits, antennas & technologies


Thomas Ernst
Research Director

Logic devices
and sensors


Olivier Faynot
International Expert

Process integration
and devices physics
of SOI technologies


Jean-Marc Fedeli
International Expert

Silicon photonics
and optical sensors


Guy Feuillet
International Expert

Optoelectronics devices,
characterization
and physics


Yves Fouillet
International Expert

Microfluidics,
lab-on-a-chip


Franck Fournel
International Expert

Direct bonding techniques
and hetero-structures


Patrice Gergaud
International Expert

X-ray characterization
in micro and
nanotechnologies


Pierre Grangeat
Research Director

Data processing for
biomedical devices


Olivier Gravrand
Research Director

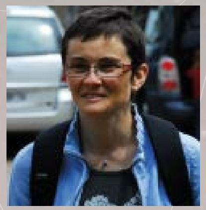
IR detection
and imaging


Jean-Michel Hartmann
Research Director

Epitaxy, hetero-structures
for microelectronics and optics


Laurent Herault
International Expert

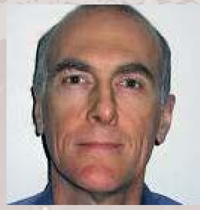
Communication systems,
radiofrequency networks
and architectures


Suzanne Lesecq
Research Director

Control theory applied to system-on-chip and power electronics,
data fusion


Pascal Mailley
Research Director

Biosensors,
bio-electrochemistry


François Martin
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Sylvie Mayrargue
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Wireless communications,
digital communications, signal
processing, propagation


Corinne Mestais
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Microtechnologies for health,
medical imaging


Dominique Morche
Research Director

Circuits and systems design
for telecommunication
applications


Hubert Moriceau
International Expert

Molecular adhesion,
direct bonding,
thin film transfer


Laurent Pain
International Expert

Lithography - optical,
electron beam,
imprint


Gilles Poupon
International Expert

Advanced packaging
and 3D integration


Christine Raynaud
International Expert

RF technologies
and components


Gilles Reimbold
International Expert

Electrical characterization
of nanoelectronic devices,
physical modeling and reliability


Alexei Tchelnokov
Research Director

Optoelectronic devices,
photonics


François Templier
Research Director

Display technologies
and systems

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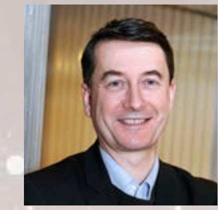

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Software Division

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Division

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Jean-Claude Royer
Head of Clinatec Platform

Collaborations

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Grenoble: A World-Class Innovation Ecosystem

Leti, a technology research institute of CEA, is situated in Grenoble in the French Alps. Leti is at the heart of Grenoble's Innovation campus for Advanced New Technologies (GIANT) which brings together leading fundamental and applied research laboratories, a high-tech industrial environment, and unique European research infrastructures such as the most intense neutron source in the world (at the Laue-Langevin Institute or ILL), Europe's largest synchrotron X-ray source (ESRF), an outstation of the European Molecular Biology Laboratory (EMBL) and the French Institut de Biologie Structurale (IBS).

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Over the years, Grenoble has become the home of many leading higher education and research institutions, and of major high-tech companies who have moved into the area or been created to become part of our dynamic and synergistic environment. Thanks to this enterprising spirit, Grenoble has received two government awards that are part of France's "Investments for the Future" (PIA) program: the Nanoelec Technological Research Institute (IRT Nanoelec) and the IDEX (Initiative d'Excellence).

The Nanoelec Technological Research Institute brings together research centers and companies working in the area of Information and Communication technologies to develop new technologies that will benefit industry, and in particular SMEs, in all activity sectors. Given Grenoble's strong innovation ecosystem, the different members of the IRT Nanoelec benefit from world-class R&D teams and infrastructure, and work together to develop new products and applications for tomorrow's IoT. The focus today is on providing new integrated circuit functionalities, based on the most recent 3D Integration and Silicon Photonics nanotechnologies. Another important component of the Nanoelec IRT's mission is to put in place new training programs to prepare the next generation of highly competent researchers in nanoscience and nanotechnology.

The academic and research community of Grenoble (named "Université Grenoble Alpes: university of innovation") was awarded one of France's Initiatives for Excellence or IDEX awards by the French government. The IDEX award recognizes scientific and pedagogical excellence and a passion for innovation and entrepreneurship. The IDEX initiative will boost disruptive pedagogical programs, stimulate multidisciplinary research projects among IDEX members, and encourage strong partnerships with industry as well as new and attractive international collaborations in the areas of ICT and the Digital Revolution, Sustainable Societies and the Planet, Health and Wellbeing Technologies and Innovative Ecosystems.

Grenoble's breathtaking natural environment and active student life also make it one of the best places to study in France. The city welcomes over 62,000 students each year from 180 different countries. Many students interested in gaining hands-on experience in innovation come to Leti to work on challenging technological research projects and benefit from top-notch clean-room and characterization facilities.

CEA-Leti:
An International CARNOT Institute

CEA-Leti is one of France's 38 Carnot Institutes. The Carnot label of excellence is granted to French public research centers dedicated to fostering innovation with industrial partners. Carnot institutes skillfully renew their scientific and technological knowledge and conduct collaborative research that improves the competitiveness and growth of their business partners.

Accordingly, Carnot institutes support upstream research projects, ambitious scientific collaborations with the best research teams worldwide and highly professional research partnerships with industry, from SMEs to large companies, with the ultimate goal of creating value through innovation. CEA-Leti is currently engaged in challenging multidisciplinary research projects to develop, for example, new methods of epitaxial growth, novel prosthetic materials, innovative LED architectures, new sensors based on 2D materials, micro and nano systems for breakthrough medical diagnoses, disruptive brain inspired circuit and memory architectures, and alternative micro-sources of energy for the IoT. Many of these projects are being carried out with first-rate research partners from around the world such as the Fraunhofer Institutes, the FZ Jülich Research Center, EPFL, Caltech, Stanford, MIT, Keio University, NII and Tsukuba University, to name a few.

Together with Enhanced Eurotalents, a four-year Marie Sklodowska-Curie Action offering one to three year international mobility fellowships for researchers and post-doctoral students, CEA-Leti has strengthened its Visiting Scholars program. In the 2016-2017 period, Leti researchers carried out joint projects with and at Stanford, MIT, Cornell and KTH Stockholm and welcomed post-doctoral students from the University of California Irvine, Rice University and TEC de Monterrey, TU Wien and University of Toronto, the Spanish CSIC and Nanyang Technological University. These projects are contributing to build CEA-Leti's scientific excellence and develop an open mindset by working with some of the best teams in our fields worldwide.

To find out more about the Carnot institutes, look us up at http:// www.instituts-carnot.eu
To know more about the Marie Sklodowska-Curie Actions go to http://ec.europa.eu/research/mariecurieactions/

SUSANA BONNETIER
International Academic Collaborations Coordinator
Scientific Directorate of Leti

PROFESSOR JÉRÔME CASAS, University of Tours (France) Leti Chair of Excellence on Bio-Inspired Technologies

Jérôme Casas, Professor at the University of Tours, Insect Biology Research Institute (IRIB), senior member of the Institut Universitaire de France, and specialist in bioinspired technology, was invited by Leti to serve as Chair of Excellence on bio-inspired technologies, funded by Leti's Carnot Program. Faced with the challenges of energy efficiency and resources, biomimicry offers new insights into innovation by emulating nature. According to Dr. Casas, *"Living organisms present a level of operational efficiency shaped by the instinct to survive and enhanced by thousands of years of natural selection. They are sophisticated and unusual enough to drive breakthrough advances in technology."*

Leti integrates biologically inspired engineering with a Casas-led team in which biologists, mathematicians, physicists, and engineers interact. With the collaboration of Dr. Casas, Leti is one of the first research institutes to go beyond traditional research on neuromorphic engineering, which mimics the brain, by taking a full systems approach: understanding the intelligence system of insects capable of synthesizing sensory information very quickly and efficiently to generate lifesaving action. One of such projects, Insect-inspired CMOS-RRAM based escape system to looming dangerous stimuli, uses RRAM technology in components that emulate the escape system of insects.

Dr. Casas collaborates with Leti researchers on another project, Biomimetic capture of odor molecules in a microfluidic system, which explores emulating the olfactory system of vertebrates and its odors-capturing mucus for the development of future innovative sensors.

Born in the foothills of the Swiss Jura Mountains, Jérôme Casas obtained his Ph.D. from the ETH Zurich in 1989. He became a full professor at the University of Tours in 1995. His research interests include the sensory ecology of mimetics and biologically-inspired technology, particularly biomimetic flow sensing. One notable feature of his approach is the blending of natural history with both state-of-the-art technology and modeling. More information about Dr. Casas and his work can be found at casas-lab.irbi.univ-tours.fr/.

PROFESSOR SUBHASISH MITRA, Stanford University (USA) Leti Chair of Excellence on Novel Technologies and Architectures for Abundant-Data Applications

CEA-Leti is pleased to host Subhasish Mitra, Professor of Electrical Engineering and Computer Science at Stanford University, as Chair of Excellence on Novel Technologies and Architectures for Big Data, funded by Leti's Carnot Program. According to Prof. Mitra, the future demands of data-intensive applications cannot be met by simple improvement of the capabilities of current electronics. Isolated refinements of transistors, data storage technologies or integrated circuit architectures alone will not be sufficient. Transformative nanosystems, holistically implementing new computing paradigms will be essential for future high-performance and highly energy-efficient electronic systems.
Prof. Mitra's research interests include robust computing, VLSI design, electronic design automation, disruptive 3D integrated circuits and their application in fields going from high performance computing to neuroscience. Leti collaborates with Prof. Mitra to identify the best suited novel architecture and emerging nanotechnologies that will allow the future disruptive applications of the day-after-tomorrow. The on-going work involves exploring and designing a Processing-in-Memory architecture, targeting Abundant-Data and dense interconnections applications. For data intensive tasks, Leti envisions a new architecture paradigm that will bring computation close to the data using advanced 3D integration. The concept will be designed and validated on silicon. In this partnership, Leti also expects to demonstrate the efficacy of Resistive Memories as basic building blocks for emerging computing paradigms as brain-inspired hyper dimensional computing.
Subhasish Mitra directs the Stanford Robust Systems Group at Stanford University and co-leads the Computation focus area of the Stanford SystemX Alliance. He is also a faculty member of the Stanford Neurosciences Institute. More information about Prof. Mitra can be found at web.stanford.edu/~subh/

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Leti to Tackle Tomorrow's Research Strategies with Stanford SystemX Alliance

In 2016 Leti became a member of Stanford's SystemX Alliance, a network of a hundred of renowned Stanford University professors and thirty leading industrial partners, joining forces in a pre-competitive environment to define tomorrow's research strategies. Leti is the first technological research organization to join the Alliance, thus benefiting from Stanford's top-notch upstream research and networks. Leti's participation to SystemX bridges the gap between academia and industry, bringing to the alliance its extensive and advanced research facilities (including an 91,500 ft2 state of the art clean room) and its scientific excellence and expertise on technology transfer.

Together, the SystemX partners are working on a wide range of next generation applications, from materials and devices to systems and applications in electronics, photonics, networks, energy, mobility, bio-interfaces, sensors, and other technical domains. Hot topics include the self-driving car; future artificial-intelligence systems that will improve performance and operation of our mobile, medical, smart-home solutions and devices; cybersecurity and precision medicine, and also quantum computing.

Involving the world's foremost technology companies – such as Google, Huawei, Xilinx, Intel, Qualcomm, Samsung, Toshiba, and Infineon – the SystemX Alliance members explore new hardware and software solutions at all levels of the system stack. This global exchange of ideas and knowledge provides an avenue for worldwide strategic discussions and helps members stay ahead of the game.

Leti shares its innovative research results during regular SystemX events and explores ambitious, innovative and collaborative projects together with the partners of the Alliance. Leti is also hosting Stanford PhD interns working within the Alliance, and sending Visiting Researchers to Stanford to work side by side with SystemX professors.

CARLOTTA GUIDUCCI

Professor at the École Polytechnique
Fédérale de Lausanne (Switzerland)

***"The technical quality of the people at Leti is extremely high"* said Carlotta Guiducci, Professor of Life Sciences Electronics at École Polytechnique Fédérale de Lausanne (EPFL).**

"They have large teams of people who are top-notch scientists in microelectronic and nanoelectronic technologies—and this is quite exceptional, even on a worldwide level."

EPFL and Leti have been collaborating for ten years on a variety of projects, including most recently, the European Research Council (ERC) project called Design and Elaboration of Multi-Physics Integrated Nanosystems (DELPHINS), which began in 2009.

The goal of DELPHINS is to build a generic multi-sensor design platform for embedded multi-gas-analysis-on-chip. A wide range of applications will be impacted by this project, including medicine (recognizing specific diseases), environmental protection (spotting toxic and complex air pollutants), perfume & fragrance, and agribusiness.

Prof. Guiducci and Leti are studying nano-sized sensors, technologies that hold great promise for obtaining the resolution and sensitivity required to quantify specific DNA molecules by means of integrated electronic chips with minimal sample preparation. The partners have already demonstrated that nanowires outperform the sensing performance of standard electronic sensors.

"Leti has technologies at standard levels used in industries," said Dr. Guiducci. "At the same time they have more forefront technologies, taking things one step forward. For a technological partner, these are very precious assets. Innovation in micro and nanoelectronics needs to be designed and proven in collaboration with partners who own the technology at the state-of-the-art, and at the same time, are driven by a scientific mission".

TAKURO YONEZAWA

Professor at Keio University
(Japan)

Professor Takuro Yonezawa said that thanks to Leti's leadership, culturally diverse groups with a range of skillsets were able to work together from across the globe to drive a significant Smart City project to completion.

Keio University's collaboration with Leti started in 2013, with the Cloud of Things (ClouT) project, which was funded by the European Commission (EC) and the National Institute of Information and Communications Technology (NICT) of Japan. According to Professor Yonezawa, "We knew Leti had very good experience and technical vision in the Smart City area. On top of that, they have very good management skills, respecting and maximizing each partners' strength. These are the reasons we decided to join the team and start a partnership with Leti."

The goal of ClouT was to collect data in different cities from a variety of data sources, including IoT devices, social networks, and mobiles. Leti's sensiNact software is an IoT platform that gathers data from IoT devices supporting various IoT protocols and platforms; Keio University's communication protocol bridge enriches the Leti's sensiNact platform's supported protocols catalogue. By integrating the two, the team was able to gather data from various European and Japanese cities, including Santander, Genova, Fujisawa and Mitaka, resulting in a unique and massive urban data platform.

The team succeeded in collecting data from more than 500 thousand physical and virtual data sources by integrating Leti's sensiNact platform and Keio's SOXFire XMPP protocol implementation.

In 2016, ClouT was completed, and a new project was kicked off. This new project, called Big Data meeting Cloud and IoT (or BigClouT), is jointly funded by the EC and NIST through 2019.

"Not only does Leti have strong technical skills, they are also very good at project management," said Professor Yonezawa. *"There are a number of cultural gaps between the different groups working on the project. Different academic teams, different cities, and different companies were involved. But Leti leads the project and is very open to discussion. Leti's teams are very good at getting the diverse groups to work together."*

The project has been more than just work. *"I've made a lot of friends through our cooperation,"* said Professor Yonezawa. *"Sometimes we go to Grenoble to work with people from Leti—and I've always appreciated the warm welcome. Our cooperation has opened my mind in a number of ways."*

THIERRY BARON

CNRS Research Director at Laboratoire des Technologies de la Microélectronique (France)

“One of the things that makes Leti unique in Europe is that they have all the facilities you need for performing high-level research in nanotechnology and characterization,” says Thierry Baron, research director of CNRS, and director of Laboratoire des Technologies de la Microélectronique (LTM).

LTM was created in 1999, by the Centre National de la Recherche Scientifique (CNRS) and Université Grenoble Alpes (UGA), to promote collaboration in nanotechnologies with Commissariat à l’Énergie Atomique (CEA). The partnership between LTM and Leti was strengthened through collaborative work in the frame of several European projects and industrial partnerships, on topics like new etching chemistry, advanced processes for nanomaterials, self-assembled nanowires, and most recently microfluidics and nanotechnologies applied to health care.

Recently, Dr. Thierry Baron has developed, in a joint collaboration between Leti, LTM, Applied Materials and STMicroelectronics, III-V thin film on silicon substrates, leading to important breakthroughs in fabricating a laser source directly grown on Si. As proof of the team’s success, University College London monolithically grew an electrically pumped continuous-wave 1.3 µm InAs/GaAs quantum dot laser in London on (001) substrates covered with a GaAs buffer layer developed in the project’s common III-V MOCVD reactor.

“With Leti’s 200 mm and 300 mm clean room, research is done on production tools, using the same facilities that you’d have in industry,” said Doctor Baron. *“Since you use the same facilities that you’d have in industry, you can tackle the main challenges of IC and manufacturers’ companies from the start.”*

Dr. Baron said, *“The technological aspect is huge with CEA-Leti. The reactivity is very good. They’re always willing to take things a step further and to move the innovation to industry. They always look at how to transform research into products. This is unique in France in this field, and very rare in the world.”*

SCOTT MANALIS

Professor at the Massachusetts Institute of Technology (USA)

“Not only were the people we worked with at Leti very creative, they were also very warm and welcoming. These things fueled our interaction,” said Professor Manalis.

The partnership between the Massachusetts Institute of Technology (MIT) and Leti began in late 2012, initially involving Leti manufacturing devices that were historically designed in labs at MIT.

According to Professor Manalis, *“A colleague at Caltech had often told me great things about Leti. I knew that Leti had an excellent team that made very complicated devices with high precision and reproducibility.”*

In 2016, the partnership evolved to focus on a scientific research and development project, involving suspended microchannel resonators (SMRs). This technology is based on a hollow cantilever beam oscillating in vertical flexural mode, with a buried microchannel inside, to allow fluid to flow within it, while the resonator is suspended in a vacuum cavity. Leti helped to design the SMR components and then manufactured them using state-of-the art techniques.

Professor Manalis said, *“What Leti did involved three different types of bonding steps—an anodic bond, a fusion bond, and a eutectic bond. Each of those bonding steps can be challenging to do well. Doing two of them in a process is certainly a lot harder than one. And Leti did three! In addition to those three bonding steps, there were many others that, taken one at a time aren’t terribly hard, but when done in combination with multiple bonding steps, become increasingly complex. These other steps include making piezo resistors, drilling holes in glass, etching glass channels, etching silicon channels, and etching deep into silicon to undercut the underside.”*

“The ability to make these sophisticated devices is unique and is a distinguishing quality of Leti. Importantly, the devices were delivered on schedule and they performed well.”

Setting up serial SMR arrays, and using piezoresistive readout to monitor several SMRs in real-time, the research and development project made it possible to measure and compare the growth rates of individual cells in a very short period of time. This technology will impact a number of applications, including those requiring the ability to assess the reactions of individual cells to drugs.

“Everybody at Leti was very supportive of our project and collaboration. They have an extremely talented team and state-of-the-art resources,” said Professor Manalis.

GÉRARD GHIBAUDO

CNRS Research Director
at IMEP-LAHC Laboratory
(France)

"Leti is very well positioned on a worldwide level in advanced technologies," said Gérard Ghibaudo, CNRS research director at the Institut de Microélectronique, Electromagnétisme et Photonique (IMEP-LAHC Laboratory, Grenoble, France).

Leti has been collaborating with IMEP for more than thirty years on a variety of European projects, dealing with miniaturization of nano-devices (including CMOS and memories) and they have shared hundreds of PhD students exploring the most challenging physics and characterization challenges of these new devices.

In 2016, Dr. Ghibaudo worked together with Leti on research around the variability and reliability of fully depleted silicon on insulator (FD-SOI) and nanowire devices, with a special focus on studying defects in these devices. The technical goals of this most recent project were to identify the critical reliability mechanisms of these key technologies, looking at the impact of electrical defects on device behavior and reliability. Statistical models able to explain and predict the device behavior were developed, based on advanced characterization, metrology and physical considerations.

As a result of this recent research, Leti and IMEP significant improved metrology techniques, making it possible to study devices at near atomic level and to model both the electrical behavior of the device and the influence of the process steps on device performance. New questions were also raised thanks to this research. For scaled-down devices, the behavior is more dispersed, and statistical studies are mandatory. Those devices operate at lower voltages, so that new physical phenomena arise which should be addressed with greater precision. The collaborators continue to work together to address new challenges stemming from miniaturization, new materials and novel architectures.

Leti has also been collaborating for several years with Dr. Ghibaudo on emerging memory concepts. In particular, the partners have been deepening their understanding of Resistive RAM (RRAM) to analyze device performance and reliability thoroughly, and increase the maturity of this technology. Dr. Ghibaudo is a renowned expert on dielectric reliability and device modeling. His expertise is helping to clarify the experimental results obtained on innovative RRAM processed in Leti's cleanroom. A topic addressed by this collaboration concerns RRAM failure during cycling. RRAM dielectric breakdown is identified as the origin of endurance collapse when a too high programming voltage is applied. Thus, to describe this failure, physics of oxide breakdown was implemented in RRAM models. This statistical approach allowed to quantify RRAM reliability at the array level, a necessary step before technology industrialization.

"We are very lucky to be associated with Leti, and to benefit from their advanced technology and devices," said Dr. Ghibaudo. *"They have world class expertise in a number of technologies that go beyond standard CMOS and the association with our characterization and physical know-how is very successful."*

SERGIO BARBAROSSA

Professor at the Università
La Sapienza
(Italy)

"Nurturing close collaboration among highly skilled team members is part of Leti's culture," said Sergio Barbarossa.

Ever since he started working with Leti in 2000, Professor Sergio Barbarossa has appreciated how well rounded Leti scientists are: *"At Leti, I find people have an excellent theoretical background, especially when it comes to the next generation of wireless networks. Most importantly, scientists at Leti exhibit breadth and depth of knowledge in technology, making the most of a wide ecosystem of partners across Europe. As an academic, this grounding in technology and participation in concrete projects are essential to me."*

Having collaborated on a number of projects, Professor Barbarossa's work with Leti is now focused on helping make "the fog" a reality. *"The fog, or edge-cloud,"* as Professor Barbarossa explains it, *"is the cloud that gets closer to the mobile user. With 5G networks, there will be a dense deployment of micro and pico-cells. Endowing small cell base stations with edge computing capability will enable services with very low latency and ultra-high reliability. Most services to be enabled by 5G networks, like automated driving or virtual reality, require very low delay—and that delay must be highly deterministic. That's why mobile edge computing is so important."*

Collaborating with Leti on the 5G MiEdge project, co-funded by the European Commission and the Japanese Ministry of Internal Affairs and Communications, Professor Barbarossa has contributed to algorithms that determine when applications should be offloaded from smartphones to computers on the network. He relies on Leti's knowledge of wireless communications and dynamic and ad hoc cluster formation of edge computing units. He considers that knowledge to be head and shoulders above what he might find elsewhere.

But perhaps the most important ingredient for such a fruitful collaboration is the chemistry between colleagues. *"I like the friendly collaboration at Leti,"* says Professor Barbarossa. *"We know each other; and we know we get along in our research. For me, work has to be enjoyable – and that's what I get from working with Leti."*

SVEN TOUGAARD

Professor at the University of Southern Denmark

In 2011, after he had developed a technique of inelastic background analysis for x-ray photoelectron spectroscopy (XPS), a powerful and versatile technique to study the electronic structure of materials, Professor Sven Tougaard reached out to Leti to collaborate on extending his technique to deeper layers in materials.

"Leti scientists are leaders in using the PEEM [photoemission electron microscopy] technique," said Professor Tougaard. *"I knew we could combine their expertise in this PEEM technique with my expertise in the analysis of the generated data to do better depth profiling of nanostructured materials and achieve true three-dimensional imaging of nanostructured materials."*

Not only did Prof. Tougaard benefit from essential know-how, he also gained access to synchrotron facilities through Leti's ecosystem of partners in Grenoble. Leti provided technological samples of interest, and performed the necessary characterization of the samples to help test and validate the method.

"With each partner bringing unique know-how to the project, the tests were a big success," he said. *"We demonstrated that the technique could indeed be extended to hard x-ray XPS [HAXPES] to provide a much higher analysis depth—and therefore, enhance the sensitivity to deeply buried interfaces and layers, as deep as 100 nanometers."*

Since there is a big demand from industry to have this kind of non-destructive technique to determine the composition and structure of deeply buried layers, the collaboration between the University of Southern Denmark and Leti will impact a range of applications, including very fast transistors, new batteries, and new solar cells. This extended technique will also have applications in other fields, including pharmaceuticals.

So what were the contributing factors to a successful outcome? According to Professor Tougaard, *"The collaboration was a big success, thanks not only to Leti's unequaled expertise in the use of synchrotron radiation, which was crucial to the project's outcome, but also to Leti's ability to produce samples, and their techniques for alternative characterization of the samples."*

GEORGE MALLIARAS

Professor at the Ecole de Mines de Saint-Etienne (France)

"Not only is Leti the best in the world at taking a technology, and maturing it to the point where it can be easily adopted by industry," said Professor George Malliaras, *"the people there are also exceptionally good scientists."*

Each of the two projects Dr. Malliaras worked on with Leti gave him perspective on the different reasons Leti is uniquely positioned as a partner in research. The first project involved biosensors using organic transistors.

"Working with Leti, we pushed the biosensors towards technological maturity, so that they could be adopted by companies," he said. *"This is what Leti does better than anybody else in the world. There aren't any other organizations that can take a prototype and make it into a concept that can be adopted by industry the way they do."*

"They took a device that was a lab prototype, and they made it in such a way that it can be produced by low-cost methods, using high-volume manufacturing. We demonstrated that the device can be used to detect analytes in a real-world environment. For example, at the end of the project, we concluded that we were able to detect lactate in a real sweat sample."

"The second project was more of a low TRL [technology readiness level] type work, where we investigated some 3D structures that were developed in our laboratory in collaboration with Cornell University targeting applications involving sensors that detect bacteria."

"We were able to show that you can grow this in a three-dimensional structure to make very efficient biosensors. This was more fundamental type of work. And this was interesting because I got to see the two sides of Leti. They have some exceptionally good scientists, on the one hand, who were able grasp the fundamentals of electrochemistry in this case. And on the other hand, Leti scientists are very good at transitioning an invention towards technological maturity to make it ready for industry. This is a very rare combination of expertise. I think it's unique in the world."

"It was a sheer pleasure working with these folks. I'm leaving France and on my way to the university of Cambridge. I will do my utmost to maintain this cooperation."

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