



**leti**  
cea tech

TECHNOLOGY  
RESEARCH  
INSTITUTE

2019

SCIENTIFIC |  
REPORT





2019

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REPORT



TECHNOLOGY  
RESEARCH  
INSTITUTE



**Emmanuel Sabonnadière**  
Chief Executive Officer

**“CREATIVITY  
IS INTELLIGENCE  
HAVING FUN.”**  
Albert Einstein

**As one of France’s leading research institutes in the fields of micro and nanoelectronics, CEA-Leti actively supports society’s digital transition—in energy, the environment, and the future of medicine—driven by the French Alternative Energies and Atomic Energy Commission (CEA).**

The digital transition, which aligns closely with CEA-Leti’s core expertise, underpins advances in all of these fields, and the institute is running a far-reaching program on embedded artificial intelligence that will accelerate/boost the digital transition. This program is foundational in that it will bring the groundbreaking semiconductor technologies we have developed with our partners over the past several years to the forefront. The innovations range from the latest advances in spiking neural networks (SNNs) combining new-generation resistive memory and FD-SOI to very-low-power MEMS, NEMS, and biosensors. Assembled in 3D architectures, these devices will meet the performance and energy-efficiency requirements of the microcontrollers and processors that will one day enable embedded artificial intelligence (AI).

The most obvious applications and biggest opportunities for AI are found in the automotive, aeronautics, energy, healthcare, and agriculture industries and in the services sector. We have acquired broad, deep knowledge of these applications through our strong, long-term partnerships with stakeholders—global companies, SMEs and startups—in all of the industries concerned. Today our research scientists, engineers, and staff are profoundly committed to the success of our embedded artificial intelligence program, and their efforts have made the program one of Leti’s flagships. We also have assigned senior scientists to the institute’s ambitious silicon quantum computing program, which unites some of France’s leading experts—both from Leti and from the CEA, as well as CNRS, France’s national center for scientific research. This program has the capacity to bring major advances in high-performance computing (HPC). As in all major Leti programs, our overall focus is on technology transfer to industry, ultimately.

Our last two programs are integrated LiDAR and 5G. They are rooted in the cyber-physical systems domain, an area in which we have a long history of early-stage research with our industrial partners. These technologies are mature, and our R&D is tailored to specific market applications. Here, we leverage the power of our cleanrooms outfitted with the most advanced More-than-Moore production equipment and the passion for innovation of our application- and industry-specific departments to continuously improve power management and energy efficiency.

Finally, environmental preservation is fundamental to all of our work. The natural world—including humanity—is a perpetual source of inspiration and innovation. Exploring the functioning of the human brain and investigating the amazing biological systems found in nature motivates and excites our scientists. In fact, our research on the brain has produced progress in interfaces between the brain and its environment, including some major advances in the brain-computer interface in 2019—a area that will remain central to our work.

We are also conducting innovative research on organs-on-chip to blend microbiology and microelectronics. This exciting pathway into the future of medicine represents an exciting new direction for our researchers, as well as for our partners. The *2019 Scientific Report* presents our most significant results and publications of the past year. Many of these projects are in support of the digital transition. I and everyone here at Leti are thrilled to be able to share our work with you. It is our hope that the following pages will spark your curiosity and inspire you to take part in creating the new innovations that will make a difference to our industrial economy, our society, and the environment.

My warmest regards,  
Emmanuel



**Thomas Ernst**  
VP for Science  
and Technology

**With the digital revolution well underway, the use of information technology is expanding faster than ever before in fields like transportation, telecommunications, healthcare, and augmented reality. The challenge now is to achieve much finer integration. This means inventing new system and device designs and architectures while innovating technologies to bring data processing (the “smart” in smart systems) as close to the device as possible. And, with increasing pressure on our planet, we must work toward these objectives with sustainability in mind at every step of the way.**

One of the things that makes Leti so unique is that we develop embedded technologies across the value chain, from material to system. In the era of More than Moore this is a real advantage: The technologies that are emerging at component level are determined by the characteristics of the end system. At Leti, we address design and technology simultaneously, and develop advanced tools and methods to optimize system bricks, components, and materials in an integrated and interrelated manner.

Leti is developing tomorrow’s technologies across the entire IT spectrum, from data collection and signal transmission and processing to secure data processing and new computing paradigms. Our groundbreaking research is backed by world-class equipment and some of the finest minds in science and technology—strengths that will position us to integrate a wide variety of emerging materials into future generations of systems.

And, as a technology research organization, we nurture our technologies to a degree of maturity compatible with transfer to established companies or with the creation of startups.

The *Leti 2019 Scientific Report* highlights the significant contributions made by our scientists, technicians, students, and partners from academia and industry over the course of the year. I would like to take this opportunity to thank them, and I hope that you will find their work as exciting and inspirational as I do.

My best regards,  
Thomas



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



TECHNOLOGY  
RESEARCH  
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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\*.

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

Leti at a glance

800  
publications per year

ISO 9001  
certified since 2000

Founded in  
1967

Based in  
France (Grenoble)  
with offices in the

US (San Francisco) and  
Japan (Tokyo)

300  
industrial partners

1,850  
researchers

3,100  
patents in portfolio

10,000  
sq. meters cleanroom space,  
100-200-300 mm wafers

65 startup created



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](http://www.cea.fr/english)

World-class scientific  
research in the heart  
of the French Alps

No matter how you measure it—from academic publications and patents to startups and job creation—the Greater Grenoble area, known as “Grenoble-Alpes”, is by far one of Europe’s most active and prolific science and technology ecosystems. Grenoble may be small, but its student and business communities are vibrant and very international. And the breathtaking mountain environment offers easy access to outdoor activities all year round.

You may be wondering just how a “minor” French city like Grenoble became an internationally-renowned hub for technological innovation. Grenoble has a long history of excellence in scientific research, but the tipping point was perhaps the advent of the Minatec micro and nanotechnology innovation campus. Minatec pioneered a groundbreaking cluster model that unites sci-tech stakeholders from education, research, and industry. Its success has inspired initiatives like the Clinattec biomedical research center, the GIANT (Grenoble Innovation for Advanced New Technologies) campus alliance of academic institutions and research organizations, the EU Nano2022 program to develop a new generation of semiconductors, and, most recently, MIAI (the Multidisciplinary Institute in Artificial Intelligence)—all located in Grenoble. Grenoble is also home to top-tier academic institutions: Grenoble-Alpes University, Grenoble Institute of Technology, and Grenoble Ecole de Management have all earned top slots in the major international university rankings. Finally, international large scientific instruments like the European Synchrotron Radiation Facility (ESRF) and the high-flux neutron beamline at the Institute Laue-Langevin (ILL) are just down the street from Leti in Grenoble’s research district.

R&D-intensive industries like microelectronics, nanoelectronics, medtech, energy, and cleantech are staples of the local economy. And a number large industrial corporations serving international



markets have located their R&D divisions in Grenoble. The high concentration of tech-oriented businesses and a strong fabric of more traditional manufacturing companies have made Grenoble particularly fertile ground for collaborative innovation projects—often funded through EU and national instruments—designed to rapidly bring novel concepts from lab to market.

Although Grenoble—a medium-sized city—may not be a European capital, it is a wonderful place to live. The city center is compact and very walkable, placing a wide range of everyday activities within easy reach. The population is extremely cosmopolitan. In fact, Grenoble is home to the second-largest English-speaking population in France, second only to Paris. But what people who live in Grenoble consistently rave about is the mountain environment. From downtown Grenoble it is possible to access major hiking trails by car within minutes, and the suburbs (and even the city center) are dotted with trailheads that can be reached by public transportation and, in some cases, on foot. Major ski resorts are close enough to make hitting the slopes for a half a day during the week a reality. A dynamic network of sports clubs is available to help newcomers discover all that is on offer.

People come to Grenoble to study or conduct research. But they stay for excellent career opportunities and top-notch quality of life.

A great place to study

The Shanghai Academic Ranking of World Universities named Grenoble-Alpes University no. 1 in France for:

- Computer Science
- Electrical & Electronic Engineering
- Energy Science
- Water Resources Engineering
- Nanoscience & Nanotechnology
- Instruments Science & Technology

Grenoble’s student population of 62,000 stands out for its diversity and excellence:

- 42% in science, technology, and engineering
- 3,700 PhD candidates
- 180 nationalities

...and launch a career!

The Greater Grenoble area is home to a workforce of 340,000:

- 28,000 engineers
- 23% management, well above the national average of 17%

First place for R&D  
First in France for  
R&D jobs

Second in France  
for engineering  
jobs



# 2019

SCIENTIFIC |  
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## Highlights

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Towards multiqubit structures



## Quantum computing

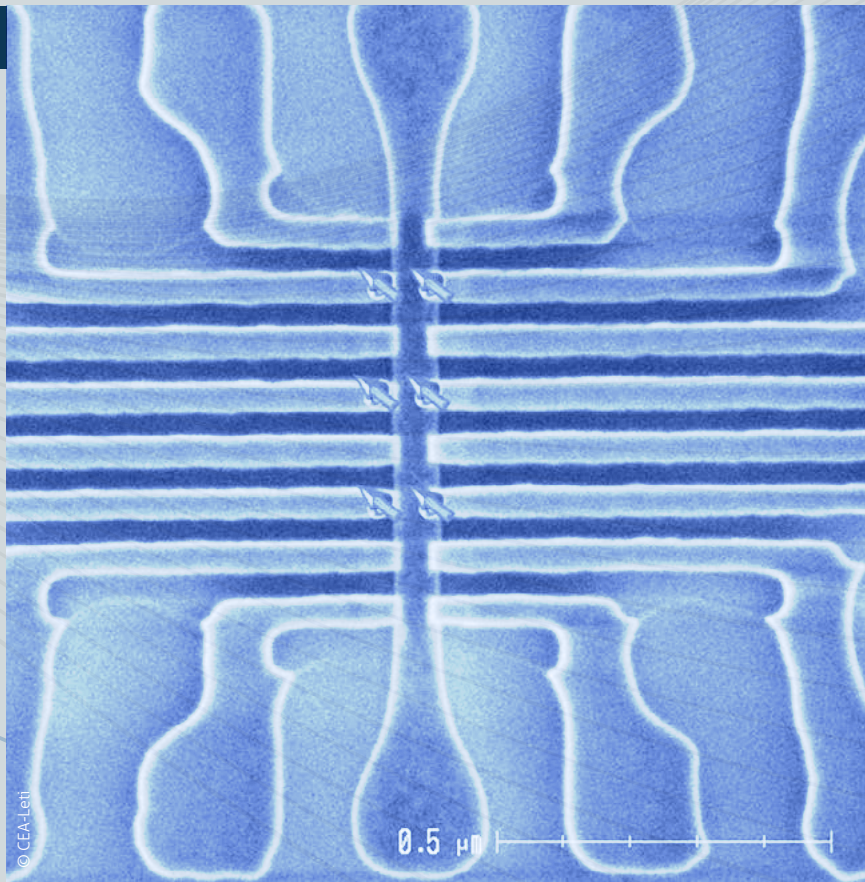
Maud Vinet  
Quantum Program Director

Leti's quantum computing research benefits from Grenoble, France's pioneering innovation ecosystem and its historic synergies between basic and applied research, from physics lab to circuit fabrication line. In 2018 Leti launched a strategic program to address the challenges of large-scale quantum computing.

Since the program's inception, we have reached some major milestones. First, our QuCube project to develop a silicon quantum processor in collaboration with IRIG and Institut Néel won a €14 million ERC Synergy Grant in October 2018. We also founded an inter-institutes team (CNRS, CEA, UGA) to move towards mastering quantum coherence at the macroscopic scale to design condensed matter devices useful for quantum technologies and large-scale quantum computing. Our research results included utilizing spin-valley coupling to generate electrically-induced spin resonance in Si **using solely a gate-induced electrical field**. In technology, we created a 28Si supply chain used to grow 28silicon

epitaxial layers with an isotopic purity greater than 99.992% on 300 mm wafers, at a level of quality compatible with standard CMOS technology. We also implemented a design flow (DK Quantum MOS) appropriate for quantum computing that includes all of the essential design building blocks. In the area of control electronics, we evaluated FD-SOI and demonstrated that local back-biasing at low temperatures can compensate for  $V_t$  increases and enable dynamic tuning of the performance/consumption tradeoff.

**From an EU ecosystem perspective**, we signed **one MOU** with the Imec innovation cluster in Belgium to support European economic and strategic sovereignty, **with a special focus on quantum computing**. **The three RTOs (Imec, FHG, and Leti), are also willing to cooperate to support the transfer of quantum technologies to industry.** **Finally, we built an industrial ecosystem with existing stakeholders to speed up scientific and technological advances and tech transfer.**



## Digital 5G

Jean-Baptiste Doré  
5G Program Director

5G deployments are rapidly gaining traction around the globe, and the era of cyber-physical systems is here. Traditional market players will draw the contours of tomorrow's 5G integrated systems. However, the automotive, smart cities, utilities, smart industry, and other vertical markets will also have a say.

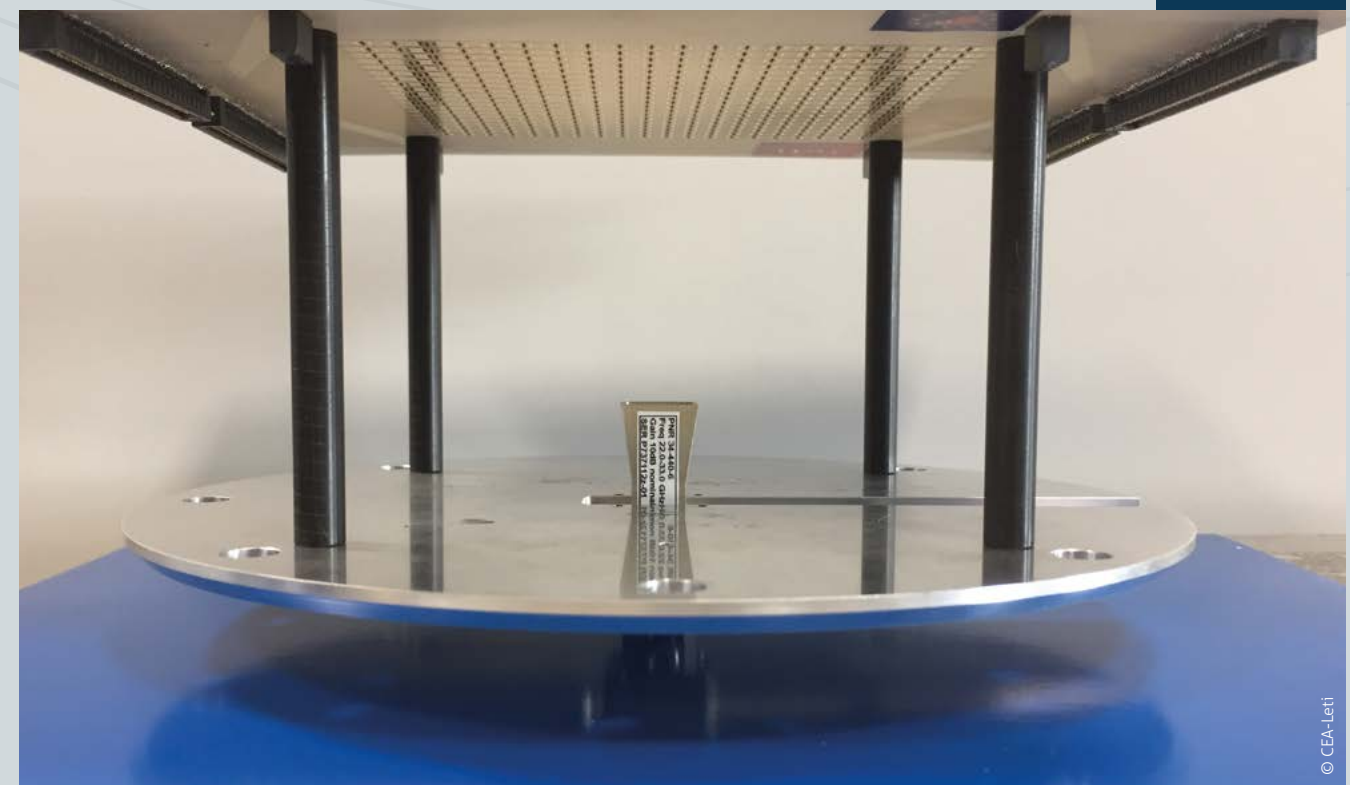
For 5G networks to deliver sufficient service quality amid an exponential increase in machines and users, ultra-dense connectivity is a must. The low-latency responses required for critical applications—and desired for others—will depend on the proximity of computing resources to network nodes. Microelectronics and integration technologies will play a key role.

Leti is positioned to run 5G trials and optimize the building blocks of sustainable business applications for its partners. We are also maintaining a focus on innovative antenna designs and radio frequency systems built

on advanced digital signal processing and software solutions.

In mid-2018 we built a demonstrator with beyond-state-of-the-art components including an electronically-steerable antenna at 26 GHz-28 GHz and the associated digital processing, a radio front-end module at 60 GHz, and a multi-Gbps digital modem. This demonstrator will lead to the deployment of a 5G network integrating a Gbps link with mm-wave access on the MINATEC campus by end-2019. We are also addressing 5G power modules, passive components like filters, CMOS integration, and the co-design and co-integration of digital, RF, and antenna technologies.

Looking ahead, we will explore the use of new spectrum bands (mm-wave, THz, and optical) and new network paradigms (non-terrestrial, satellite, and vehicular communications).



26GHz antenna



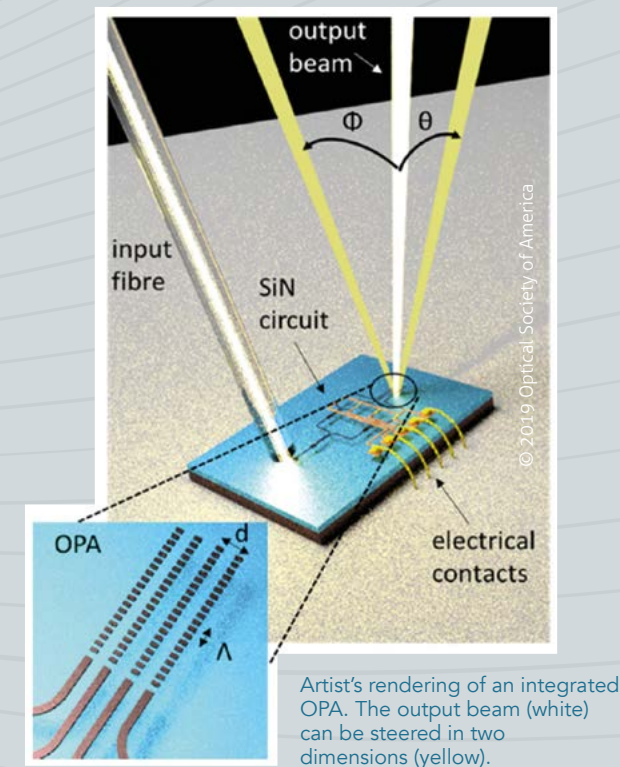
## LiDAR



François Simoens  
LiDAR Program Director

**L**iDAR (Light Detection and Ranging) has recently emerged as a key enabling technology for tomorrow's sensing and vision systems. The future of LiDAR is on the mass market, where it will enable semi-autonomous and autonomous mobility in drones, ADAS, autonomous driving systems, robots, and industrial automation. This mass-market appeal has garnered hundreds of millions of dollars in investments in dozens of new companies. However, the widespread adoption of LiDAR will hinge on lower system costs and smaller form factors. Further research is required to reach these goals while increasing reliability and robustness.

To help its R&D partners stay ahead of the LiDAR curve, Leti launched its strategic chip-scale LiDAR for CPS program in 2018. The program is developing agile chip-scale LiDARs, which go a step further than the



➤ mechanical scanning-based LiDARs currently on the market, as well as newer systems based on MEMS mirrors and flash illumination, which are still in the qualification testing stage.

In 2018 the program leveraged expertise in silicon photonics, III-V materials, heterogeneous technologies, and 3D integration to achieve two major, fully CMOS-compatible advances on the path to fabricating low-cost, small-footprint chip-scale LiDAR systems. The first was a LiDAR source utilizing optimized integrated hybrid III-V materials on silicon single-mode lasers with a fully CMOS-compatible process on large-wafer format. The second was the first-ever demonstration of laser scanning with  $17.6^\circ \times 3^\circ$  two-dimensional beam steering in the near-infrared spectrum using a SiN integrated circuit containing optical phased arrays.

Leti's unique expertise at the crossroads of microelectronics, photonics, and software algorithms positions the institute at the top of the game towards the development of the third generation of LiDAR systems.

## Artificial intelligence

Frédéric Heitzmann  
AI Program Director

**L**eti's artificial intelligence research is closely intertwined with a new initiative that became official in 2019, the Grenoble-Alpes University Multidisciplinary Institute in Artificial Intelligence (MIAI). As a member of MIAI, Leti will benefit from opportunities for cooperation on embedded AI, healthcare, and core AI technologies.

More broadly, MIAI aims to establish a vibrant AI community to bring together stakeholders of all types and sizes, from large government research organizations and private-sector corporations to startups and schools around joint research activities, networking events, and educational outreach. Leti's experience bringing new technologies from the lab to the market will add value to this burgeoning community.

A total of 28 endowed research chairs have been established under MIAI, and Leti is directly involved in four of them. "Hardware for Spike-Coded Neural

Networks Exploiting Hybrid CMOS Non-volatile Technologies" will investigate new architectures based on emerging memory technologies, a field in which Leti scientists are driving major advances.

"Patient Empowerment via a Participatory Health Project" will address the potential of AI algorithms for the processing of health data, from data collection through to extracting value from data to make healthcare systems more efficient. "Edge Intelligence" will tackle the problem of distributed AI. Finally, "Toward

Robust and Understandable Neuromorphic Systems" will explore novel neural network architectures and functions in collaboration with neuroscience research groups.

Leti will play a unique role in MIAI, coupling the capabilities of semiconductor technologies—Leti's core area of expertise—with new concepts coming out of academic research labs to address a variety of market applications.



## Leti founding member of ambitious new artificial intelligence community

**As one of the world's leading institutes for semiconductor technology research and development with keen insights into current and emerging market applications, Leti is helping to build MIAI, the Grenoble-Alpes University Multidisciplinary Institute in Artificial Intelligence.**

**L**eti is a founding partner of the newly-established (2019) Multidisciplinary Institute in Artificial Intelligence (MIAI), bringing together academic institutions, government research organizations, private-sector corporations, and startups around joint research programs in artificial intelligence. Eric Gaussier, Director of Grenoble IT lab LIG and coordinator of MIAI, is looking forward to working with Leti under this exciting new initiative. Gaussier said, "LIG and Leti had previously worked together under the PERSYVAL-lab (Pervasive Systems and Algorithms) initiative in Grenoble. In terms of artificial intelligence, Leti's expertise in hardware and embedded architectures is a real differentiator for MIAI." MIAI officially launched in the spring of 2019. For Leti, membership in MIAI will provide opportunities to cooperate with academic research labs and tech companies on a variety of AI topics. Leti scientist Frédéric Heitzmann said, "Coupling hardware, software, and advanced Learning algorithms is one area where we are looking for synergies with academic experts in AI".



### PARTNER:

MIAI, the Grenoble-Alpes University Multidisciplinary Institute in Artificial Intelligence.

**OBJECTIVES:** Investigate how Leti's semiconductor technologies can be applied to new AI concepts developed by academic research laboratories.



Eric Gaussier





# Working to make the electronics industry more sustainable

The energy and digital revolutions are here, making more sustainable electronics more important than ever. At Leti, our research focuses on solutions to reduce the amount of critical materials used in electronics manufacturing and to lower electronic devices' energy consumption. Our work encompasses the entire value chain, from novel materials implementation techniques like thin-layer transfer, atomic-layer deposition, etching, and local transfer and/or deposition through to energy efficiency, with ultra-low-power solutions and energy harvesting. We also strive to use as little water as possible in our processes, and we recycle our research wafers. Read on to learn more about how our programs and partnerships are supporting a more sustainable electronics industry.



”

**Bernard Comte**  
Technical Supervisor, Leti cleanrooms

We have a comprehensive policy to reduce the environmental impacts of our cleanrooms now and ensure that we grow sustainably moving forward. We keep a particularly close watch over our water consumption. We have implemented measures to reduce the nitrogen content of our liquid effluent emissions. We also control silicon emissions. In 2018 and 2019 we made improvements that drastically reduced our silicon emissions and started collecting and treating the water from our washers. Finally, we are already planning ahead for the arrival of a substantial amount of new equipment in the coming years so that we can continue to mitigate our environmental impacts.



”

**Ernesto Quisbert Trujillo**  
PhD candidate, Leti

I am doing my PhD dissertation on design methodology for sustainable IoT devices. As the IoT gains traction, the number of connected devices and the volumes of data circulating will explode, and today's design and eco-design approaches will reach their limits. My model includes an environmental assessment not only of the IoT device itself, but also of the infrastructure that supports it. I will be working with DSYS to apply the model to three IoT projects, where it will be used to improve the tradeoff between local (edge devices like sensor systems, relays, base stations, and local servers) and shared resources (internet and cloud computing).



**François Martin**  
Leti scientist and rare-materials expert

”

When we decide whether or not to pursue a technology, we look at the impact critical materials like precious or semi-precious metals and III-V materials will have. We either try to reduce the amount of these materials used in our processes or find alternative materials. These efforts are a constant source of innovation. And the new EU raw materials import laws have caused us to look at our entire supply chain to identify risks and orient our More than Moore and photonics research strategies accordingly. The goal is to find solutions to materials supply risks in the medium to long term so that the devices we develop are as sustainable as possible.



”

**Karine Samuel**  
Professor of Management Science,  
Grenoble Institute of Technology

The 'Need for IoT' project is addressing issues crucial to the sustainability of the electronics industry. The project's multidisciplinary partners—which include Leti—are looking at product lifecycle management from design to end-of-lifecycle issues. Rare materials—which will pose a threat to the industry within the next decade if alternatives are not found—are also being addressed. Specifically, the project partners will find solutions to limit or replace critical materials like indium, platinum, and gallium in communicating devices and create partnerships between academic researchers and microelectronics industry stakeholders to bring real change and foster agility in research practices and design.



”

**Jean-Pierre Raskin**  
Professor of Information and Communication  
Technologies, Electronics and Applied  
Mathematics, UC Louvain (Belgium)

Sometimes the best thinking happens outside of the classroom. I was on a fact-finding trip to Burundi in 2014 when I had a realization about how deeply technology affects us—for better and for worse. I was pleased to learn—over drinks this time—that Thomas Ernst of Leti shared this view. We decided right then and there to take action, and ENCOS (European Nanoelectronics Consortium on Sustainability) was born. Researchers from Grenoble-Alpes University, UC Louvain, and Leti are working together under the consortium to make tomorrow's micro and nanoelectronics more sustainable from design to materials to business models, something I feel is vital to the future of the industry in Europe.



# Highlights

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the fuel of innovation

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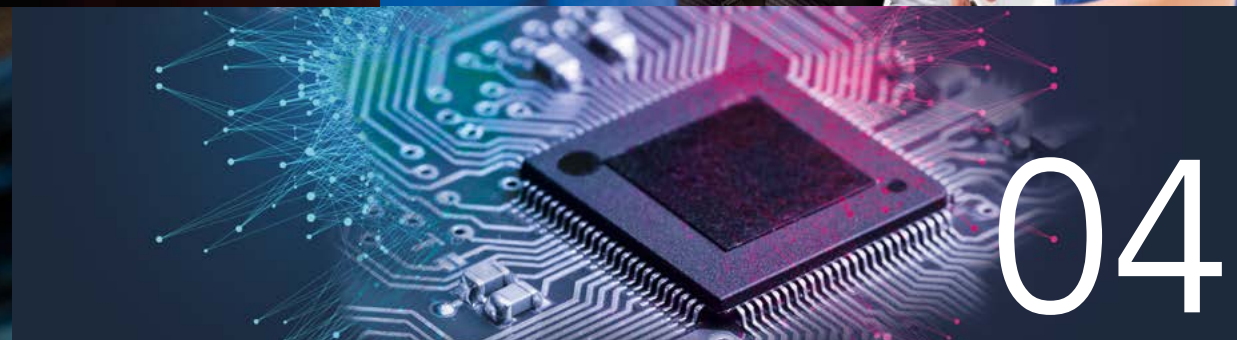
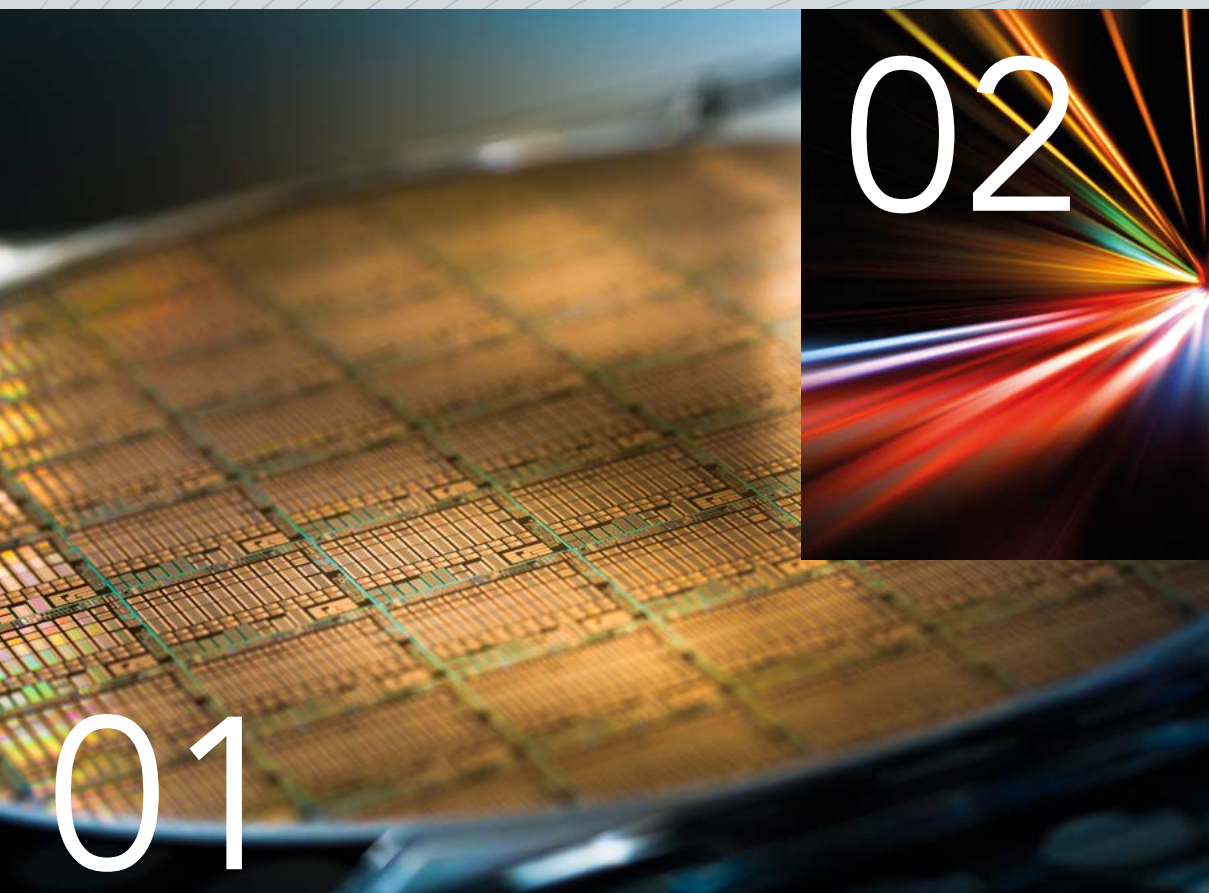
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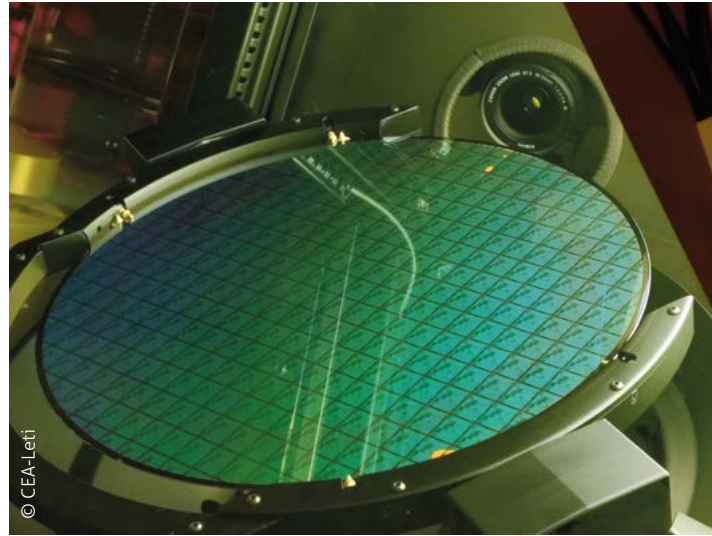
# 01

## New advanced materials and processes, the fuel of innovation

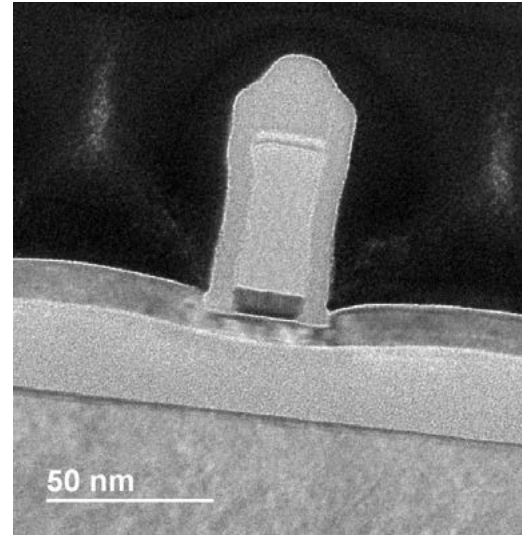
Advanced materials and processes are crucial to Leti’s device development and innovation activities. This chapter showcases a selection of the year’s highlights. However, our materials and processes are also key enablers of the technologies featured in the other chapters of this report and, especially, the GeSn epitaxy for laser applications in Chapter 2. This year we made major breakthroughs in 3D sequential integration and hybrid bonding, developed a new approach to advanced lithography, and made promising developments in OxRAM memory and thin-film batteries. None of these advances would have been possible without the development of advanced nanocharacterization techniques suitable for small complex devices. Looking forward, 2020 will be a big one for advanced SiC substrates, with a major collaboration and pilot just over the horizon.

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First demonstration of Smart Cut™ over CMOS



Low-temperature silicon epitaxy

## Leti's CoolCube 3D sequential integration technology overcomes major hurdles to market release

Claire Fenouillet-Béranger,  
Laurent Brunet  
Leti scientists

**With advantages like high interconnect densities and enhanced energy efficiency, 3D sequential or "monolithic" integration holds great promise for More Moore and More than Moore devices.**

**THE BREAKTHROUGH:** Breakthroughs in several 3DSI process steps.

**WHY IT MATTERS:** These advances have made a major contribution to readying 3DSI for industrial scale-up.

**NEXT STEPS:** Investigate application-specific stack processes.

**3D** sequential integration (3DSI) is a type of integration in which devices are fabricated sequentially on different layers, transferred by low temperature molecular wafer bonding, that are stacked on a single wafer. This approach enables very small 3D contact pitches and yields gains in both power and performance, making it an excellent candidate for heterogeneous material integration, for in-memory, neuromorphic, and quantum computing, as well as for sensor array interfaces. However, improvements must be made to several process steps to successfully bring the technology to the market.

Our research made several advances that address 3D sequential low-temperature challenges. We achieved low gate access resistance while preserving bottom level integrity and completed full raised source/drain silicon epitaxy at 500 °C. We also

demonstrated the integration of a low-temperature SiCO spacer deposited at 400 °C in both standard and low-temperature CMOS FDSOI annealing process flows—a first. Equivalent static performance (Ion/Ioff trade-off, SCE, DIBL, access resistance, EOT, mobility) was obtained, confirming the potential of SiCO as a low-k and low-temperature offset spacer for 3D sequential integration. Finally, we utilized an ingenious BEOL to FEOL strategy at the bottom wafer edge and completed characterization of ULK/copper iBEOL compared to thermal treatment. In addition, the Smart Cut™ process was used for the first time ever on a SOI substrate above a CMOS wafer.

These advances will help boost the performance and reliability of 3D sequential integration while reducing costs, ultimately helping to bring this technology to a wide range of applications.

**RESEARCH PARTNERS:** STMicroelectronics (interconnect reliability measurement and testing); Screen/LASSE (ns laser annealing); AMAT (low-temperature epitaxy); LAM Research (SiCO spacer deposition)

Further reading: • "Breakthroughs in 3D Sequential technology", IEEE IEDM 2018. Laurent Brunet, Claire Fenouillet-Béranger, Perrine Batude, Sylvain Beaurepaire.  
• "Integration of Low-k Low Temperature 400°C SiCO as Offset Spacer in view of 3D Sequential Integration", SSDM 2018. Claire Fenouillet-Béranger et al.

## Sub-10 nm technology: Leti process and materials know-how leads to new approach to patterning

Guido Rademaker,  
Maxime Argoud  
Leti scientists

**A cost-effective sub-10 nm patterning process flow was successfully demonstrated in the lab and could meet the future needs of CMOS logic, metal layers, novel memories, photonics, and biosensors.**

### THE BREAKTHROUGH:

A new chemo-epitaxial DSA process flow for sub-10 nm linewidth was developed and successfully demonstrated.

### WHY IT MATTERS:

A wide range of applications require cost-effective ultra-low-linewidth patterning.

**NEXT STEPS:** Fine-tune the process using state-of-the-art fabrication, metrology, and defectivity measurements.

In a post-Moore's Law world, the cost of continued miniaturization has become a fundamental challenge—one that will require taking innovative new routes to enhanced performance while maintaining affordability.

Our research addressed a promising lithography technique—chemo-epitaxial directed self-assembly (DSA) of block copolymers (BCP)—to create dense line-space patterns by surface energy contrast from a chemical template. This allows for linewidths in the range of 7 nm–20 nm, much denser than the most advanced patterning techniques currently employed in semiconductor manufacturing.

We developed the ACE (Arkema-CEA) process flow with Arkema. The flow consists of a sidewall image transfer (SIT) process—an advanced patterning technique—followed by DSA. The idea was to obtain a larger process window by multiplying the pitch and controlling the lateral dimension of the chemical template

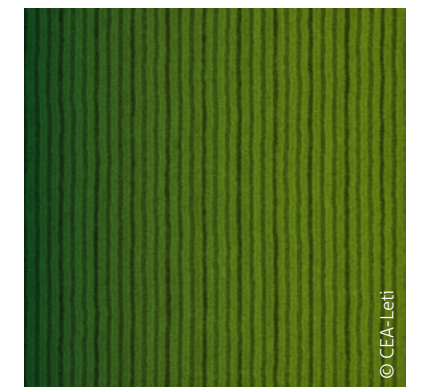
by the spacer deposition thickness. We demonstrated a process window for BCP alignment using both electron beam and optical immersion lithography.

We also developed advanced metrology techniques to respond to the challenges of the ultra-small critical dimensions and high aspect ratios in the presence of polymers. These included ultra-sharp tip tapping mode AFM; special preparation techniques to prevent damage to the polymers during TEM imaging; advanced backscattered electron imaging to detect nanometric etching residuals and buried DSA defects; and advanced image analysis for extraction of the power spectral density (PSD) of linewidth roughness (LWR).

Now that we have a better understanding of the process flow, we will focus on improvements, in particular to our control of the spacer morphology and surface energies, and implement 3D metrology techniques.

**RESEARCH PARTNERS:** Arkema and Brewer Science (materials); academic research labs LTM (Grenoble-Alpes University) and LCPO (Bordeaux University); Screen and Applied Materials (DSA process scale-up)

Further reading: • "Spacer patterning lithography as a new process to induce block copolymer alignment by chemo-epitaxy," Proceedings of SPIE Advanced Lithography (2019).  
A. Paquet, A. Le Pennec, A. Gharbi, T. J. Giammaria, G. Rademaker, M.-L. Pourteau, D. Mariolle, C. Navarro, C. Nicolet, X. Chevalier, K. Sakavuyi, L. Pain, P. Nealey, R. Tiron.

DSA of a BCP of  $L_0 = 30$  nm after PMMA removal (1  $\mu\text{m} \times 1 \mu\text{m}$ )DSA of a BCP of  $L_0 = 18$  nm before PMMA removal (500 nm x 500 nm)



# Robust 3D hybrid bonding process paves the way toward denser, faster smart imagers

Lucile Arnaud  
Leti scientist

**A wafer-to-wafer hybrid bonding process delivered outstanding alignment precision, performance, and robustness at an interconnect pitch of 1.4  $\mu\text{m}$ .**

**THE BREAKTHROUGH:** Mature direct hybrid wafer-to-wafer bonding process achieves 3D interconnect pitch record of 1.4  $\mu\text{m}$ , enabling new imager architectures.

**WHY IT MATTERS:** Finer interconnect pitches (1  $\mu\text{m}$ ) will meet the needs of new smart imager architectures, including for 3D vision systems.

**NEXT STEPS:** Explore chip-to-wafer bonding and the bonding of heterogeneous substrates.

The potential applications for 3D imaging are virtually limitless. From manufacturing automation and quality control through to medicine, 3D imaging is driving some major shifts in how humans and human-engineered systems perceive the world. One of the ways to enable the new architectures that tomorrow's imagers will require is to achieve finer interconnect pitches—a field in which Leti is a pioneer.

We decided to investigate 3D direct hybrid wafer-to-wafer with Cu-Cu bonding—a technology that is mature for imager applications at pitches between 5  $\mu\text{m}$  and 10  $\mu\text{m}$ —to better understand the effects of finer pitches on imager electrical and optical performance. Working in partnership with STMicroelectronics, we demonstrated that the transition from 9  $\mu\text{m}$  to 1.4  $\mu\text{m}$  did not alter the performance of a 14 megapixel imager.

Finer pitches create new demands in terms of bonding surface flatness and alignment. Our research leveraged surface preparation processes developed by Leti suitable

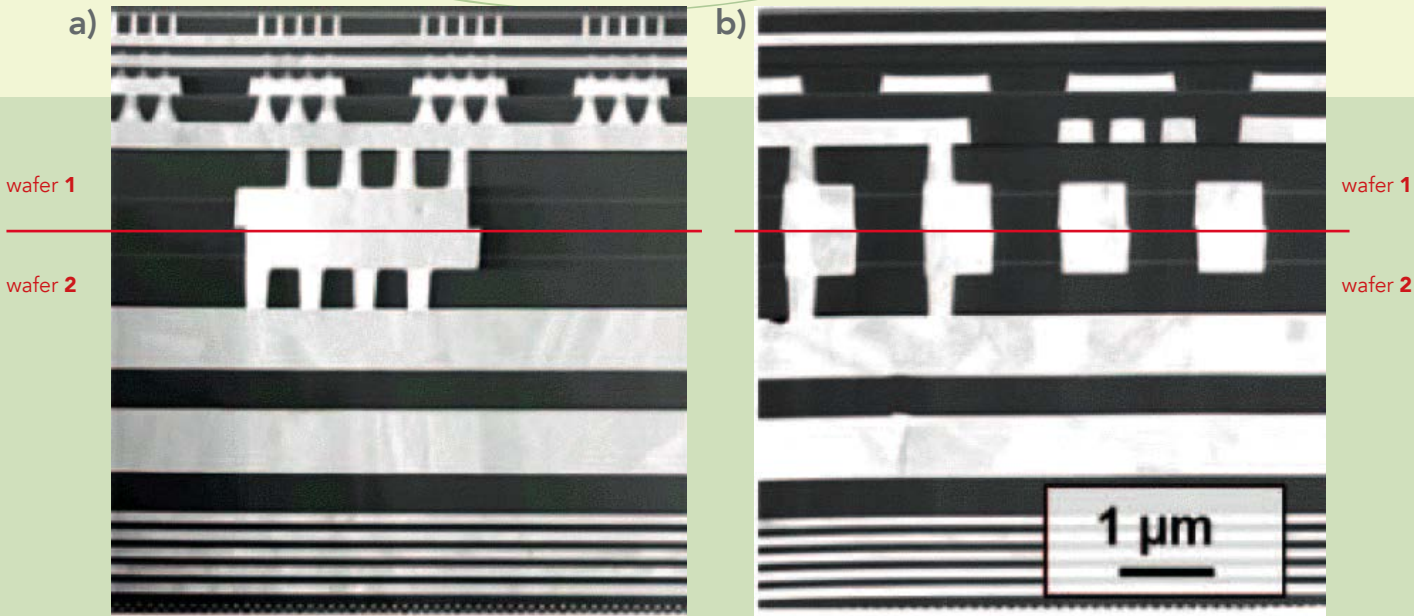
for these finer pitches. Leti also completed physico-chemical analyses of the bonding interfaces to make sure they were appropriate for the smaller dimensions. Special equipment at Leti supplied by EVG in 2017 ensured precision alignment.

Electrical testing was completed after bonding to validate the alignment, and overall electrical measurements were taken. We also used multi-scale optical interferometry to complete topological characterization. The resulting measurements will be useful in determining the appropriate surface preparation process for different interconnect dimensions and product designs.

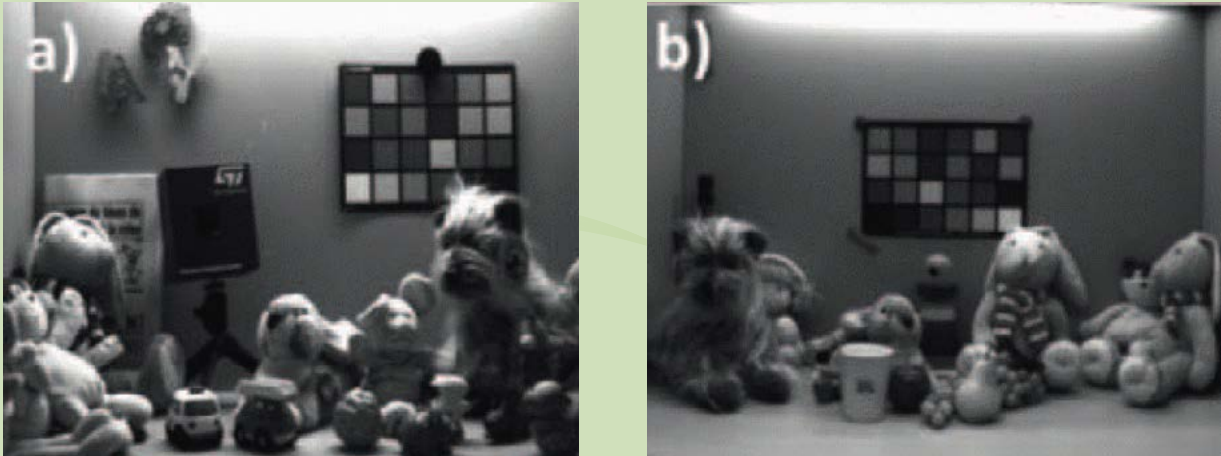
**RESEARCH PARTNERS:**  
**STMicroelectronics, EVG**

- "Fine pitch 3D interconnection with hybrid bonding technology: from process robustness to reliability," *Proceedings of IEEE IRPS 2018*.  
L. Arnaud, S. Moreau, A. Jouve, I. Jani, D. Lattard, F. Fournel, C. Euvrard, Y. Exbrayat, V. Balan, N. Bresson, S. Lhostis, J. Jourdon, E. Deloffre, S. Guillaumet, A. Farcy, S. Gousseau, M. Arnoux.
- "Hybrid bonding for 3D stacked image sensors: impact of pitch shrinkage on interconnect robustness," *Proceedings of IEEE IEDM 2018*.  
J. Jourdon, S. Lhostis, S. Moreau, J. Chossat, M. Arnoux, C. Sart, Y. Henrion, P. Lamontagne, L. Arnaud, N. Bresson, V. Balan, C. Euvrard, Y. Exbrayat, D. Scevola, E. Deloffre, S. Mermoz, A. Martin, H. Bilgen, F. Andre, C. Charles, D. Bouchu, A. Farcy, S. Guillaumet, A. Jouve, H. Fremont, S. Cheramy.

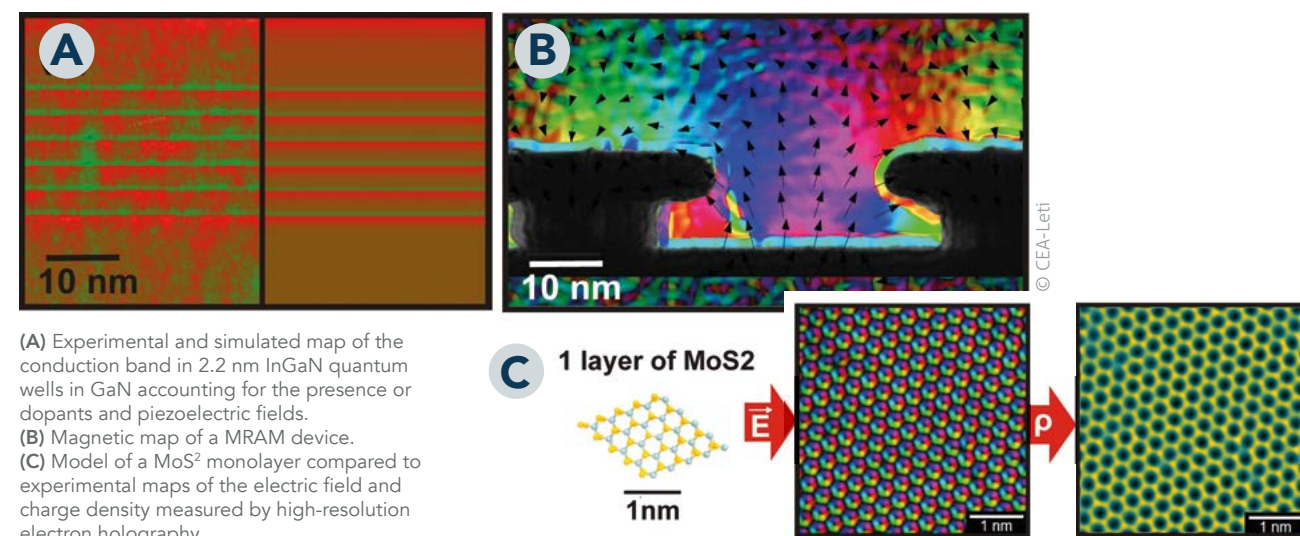
TEM cross-section of 3D stacked image sensor with 8.8 (left) and 1.44  $\mu\text{m}$  pitch (right) and Cu-Cu bonding. All BEoL levels are visible.



Pictures taken with 3D stacked image sensor with a resolution of 14 MPixels 1.5  $\mu\text{m}$  pixel pitch, monochrome array.







## Algorithms enable more accurate electron holography, a crucial need for future generations of semiconductor devices

David Cooper  
Leti scientist

**Electron holography can now deliver sub-nanometer resolution due to advanced reconstruction methods and computer-controlled microscopes, opening the door to new strain and dopant analysis capabilities.**

**THE BREAKTHROUGH:** Improved spatial resolution, high-sensitivity field mapping compatible with latest-generation semiconductor devices.

**WHY IT MATTERS:** It is now possible to characterize the “moving parts” of even the tiniest devices.

**NEXT STEPS:** Conduct in situ TEM observations of working devices.

In a semiconductor device, the internal fields—which control electron movement and mobility—are essentially the working parts. To understand the properties of a device, information is needed about the distribution of these fields. Powerful transmission electron microscopes (TEMs) can measure these at high-resolution. However, given the increasingly tiny dimensions of devices currently being developed—2 nm for LED quantum wells—even higher spatial resolutions and sensitivities are needed to address the semiconductor industry’s development needs.

Our research, which focused on improvements to electron holography, was part of the broader ERC Holography project to develop atomic-resolution field mapping. TEMs are becoming increasingly powerful, making computer control of these microscopes crucial to fully utilizing their potential. Building upon Leti’s extensive experience with field mapping and the

availability of state-of-the-art TEMs, we developed and introduced novel reconstruction algorithms combined with microscope automation to significantly improve the capabilities of electron holography.

Specifically, we wrote software to control a double-aberration-corrected TEM so that large stacks of electron holograms could be acquired and combined. Software was written to correct microscope aberrations as well as drifts in the specimen, electron beam, and biprism. We then implemented novel hologram reconstruction algorithms that again doubled the spatial resolution.

This enhanced technique is already being used on a daily basis to measure the dopant fields in tunnel junctions, the piezoelectric fields in LEDs, and the magnetic fields in MRAM devices; the measurement of electrostatic potential in a monolayer of MoS<sub>2</sub> was also demonstrated. The next step will be to use the technique on working devices operated in situ in the TEM.

### RESEARCH PARTNERS: Spintec, EPFL, CNRS-CRHEA

Further reading: • “Direct comparison of off-axis holography and differential phase contrast for the mapping of electric fields in semiconductors by transmission electron microscopy”, *Ultramicroscopy* 198, 58-72 (2019).  
Benedikt Haas, Jean-Luc Rouvière, Victor Boureau, Remy Berthier, David Cooper.  
• “Off-axis electron holography combining summation of hologram series with double-exposure phase-shifting: theory and application”, *Ultramicroscopy* 193, 52-63 (2018).  
Victor Boureau, Robert McLeod, Benjamin Mayall, David Cooper.

## Statistical analysis enables dramatic improvement to Resistive RAM (RRAM) reliability

Gabriel Molas  
Leti scientist

**If Resistive RAM (RRAM) is to become the memory of choice for tomorrow’s computing systems, reliability must be improved dramatically. Optimized programming patterns and programming energy have made major progress toward reliable RRAM and oxide-based RRAM (OxRAM).**

**THE BREAKTHROUGH:** A substantial improvement to OxRAM and RRAM reliability.

**WHY IT MATTERS:** Reliable RRAM has the potential to break through the memory bottleneck in computing.

**NEXT STEPS:** Co-integrate RRAM with a back-end selector to achieve dense memory arrays.

Today’s data-centric computing has made energy consumption—whether it is for data transfer between the logic and memory blocks or for data storage—a major issue. With advantages like speed, endurance, scalability, and compatibility with integration into the back end of line and in dense crossbar or 3D vertical memory arrays, RRAM could break through the memory bottleneck, but only if it can be made more reliable.

We studied RRAM arrays (in particular oxide-based RRAM, also referred to as OxRAM) using statistical analysis. Specifically, we looked at the physical mechanisms that underpin endurance failure and came up with a methodology to effectively optimize the memory stack for the target performance requirements. We also developed a model for predictive extrapolation. This provided us with a preliminary understanding of the failure mechanisms at work.

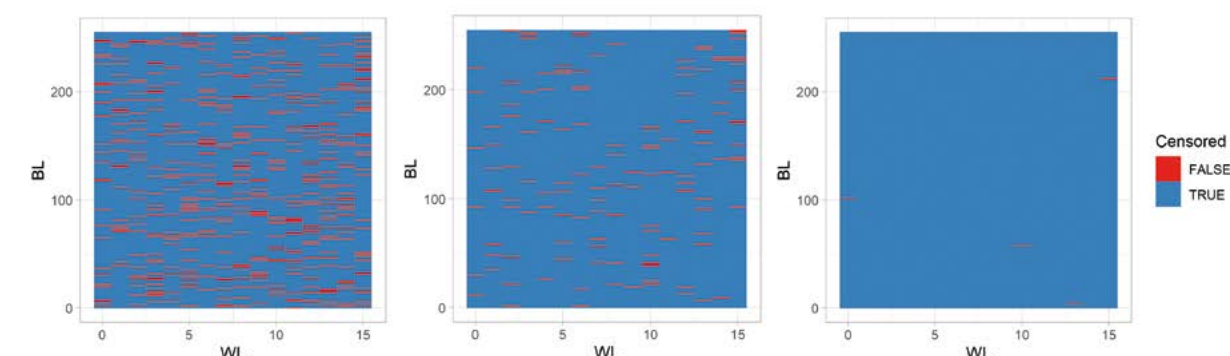
Next, we made improvements to the programming patterns and tweaked

the programming energy to achieve a substantial increase in performance. Maximum endurance was improved by approximately 2 decades, ensuring a stable median window margin at 107 cycles that was maintained at 95% after 106 cycles at 50µA. A specific program verification sequence was employed to achieve reliability of more than 99.99% with acceptable latency. This level of performance meets the needs of storage-class applications. Finally, we implemented aggressive optimized patterns and specific circuits to bring energy consumption down to sub-pJ levels, opening the door to low power applications.

Leti’s leadership in emerging resistive memory, from materials through to integration, and the institute’s 200 mm and 300 mm cleanrooms played an important role in our research. We will continue to take full advantage of Leti’s circuit design, modelling, testing, and integration capabilities to develop RRAM-plus-selector solutions for high-density memory arrays for storage-class and computing memory.

### RESEARCH PARTNERS: IMEP-LaHC (CNRS); IM2NP (Universities of Aix-Marseille and Toulon)

Further reading: • “Hybrid-RRAM Towards Next Generation of Non-volatile Memory: Coupling of Oxygen Vacancies and Metal Ions”, *Advanced Electronic Materials*, 1800658, 2018. Cécile Nail, Gilbert Sassine, Philippe Blaise, Benoit Sklenard, Rémy Gassilloud, Aurélie Marty, Marc Veillerot, Christophe Vallée, Etienne Nowak, Gabriel Molas.  
• “Novel Computing Method for Short Programming Time and Low Energy Consumption in HfO<sub>2</sub> Based RRAM Arrays”, *IEEE Journal of the Electron Device Society*, 6, pp. 696-702, 2018. Gilbert Sassine, Carlo Cagli, Jean-François Nodin, Gabriel Molas, Etienne Nowak.







Actual photograph of a 25 × 25 mm² transparent thin-film battery (TFB).

## Optically transparent 100%-solid-state inorganic thin-film battery ideal for IoT applications

Sami Oukassi  
Leti scientist

**An award-winning\* advance in lithium-ion batteries could lead to smaller, lighter, longer lasting, and more flexible power sources that can be seamlessly integrated into IoT devices.**

### THE BREAKTHROUGH:

The fabrication of optically transparent 100%-solid-state inorganic thin-film batteries capable of delivering excellent electrochemical performance.

### WHY IT MATTERS:

We developed advanced microfabrication techniques effective on hygroscopic lithium-based materials that are compatible with standard microelectronics-industry processes.

**NEXT STEPS:** Increase areal energy storage without compromising the batteries' optical characteristics.

Trends like the Internet of Things and wearables are driving the emergence of a wide range of new electronic products, from implantable medical devices to environmental monitoring sensors. Conventional batteries cannot be integrated effectively into the architectures of these often tiny devices. In addition, IoT devices are often located in remote or hard-to-reach locations, so they have to be able to run for a very long time off of their own internal power sources. This has created a pressing need for a long-lasting, cost-effective power source that can be seamlessly integrated into the final product while performing an additional structural function.

We produced an optically transparent solid-state inorganic thin film battery to respond to the power needs of new and emerging electronic devices. Our approach involved photolithography and etching process blocks developed specifically for lithium-based materials on existing MEMS production equipment. These new processes address the hygroscopic aspect of the materials during and after fabrication. In addition, a versatile architecture will enable further developments, such as optimized pattern design, stacks containing multiple devices,

variations on the electrode thickness balance, and even the implementation of the approach on ultra-thin transparent substrates.

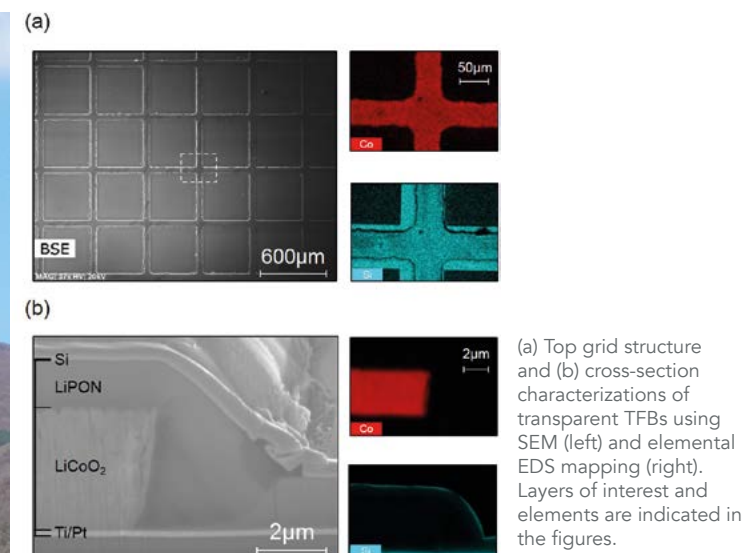
The battery produced obtained lab results with superior electro-optical performance (60% transmission, 0.15 mAh capacity at C/2). Given its excellent performance and flexibility, this technology will help broaden the scope of possible form factors and integration schemes.

We are already investigating a variety of approaches to increasing areal storage capacity, including further improving the electrode material's microstructure and stacking multiple devices. The TFB performance we obtained is compatible with integration into wearable electronics, imperceptible electronics, electronic skin, and smart eyewear.

\*IDTechEX 2019 "Best Technical Development within Energy Storage Award"

### RESEARCH PARTNERS: n/a

Further reading: • "Transparent Thin Film Solid-State Lithium Ion Batteries," *ACS Applied Materials & Interfaces* 2019, 11, 1.  
S. Oukassi, L. Baggetto, C. Dubarry, L. Le Van-Jodin, S. Poncet, R. Salot.



(a) Top grid structure and (b) cross-section characterizations of transparent TFBs using SEM (left) and elemental EDS mapping (right). Layers of interest and elements are indicated in the figures.

## New characterization capabilities for tomorrow's miniaturized microelectronics and memory devices

Zineb Saghi, Jean-Paul Barnes  
Leti scientists

**A multi-technique approach and smart algorithms are driving advances in nanocharacterization that will benefit the semiconductor industry.**

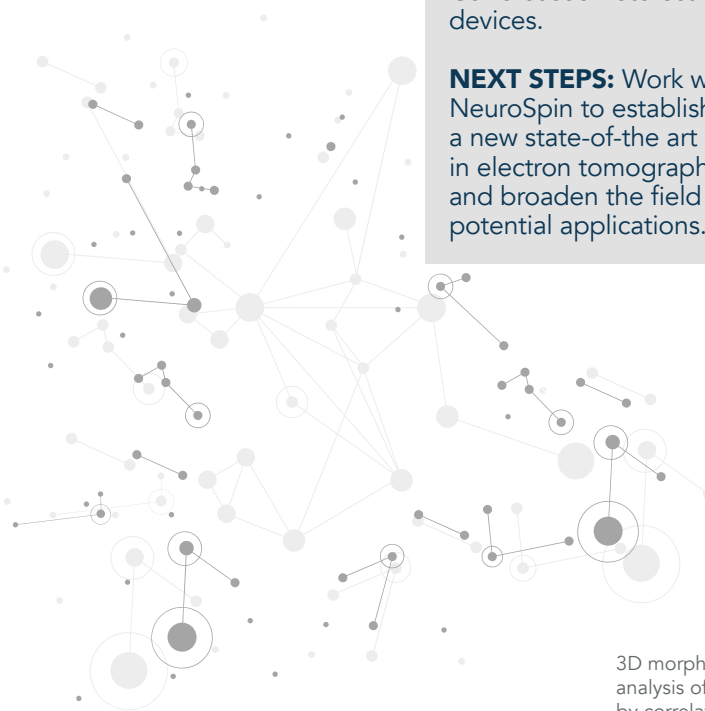
### THE BREAKTHROUGH:

A correlative, multi-technique approach to 3D chemical and morphological reconstructions.

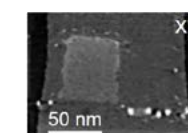
### WHY IT MATTERS:

Nanoscale 3D chemical analysis can now be used for complex structures such as phase-change memory devices, gate-all-around stacked-nanowire FETs, and GaAs-based heterostructure devices.

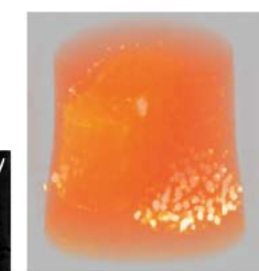
**NEXT STEPS:** Work with NeuroSpin to establish a new state-of-the-art in electron tomography and broaden the field of potential applications.



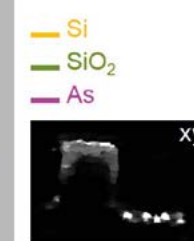
3D morphological and elemental analysis of an As-doped Si structure by correlative HAADF-STEM and EDX-STEM tomography.



HAADF-STEM tomography



EDX-STEM tomography



© CEA-Leti

As device architectures become increasingly complex and heterogeneous, more accurate 3D characterization is required at a variety of length scales. Combining techniques that produce reliable morphological information with ones that supply compositional information is crucial to reducing measurement artefacts and delivering robust 3D data.

We explored how time-of-flight secondary ion mass spectrometry (ToF-SIMS) and atomic force microscopy (AFM) can be combined to provide accurate 3D chemical composition of a GaAs/SiO<sub>2</sub> heterostructure by factoring in the topography of the sample. Using this approach, the 3D compositional data morphology can be corrected and piezoelectric, resistance, mechanical, and other properties can be correlated with composition.

For characterization at smaller scales, we showed how high angle annular dark field scanning TEM (HAADF-STEM) tomography and energy dispersive X-ray (EDX)-STEM tomography can be coupled

to provide a comprehensive morphological and chemical analysis of an arsenic-doped silicon fin-shaped structure. Electron tomography (ET) is routinely employed for the 3D structural and morphological assessment of semiconductor devices (in HAADF-STEM mode). The state-of-the-art microscopes at the CEA Grenoble nanocharacterization platform were used to extend ET to spectroscopic modes to deliver valuable 3D chemical information at the nanoscale. To reduce the long exposure times and high beam currents this technique requires, we optimized the acquisition parameters and developed sophisticated tomography algorithms, including compressed sensing algorithms that can effectively leverage prior information about the sample. The technique performed better than conventional approaches on chemically-sensitive datasets.

The approach developed will be of interest to microelectronics-industry stakeholders and will also be used in other CEA research programs.

### RESEARCH PARTNERS:

NeuroSpin, CosmoStat, Arizona State University, INSA Lyon, CNRS-LTM

Further reading: • "Correlative HAADF-STEM and EDX-STEM Tomography for the 3D Morphological and Elemental Analysis of FinFET Semiconductor Devices," *Microscopy and Microanalysis*, 24(S1), 388-389 (2018).

J. Sorel, M. Jacob, T. Sanders, A. Grenier, R. Pinheiro, F. Mazen, Z. Saghi.  
• "Combined ToF-SIMS and AFM protocol for accurate 3D chemical analysis and data visualization," *Journal of Vacuum Science & Technology B* 36, 03F122 (2018).  
M. Moreno, I. Mouton, N. Chevalier, J. P. Barnes, F. Bassani, B. Gautier.

	HAADF-STEM	EDX-STEM
RMS roughness	3nm	No
Mean cluster size	≈ 15 nm <sup>3</sup>	≈ 20 nm <sup>3</sup>
Implantation depth	No	20 nm



# Market news from our R&D partners

## Soitec announces joint development program with Applied Materials on next-generation silicon carbide substrates

Program aims to provide technology and products to improve the performance and availability of silicon carbide to address surging demand from electric vehicles, telecommunication and industrial applications.

Bernin, France, November 18<sup>th</sup>, 2019 — Soitec (Euronext Paris), an industry leader in designing and manufacturing innovative semiconductor materials, announced a joint development program with Applied Materials on next-generation silicon carbide substrates. Demand for silicon carbide-based chips has been rising, particularly in electric vehicles, telecommunication and industrial applications; however, adoption has been limited due to challenges related to supply, yield and cost of silicon carbide substrates. Soitec will be working with Applied Materials to develop substrates that can overcome these challenges and bring increased value to the industry.

The development program will combine Soitec's leadership in engineered substrates with that of Applied Materials, the leader in materials engineering solutions (...). Under the development program, the companies will install a silicon carbide engineered substrate pilot line at the Substrate Innovation Center located at CEA-Leti. The line is expected to be operational by the first half of 2020, with the goal of producing silicon carbide wafer samples using Soitec's Smart Cut™ technology in the second half of 2020.



Learn more:  
<https://bit.ly/2Olj5No>

## CEA-Leti extends 300mm wafer line and adds avenues for developing disruptive memory, photonics, 3D and quantum technologies

Execution relies on CEA-Leti's fully implemented technology with module-level innovations & devices and their architectures.

SAN FRANCISCO, CA – Dec. 3, 2018 – Leti, a research institute at CEA Tech, today announced during IEDM an extension of its 300mm silicon-based wafer line to open new R&D avenues for its industrial partners. This extension will allow new innovative technological modules to be inserted in, or made compatible with, industrial flows up to completely pioneered technology routes that enable edge AI, HPC, in memory computing, photonics, power electronics and other high-end applications.



Learn more:  
<https://bit.ly/2OljKOS>



# 02

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## The virtues of photons for the connected society

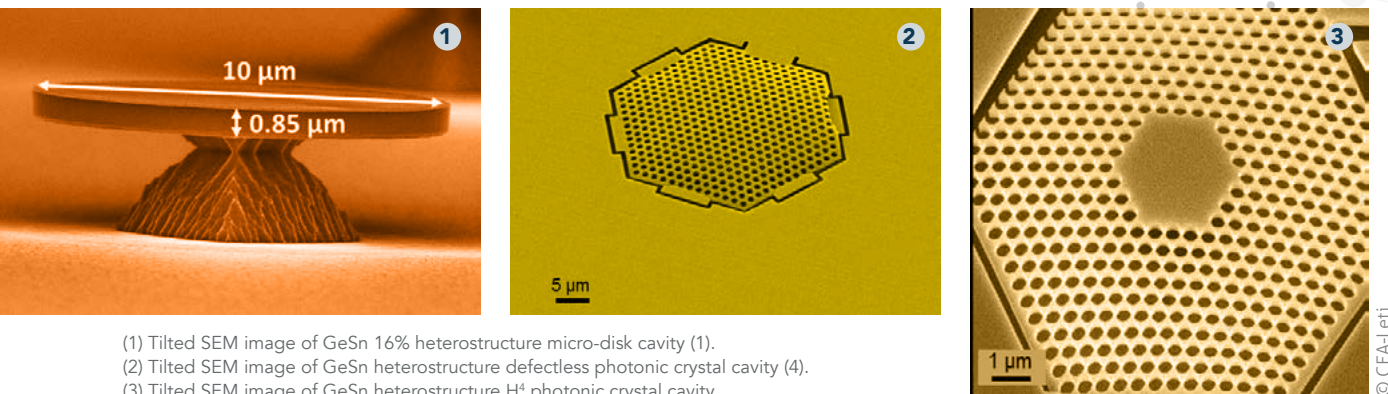
From the terahertz band to X-rays, photonic technologies generate, emit, detect, collect, transmit, modulate, and amplify photon beams. Behind the science lies an exciting and rapidly-growing field that is closely intertwined with our day-to-day lives. Photons are present in everything from lighting, imaging, displays, and land transportation to fiber optic data transmission, medical diagnostics, environmental monitoring, industrial processes, and aerospace.

This year's highlights represent a fraction of what Leti is doing in photonics. Our scientists are creating technologies that allow us to observe phenomena in the terahertz, infrared, and visible wavelengths with unrivalled degrees of precision and developing new generations of ultra-compact environmental sensors that leverage the power of miniaturization and merge legacy infrared technology with the latest silicon microelectronics fabrication processes.

Lasing in high-Sn-content germanium alloys obtained up to 230 K, bringing a room temperature laser within reach	32
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## Lasing in high-Sn-content germanium alloys obtained up to 230 K, bringing a room temperature laser within reach



(1) Tilted SEM image of GeSn 16% heterostructure micro-disk cavity (1).  
(2) Tilted SEM image of GeSn heterostructure defectless photonic crystal cavity (4).  
(3) Tilted SEM image of GeSn heterostructure H<sup>4</sup> photonic crystal cavity.

Vincent Reboud,  
Jean-Michel Hartmann  
Leti scientists

**Obtaining a high crystalline quality tin-germanium heterostructure is one of the keys to efficient MIR light sources for integrated optical sensing and data transmission.**

### THE BREAKTHROUGH:

First-ever demonstration of lasing in high-Sn-content SiGeSn/GeSn heterostructures up to 230 K.

### WHY IT MATTERS:

This demonstration marks a major advance toward room temperature lasers into SWIR and MIR Si photonic systems for future sensing and data transmission solutions.

### NEXT STEPS:

Reduce the laser threshold, increase lasing operating temperature, and electrically inject carriers into high-Sn-content GeSn heterostructure layers.

From laser-based sensors for industrial, automotive, environmental, and medical applications through to short-range optical communications for data centers, lasers are in high demand. Tomorrow's laser-based devices will require a high level of integration and, to keep product costs down, they must be compatible with CMOS foundries.

Silicon photonics presents the advantages of being fully CMOS compatible. However, silicon's indirect and relatively high bandgap limits its usefulness for light emission functions. Group-IV lasers are garnering interest as an alternative to the complex integration of III-V lasers on silicon. To meet the needs of tomorrow's applications, these Group-IV lasers must be able to operate at substantially higher temperatures.

Germanium (Ge)-based materials, also CMOS-compatible, are in

the running to overcome silicon's limitations. Thanks to recent progress in chemical vapor deposition (CVD), it is now possible to incorporate substantial amounts of tin (Sn) into the Ge crystalline matrix. And, if the conditions are right—high Sn content and low residual compressive strain—these heterostructures are efficient light emitters.

We used step-graded GeSn buffers to grow homogeneous and high-crystalline-quality GeSn layers over the entire 200 mm wafer surface. Lasing was achieved from 25 K to 230 K in microdisk cavities at wavelengths around 3.1 μm, with 16% of Sn in the optically active GeSn layers and SiGeSn barriers. These emission wavelengths bode well for IR sensing applications. We also observed lasing in GeSn suspended photonic crystal cavities—proof that the optical gains obtained are robust.

### RESEARCH PARTNERS:

Nicolas Pauc, Vincent Calvo, IRIG (formerly INAC); Paul Scherrer Institut Villigen (Switzerland), ETH Zurich (Switzerland)

Further reading: • "GeSn heterostructure micro-disk laser operating at 230 K," *Optics Express* 26, 32500 (2018). Selected as "Editor's Pick." Q. M. Thai et al.  
• "Growth and characterization of SiGeSn pseudomorphic layers on 200mm Ge virtual substrates," *Semicond. Sci. Technol.* 33, 124011 (2018). R. Khazaka et al.  
• "2D hexagonal photonic crystal GeSn laser with 16% Sn content," *Applied Physics Letters* 113, 051104 (2018). Q. M. Thai et al.  
• "Impact of Pt on the phase formation sequence, morphology, and electrical properties of Ni(Pt)/Ge<sub>0.9</sub>Sn<sub>0.1</sub> system during solid-state reaction," *Journal of Applied Physics* 124, 085305 (2018). A. Quintero et al.  
• "Growth and structural properties of step-graded, high Sn content GeSn layers on Ge," *Semicond. Sci. Technol.* 32, 094006 (2017). J. Aubin et al.  
• "Optically pumped GeSn micro-disks with 16 % Sn lasing at 3.1 μm up to 180K," *Applied Physics Letters* 111, 092101 (2017). V. Reboud et al.

## New long-wave infrared chemical-sensing platform could expand applications and bring costs down

Jean-Marc Fédéli  
Leti scientist

**Leti's leadership in silicon germanium drove a major advance in gas sensing technology that could enable multi-gas detection and analysis at a cost compatible with the needs of industry, healthcare, defense, and environmental monitoring.**

### THE BREAKTHROUGH:

Successful demonstration of a multiplexer with up to 63 input channels in the LWIR with integrated SiGe-clad Ge waveguides.

### WHY IT MATTERS:

This advance will enable operation at wavelengths beyond 8 μm, creating the potential to detect gases like ammonia, acetone, ozone, and benzene.

### NEXT STEPS:

Explore Ge photonics—the next paradigm—with chalcogenide-clad Ge cores.

Gas detection technologies are utilized to ensure health, safety, and regulatory compliance in a wide range of fields, from industry and transportation to healthcare, defense, and environmental monitoring. The cost-effective miniaturization of gas sensors is a prerequisite to the development of solutions for these markets.

Given the recent advances in integrated silicon photonics and the advent of efficient quantum cascade lasers, we felt the time was right to investigate integration on planar Si substrates as a path to new gas sensors selective and sensitive enough to be used for multi-gas sensing and atmosphere analysis.

Using a new platform of Ge cores clad in thick SiGe layers developed based on Leti's deep knowledge of the epitaxial growth and reactive ion etching of SiGe compounds,

we designed, fabricated, and characterized array waveguide grating (AWG) devices with arrays of QCL sources to simultaneously detect multiple gases. The design of the AWG in the mid-IR range was well-conceived, and the device obtained almost flat transmission over a full 200 cm<sup>-1</sup> operational range with peak-to-valley modulation of -5 dB. These results enable operation at wavelengths beyond 8 μm, where gases like ammonia, acetone, ozone, and benzene can be detected.

This advance opens the door to more advanced gas sensors at a cost compatible with the demands of numerous markets. The next challenge will be to develop even more compact devices built on Ge-core waveguides. However, the upper and lower cladding could be improved, and chalcogenide materials developed at Leti could play a key role.

### RESEARCH PARTNERS:

n/a

Further reading: • "Mid-Infrared (Mid-IR) Silicon-Based Photonics," *Proceedings of the IEEE* (Dec. 2018). J.-M. Fedeli, S. Nicoletti.  
• "Ge/SiGe photonic devices for the long mid-infrared," *Proceedings of SPIE 10686, Silicon Photonics: From Fundamental Research to Manufacturing* (May 22, 2018). J.-M. Fédéli, P. Labeye, A. Marchant, O. Lartigue, M. Fournier, J. M. Hartmann.



# High-yield manufacturing of low-cost quantum cascade lasers within reach

Jean-Guillaume Coutard  
Leti scientist

**Quantum cascade lasers are powerful tools in mid-infrared spectroscopy, which is employed in a vast range of applications from gas monitoring to medicine. Leti research has overcome a major barrier to massive rollout of the technology: cost.**

## THE BREAKTHROUGH:

Fabrication and testing of quantum cascade laser sources on a CMOS line with excellent yields.

## WHY IT MATTERS:

This advance will bring today's costs down from thousands of euros for a single InP QCL to just a few euros, creating opportunities on a very wide range of markets.

**NEXT STEPS:** Improve performance through coupling heating with the Si substrate and coupling light between the laser and photonic function on silicon.

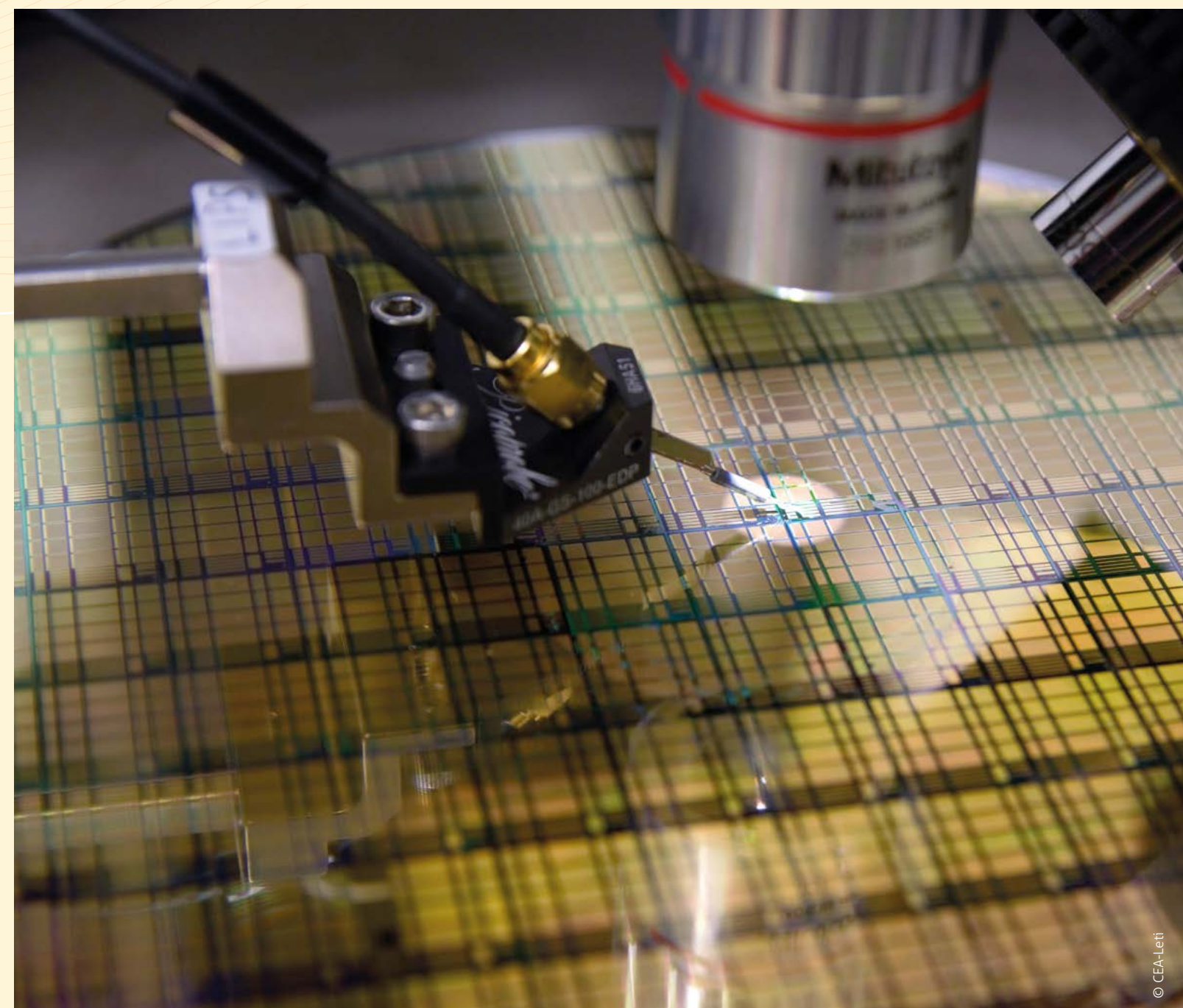
Quantum cascade laser (QCL) sources use the mid-infrared range, where molecules' absorption peaks are highest. This "chemical footprint" is the most efficient way to identify a substance, making QCL a key enabling technology for spectroscopic measurements of virtually all kinds. The main barrier to the massive rollout of QCL technology is the high manufacturing cost of the laser sources.

Utilizing standard microelectronics-industry CMOS processes is one way to bring QCL costs down. In addition, manufacturing on silicon makes it possible to co-integrate mid-infrared sources with Si waveguides to obtain miniaturized spectroscopic devices fully integrated on a planar substrate.

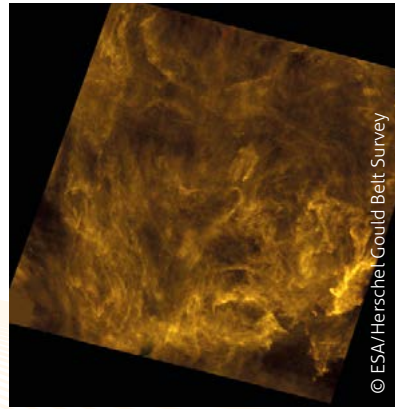
We developed a 100% CMOS-compatible process flow and an automated wafer-level electro-optical testing process step on a prober station. We fabricated and measured thousands of devices showing average threshold current densities from 2.5 kA/cm<sup>2</sup> to 3 kA/cm<sup>2</sup> with a relative dispersion of around 5%. The devices' optical power was measured at 1 mW at ambient temperature for a 1.5% duty cycle. FWHM was measured at 0.16 cm<sup>-1</sup> in the same operating conditions. Our DFB QCL sources operated at 7.4 μm on a silicon substrate on a 200 mm CMOS/MEMS pilot line. In short, we achieved state-of-the-art performance for this fabrication run, in line with the performance of the much costlier QCL sources fabricated on an InP substrate. And, with yields of up to 98% our work has strong potential to enable affordable QCL sources.

Publication forthcoming

QCLs on 200 mm silicon wafer being tested on prober station. All lasers are electro-optically characterized at wafer level.







## Leti detector could bring advanced imaging to European Space Agency observation mission

Laurent Dussopt  
Leti scientist

**A millimeter-wave detector developed by Leti is in the running for ESA's 2030 space observation mission, SPICA. The detector could make the satellite's B-BOP polarimetric imager two times more sensitive than instruments on board the agency's Herschel mission.**

### THE BREAKTHROUGH:

A millimeter-wave cryogenic bolometer with dual polarization detection.

### WHY IT MATTERS:

This advance will enable high-performance detectors for astrophysics and cosmology research.

**NEXT STEPS:** Develop a sub-millimeter-wave polarimetric imager for the SPICA space telescope.

The millimeter (mm) and sub-mm wave frequency bands are useful in astrophysics and cosmology research. "Cosmic rays," which contain traces of the early evolution of our universe, are made up of diffuse radiation in the millimeter-wave spectrum. And dust clouds in our galaxy and neighboring galaxies, which contain information on star formation that can provide insights into how galaxies evolve, are opaque in the infrared and visible wavelengths but can be observed in the millimeter and sub-millimeter frequency bands.

Our lab worked with fellow CEA lab IRFU to design a novel silicon bolometer detector for imaging at millimeter wavelengths in telescopes used in astrophysics and radio-astronomy. The detector, manufactured in Leti's 200 mm cleanrooms, offers the advantage of measuring the two polarization components



of radiation simultaneously—a major advance over unpolarized or single-polarization detectors, which require external polarization selection devices. It could also help make imaging instruments more sensitive (with operation at very low temperatures), accurate, compact, lightweight, and energy efficient. Finally, we developed 16 x 16 pixel arrays representative of future imager focal planes.

This development leveraged the knowledge we have continued to accumulate since the European Space Agency's Herschel space observatory. Our results supported our proposal for a sub-mm imaging instrument for the SPICA (SPace IR telescope for Cosmology and Astrophysics) observatory satellite, which has been shortlisted by ESA for a mission to be launched in the early 2030s. Our detectors will be at the heart of the B-BOP polarimetric imager, one of the satellite's three instruments.

### RESEARCH PARTNERS: IRFU (CEA Institute of Research into the Fundamental Laws of the Universe).

Further reading: • "Fabrication and characterization of cooled silicon bolometers for mm wave detection", SPIE Astronomical Telescopes + Instrumentation Conference, Austin, TX, June 10-15, 2018. V. Goudon et al.  
• "Superconducting Ti/TiN Thin Films for mm-Wave Absorption", Journal of Low Temperature Physics, 193:655–660, 2018. A. Aliane et al.

## Free-space optical communications and atmospheric LiDAR to benefit from microlensed HgCdTe APDs

Johan Rothman  
Leti scientist

**Leti leveraged its in-depth knowledge of photonics and optical systems to develop a reproducible process that will bring higher bandwidths and lower noise to tomorrow's optical communication and LiDAR systems.**

### THE BREAKTHROUGH:

A precise, reproducible process for shaping free-form refractive micro-optical elements in the high-index substrate of HgCdTe detectors.

### WHY IT MATTERS:

This advance will bring the technology in line with specifications for emerging technologies like FSO and atmospheric LiDAR.

**NEXT STEPS:** Further developments to enable larger lens areas, microlens arrays, and new functions machined into the HgCdTe APDs.

HgCdTe avalanche photodiodes have the capacity to observe meso-photon light at the infrared wavelength, making it a prime candidate for atmospheric LiDAR, which is used to survey greenhouse gases in the atmosphere, and for the free-space optical (FSO) communications that will enable tomorrow's satellite constellations to provide global telecommunications coverage. Both of these applications demand the highest levels of performance.

Our research addressed the coupling of light onto the photodetector, an issue that affects meso-photon applications in particular, where the objective is to transfer or capture information contained in just a few photons—sometimes just one. Here, most of the detector's light must be coupled in conditions where the size of the detector has been reduced as much as possible to minimize thermal and photonic dark noise.

We drew on Leti's deep understanding of optimized optical coupling for FSO communication and atmospheric LiDAR to develop a reproducible process for shaping free-form refractive micro-optical elements in the high-index substrate of HgCdTe detectors. We obtained good spatial alignment with the photodetector so that light can be coupled over a large active optical area onto small detectors with low dark noise.

The process is currently being used to develop groundbreaking detectors for FSO and LiDAR, where the goal is to be able to form monolithically-integrated microlenses in HgCdTe APDs. Once these advances are mature, they should benefit a wider range of applications in materials science, microelectronics, biomedicine, and space. Further developments are in progress as part of the EU Horizon 2020 project HOLDON.

### RESEARCH PARTNERS:

CNES, ESA, Airbus DS, Mynaric, Ecole Polytechnique

Further reading: • "HgCdTe APDs detector developments at CEA/Leti for atmospheric LiDAR and free space optical communication", Proc. SPIE 11180, 111803S (2019).

J. Rothman et al.

• "HgCdTe APDs for free space optical communications", Proc. SPIE 10524, 1052411 (2018). J. Rothman et al.





# High-performance silver dielectric interference filters create new RGBIR imaging capabilities

Laurent Frey  
Leti scientist

**The number of potential applications for RGBIR imaging is virtually limitless. However, even the best RGB organic resists can only detect up to three channels and require an IR-cut filter that makes implementation on very small pixels challenging. Leti's remarkable filter helps solve this problem.**

## THE BREAKTHROUGH:

The first-ever demonstration of high-transmission silver/dielectric multilayer filters patterned on small pixels compatible with four-plus channels.

## WHY IT MATTERS:

This technology provides high-performance color imaging in an unprecedentedly small form factor for applications in photography, automotive perception, and medical imaging.

**NEXT STEPS:** Determine the feasibility of etching the full multilayer stack with vertical edges to eliminate pixel-level filters and increase sensitivity.

**R**GBIR imaging combines high-performance color imaging with up to several near-IR channels and offers filter mosaics with small pixels. This gives the technology some unique capabilities. For example, the fusion of RGB and IR images can bring image dehazing, skin smoothing, shadow detection, and object segmentation to enhanced photography. Additionally, the availability of both types of images means that a single imager can provide both day and night vision. For automotive applications, an IR LED can illuminate the passenger cabin while the IR channel handles detection in low-light conditions. Finally, the technology can enhance endoscopy systems, with their tiny cameras and active imaging systems, by using the IR channel to identify tissues and organs with specific spectral signatures.

The focus of our research was thin-film optical filters for advanced imaging applications. Color image sensors are made up of CCD or CMOS photodiode arrays with megapixel resolution fabricated on silicon chips.

## RESEARCH PARTNERS:

**STMicroelectronics for the 2011 research that contributed to this advance.**

Further reading: • "High-performance silver-dielectric interference filters for RGBIR imaging", *Optics Letters* 43, 1355 (2018).  
Laurent Frey, Lilian Masarotto, Loubna El Melhaoui, Sophie Verrun, Stéphane Minoret, Guillaume Rodriguez, Agathe André, Frédéric Ritton, Pascale Parrein.

Special filter arrays are placed on top of the image sensor so that several spectral channels can be detected simultaneously. Specifically, we drew on Leti's materials characterization expertise and built on previous research to come up with new filter architectures and improve the optical constants of the silver by working on the interfaces between the silver and dielectric layers.

For the first time ever, we demonstrated high transmission rates (around 80%) on thin film multilayer optical filters with small pixels (as small as 1.4  $\mu\text{m}$ ) using a single-filter approach that consists of stacks of alternating Ag and dielectric layers and that is suitable for four or more spectral channels (typically RGB and IR). Our next step will be to investigate the complete etching of the full multilayer stack with close-to-vertical edges at the pixel level to enable filterless pixels and improve imager sensitivity. The technology could also be combined with amorphous silicon multilayers to obtain combined color and depth ranging and develop multispectral applications.

Example of IR image that a camera sensor including Ag filters could potentially capture (source: EPFL).

# Antenna-coupled microbolometer arrays bring THz imagers to new levels of performance

Jérôme Meilhan  
Leti scientist

**Leti researchers have put their modelling and design know-how to work, successfully demonstrating a fully-integrated THz imager that could meet the needs of a wide range of imaging and detection applications from security to medicine.**

## THE BREAKTHROUGH:

A fully-integrated THz imager with minimum detectable power under 10 pW in real-time imaging conditions.

## WHY IT MATTERS:

Compact, easy-to-use, highly-sensitive THz imagers will respond to the needs of a wide range of markets.

## NEXT STEPS:

Enable sourceless passive detection capabilities to further simplify THz imaging systems and encourage their development.

**T**Hz imagers have the capacity to enhance performance in a number of detection and imaging situations, from standoff imaging used in security screening to medical imaging, food quality control, and anti-counterfeiting measures. With advantages like the ability to penetrate non-metallic, nonpolar materials, high sensitivity to water content, spatial resolution ten times that of millimeter-wave radiation, and unique spectral fingerprints for many substances, THz technology offers vast potential. However, the market is lacking imagers that are compact, easy to use, sensitive, and affordable.

We drew on Leti's modelling know-how and the high-end imager expertise of our partner, I2S, to optimize a 320x240 pixel antenna-coupled microbolometer array with a 50  $\mu\text{m}$  pitch, which we then successfully integrated into a

dedicated THz vacuum package. The array is run by compact, efficient electronics. With an MDP under 10 pW, the array performs better than the state of the art in room-temperature THz imagers in the THz range.

Our imager offers a number of benefits that will make it an attractive solution for imaging and spectroscopy applications. Standard Si technology keeps production costs down while maintaining high yields; a monolithic design ensures a compact form factor; a 2D array configuration could enable a wide FoV and limit the need for raster scanning; and, because it operates at room temperature, the detector is cost-effective to run. Finally, if pixels are processed above a CMOS readout integrated circuit, the imager can provide real-time acquisition.

## RESEARCH PARTNERS: I2S (high-end imager operation)

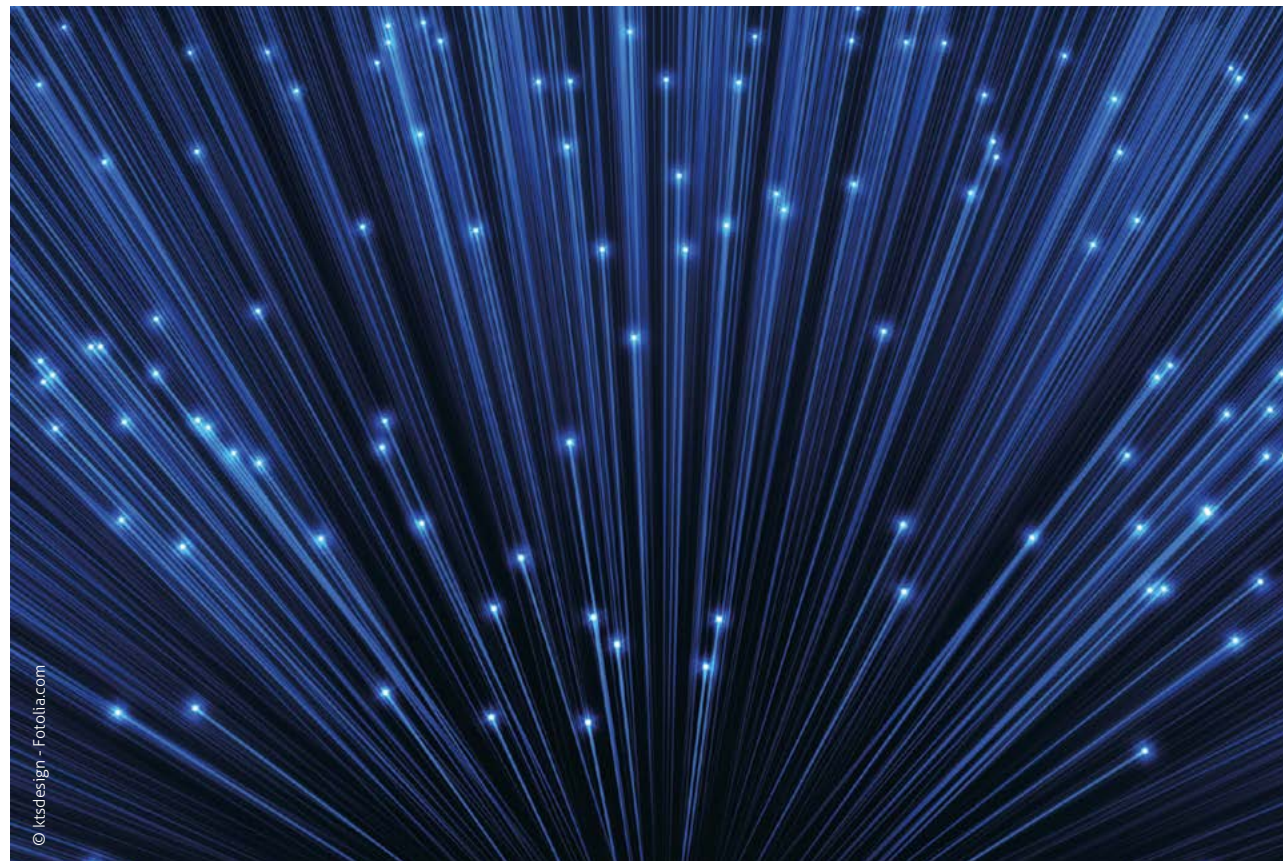
Further reading: • "Shape-from-focus for real-time terahertz 3D imaging", *Opt. Lett.*, OL, vol. 44, no. 3, p. 483-486, Feb. 2019.  
J.-B. Perraud, J.-P. Guillet, O. Redon, M. Hamdi, F. Simoens, P. Mounaix.  
• "Towards industrial applications of terahertz real-time imaging", in *Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications XI*, 2018, vol. 10531, p. 105310T. F. Simoens et al.  
• "Uncooled Terahertz real-time imaging 2D arrays developed at LETI: present status and perspectives", in *Micro- and Nanotechnology Sensors, Systems, and Applications IX*, 2017, vol. 10194, p. 101942N. F. Simoens et al.

**TZcam (I2S) TeraHertz camera equipped with optics designed specifically for the THz range and offering a wide aperture (F/0.8). The camera is fitted with a THz sensor based on antenna-coupled bolometers developed at Leti. Sensor pictured after packaging and assembly on the electronic circuit board.**





# Market news from our R&D partners



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## Scintil Photonics enables better-performing and more cost-effective optical communications

Startup Scintil Photonics, a spinoff of Leti, a CEA Tech institute, is developing optical communications technologies capable of achieving speeds of 800 Gbit/s at a very competitive cost. The company won the Bpifrance i-lab award in 2018. CEO Sylvie Menezo told us more.



Learn more:  
<https://bit.ly/2OmZwnX>

## CEA-Leti combines integrated optics and holography in novel lens-free, augmented reality technology

Leti, an institute of CEA-Tech, has developed a novel retinal-projection concept for augmented reality (AR) uses based on a combination of integrated optics and holography. The lens-free optical system uses disruptive technologies to overcome the limitations of existing AR glasses, such as limited field-of-view and bulky optical systems.

TVs and smartphones that project digital images emit light all around them, as quasi-isotropic sources. Because the images are projected generally over the air without directivity, many viewers see the same image. In typical AR glasses, images are transmitted close to the eyes (high directivity) by a microdisplay that includes an optical system and an optical combiner.



Learn more:  
<https://bit.ly/2KQoXfF>



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# 03

## Technology with the power to improve human health

According to the World Health Organization (WHO), "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." And when human health is addressed from a position that encompasses not only a person's physiological state, but also his or her interactions with the environment, prevention—measures to prevent or reduce the occurrence and severity of disease, accidents, and disabilities—becomes crucial.

Among the technologies under development in Leti labs are the preparation of complex biological samples for diagnostics, the treatment of chronic diseases like diabetes, the prevention of acute diseases, and rehabilitation. Our scientists are bringing their knowledge of micro and nanotechnology to the design of advanced sensors and actuators, exploring the potential of artificial intelligence, investigating nanomedicine, and creating cyber-physical systems to improve human health.

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The DBLG1® System includes a continuous glucose monitor, an insulin pump, and a handset



## Algorithms improve Diabeloop's artificial pancreas and enable more personalized type-1 diabetes treatment

Maeva Doron  
Leti scientist

**Leti assisted Diabeloop with advanced algorithms to make the company's artificial pancreas more effective. A first-ever out-of-hospital clinical trial was completed on the improved device.**

### THE BREAKTHROUGH:

The first out-of-hospital clinical trial of Diabeloop's DBLG1 wearable artificial pancreas on type-1 diabetes patients.

### WHY IT MATTERS:

Beyond its impact on patients and their families, diabetes is a public health issue in that it results in life-threatening complications, hospitalizations, and premature death.

**NEXT STEPS:** Further reduce the amount of information the wearer has to input and, ultimately, develop an artificial pancreas specifically for children and teens living with type-1 diabetes.

Managing type-1 diabetes is a huge burden for patients and their caregivers. Blood glucose is regulated with subcutaneous insulin injections—a treatment protocol that involves making many complex decisions every day. Patient responses to treatment vary widely, making it difficult to stabilize blood glucose in practice. The effects range from fainting to health- and life-threatening complications and, ultimately, premature death.

Diabeloop developed an artificial pancreas (or hybrid closed-loop) for adults **that is among the first devices of this kind to enter the market in Europe.** The wearable system consists of a continuous glucose sensor and a miniature patch insulin pump connected by Bluetooth to a dedicated smartphone equipped with algorithms developed by Diabeloop in partnership with Leti to calculate insulin doses, send the information to the pump automatically, and transfer the data to a patient

monitoring facility.

The purpose of our research was to improve the product's algorithm to enable more advanced personalization of treatment based on the real-time processing of patient-dependent and time-dependent information. Our model uses the continuous glucose measurement history, insulin delivery history, meals, and physical activity. We had previously completed in-hospital clinical trials, but this was the first out-of-hospital trial of the device.

Leti's know-how in signal processing, algorithm development, and closed-loop systems was crucial to our research. This out-of-hospital clinical trial marks a major step toward easier and more effective treatment of type-1 diabetes. We plan to pursue development with the goal of further reducing the amount of information patients must input and, ultimately, developing an artificial pancreas for children and teens.

### RESEARCH PARTNERS: Diabeloop; CERITD (a diabetes research center); and a dozen university medical centers and hospitals in France.

Further reading: • "Closed-loop insulin delivery in adults with type 1 diabetes in real-life conditions: a 12-week multicentre, open-label randomised controlled crossover trial," *The Lancet Digital Health* (May 2019). P-Y Benhamou et al.

## Optomechanical biosensing makes major advance toward a blood test for cancer

Thomas Alava  
Leti scientist

**A recent advance in silicon optomechanical microdisk resonators will enable precision biological analysis of fluid samples like blood. This technology will open the door to the development of biological sensing devices for tomorrow's medical diagnostics.**

### THE BREAKTHROUGH:

First-ever demonstration of biological sensing in liquid by a silicon optomechanical microdisk resonator.

### WHY IT MATTERS:

This technology will enable highly-sensitive biological analysis that will benefit medical diagnostics and research.

**NEXT STEPS:** Use several of these devices to analyze multiple biological factors simultaneously, with potential application in the early diagnosis of cancer.

A simple blood test capable of diagnosing cancer in its earliest stages is just one of the potential applications for highly-sensitive, minimally-invasive, low-cost biological microsensors. Optomechanical resonators are considered the best candidates for biological sensing in biologically-relevant fluid samples like blood. Until now, however, only gallium arsenide optomechanical resonators—which are difficult to mass-fabricate and to functionalize—have been successfully demonstrated to vibrate in the presence of viscous fluids. Silicon resonators would open the door to the development of innovative biological sensing devices.

We used VLSI silicon technology to mass-fabricate microdisks with a precisely-controlled shape and dimensions. Leti's advanced characterization capabilities were instrumental in measuring the discs with a high degree of precision.

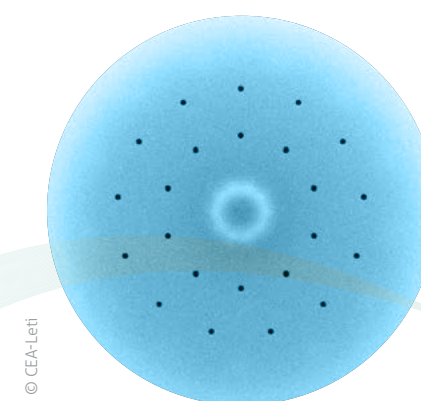
We then utilized a reference functionalization protocol to graft biological modules onto the microdisks for a specific biological target. The resonator-instrumentation system obtained delivered unprecedented sensitivity in terms of transducing the motion of the disks into an electrical signal even in the presence of viscous liquid.

The mechanical resonance of the microdisks in water was demonstrated in the lab with unprecedented motion sensitivity for silicon resonators in viscous media. Finally, we were able to detect albumin proteins, a world first for optomechanical resonating microdisks.

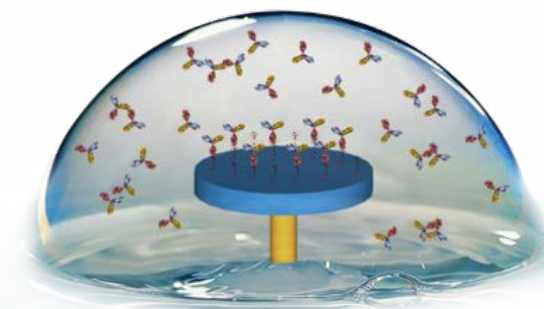
We now plan to demonstrate the parallel analysis of multiple biological factors in a single test on a small biological sample, an approach that could be used to develop a blood test for early cancer detection.

### RESEARCH PARTNERS: Laboratoire Matériaux et Phénomènes Quantiques (MPQ lab); Institut de biologie intégrative de la cellule (I2BC Lab).

Further reading: • "Ultra-sensitive optomechanical microdisk resonators with very large scale integration process", *IEEE Micro Electro Mechanical Systems (MEMS)*, 2018. Maxime Hermouet, Marc Sansa, Louise Banniard, Alexandre Fafin, Marc Gély, Pierre Etienne Allain, Eduardo Gil Santos, Ivan Favero, Thomas Alava, Guillaume Jourdan, Sébastien Hentz. • "1 Million-Q Optomechanical Microdisk Resonators with Very Large Scale Integration", *Proc. SPIE 10491, Microfluidics, BioMEMS, and Medical Microsystems XVI*, 2018. Maxime Hermouet, Louise Banniard, Marc Sansa, Alexandre Fafin, Marc Gély, Sébastien Pauliac, Pierre Brianceau, Jacques-Alexandre Dallery, Pierre Etienne Allain, Eduardo Gil Santos, Ivan Favero, Thomas Alava, Guillaume Jourdan, Sébastien Hentz.



Scanning Electron Micrograph of an optomechanical resonating disk as fabricated in Leti clean room. Radius is 10 µm. On top of the image the optical waveguide ensuring the travel of light from the laser to the vibrating disk.



Artist's rendering of a resonating optomechanical disk vibrating in liquid media and bearing a specific biological functionalization comprised of immunoglobulin attached to the disk surface.



## Nanomedicine could hold the key to an effective HIV vaccine

Fabrice Navarro  
Leti scientist

**Engineered drug delivery systems have the capacity to boost the efficacy of vaccines. Leti scientists recently used Lipidots® lipid nanodroplets to deliver protein antigens and vaccine components. Their results could overcome some of the challenges that have hobbled HIV vaccine development for decades.**

### THE BREAKTHROUGH:

Delivery of protein antigens and vaccine components using 100 nm stabilized lipid nanodroplets.

### WHY IT MATTERS:

This new form of drug delivery opens the door to new safe, effective, and affordable vaccines to prevent the spread of serious infectious diseases like HIV.

**NEXT STEPS:** Place other antigens on the surface of the lipid nanodroplets and test their efficacy against pathogens.

The HIV pandemic has claimed the lives of tens of millions of people around the globe, and scientists have been working tirelessly to come up with an effective vaccine for decades. One of the reasons behind the failed clinical trials that have plagued HIV vaccine research is the poor immunogenicity of HIV antigens. These clinical trials have, however, highlighted gaps like new ways of identifying relevant antigens and adjuvants capable of triggering an effective and broad immune response and more effective vaccine delivery methods.

We felt that technological innovation could help fill these gaps and overcome some of the challenges facing HIV vaccine research. Specifically, sub-unit vaccines, which use aluminum-hydroxide-based adjuvants or immunostimulatory molecules, suffer from a lack of efficacy. And viral particles raise safety and cost issues. We demonstrated that, with adequate safety controls, engineered particles can reach

the lymph nodes directly after injection, and then interact with immune cells, where they can deliver either protein antigens or immunostimulatory molecules or both. This new adjuvant delivery system is of a great interest: The adjuvants appear to mimic their viral counterparts and are relatively easy to produce in large volumes.

This approach could enable novel vaccine formulations and, especially, "cocktail" treatments based on a combination of several antigens on one or several lipid nanodroplets. The process for preparing the droplets can be utilized in large-scale production scenarios without cellular hosts or bioproduction methods.

The potential uses include preventing or treating diseases for which there is no available vaccine or for which existing vaccines are less effective on some types of patients, as well as for developing new immunotherapies, which are playing an increasing role in medicine.

### RESEARCH PARTNERS: INSERM (immunology); IDMIT (HIV and animal model).

Further reading: • "Overcoming immunogenicity issues of HIV p24 antigen by the use of innovative nanostructured lipid carriers as delivery systems: evidences in mice and non-human primates", *Npj Vaccines* 3, 2018.  
Emilie Bayon, Jessica Morlieras, Nathalie Dereuddre-Bosquet, Alexis Gonon, Leslie Gosse, Thomas Courant, Roger Le Grand, Patrice N. Marche, Fabrice P. Navarro.  
• "Tailoring nanostructured lipid carriers for the delivery of protein antigens: Physicochemical properties versus immunogenicity studies", *Biomaterials*, 2017.  
Thomas Courant, Emilie Bayon, Hei Lanne Reynaud-Dougier, Christian L. Villiers, Patrice N. Marche, Fabrice P. Navarro.

## Non-contact evanescent acoustic tweezers successfully manipulate cells and bacteria

Cédric Poulain  
Leti scientist

**The contactless manipulation of fluids is useful in a number of biomedical applications. Leti researchers have overcome some of the hurdles to commercial use of the technology with a low-cost solution that is easy to manufacture and implement.**

### THE BREAKTHROUGH:

Creation of an evanescent acoustic Bessel beam of order zero by low-frequency ultrasound.

### WHY IT MATTERS:

This technology could replace conventional propagative SAW technologies for the manipulation of tiny particles and create opportunities in commercial biomedical applications.

**NEXT STEPS:** Modify the technique to enable the flexible trapping and spinning of individual living cells in culture.

### RESEARCH PARTNERS: n/a

Further reading: • "Near-field acoustic manipulation in a confined evanescent Bessel beam", *Nature Communications Physics*, 2019.  
Pierre-Yves Gires, Cédric Poulain.  
• "A simple acoustofluidic chip for microscale manipulation using evanescent Scholte waves", *Lab on a Chip*, 2016.  
Vivian Aubert, Régis Wunenburger, Tony Valier-Brasier, David Rabaud, Jean-Philippe Kleman, Cédric Poulain.  
• "Chladni Patterns in a Liquid at Microscale", *Physical Review Letters*, 2016.  
Gaël Vuillermet, Pierre-Yves Gires, Fabrice Casset, Cédric Poulain.

Acoustic tweezers and their microfluidic implementation on labs-on-chip have garnered increasing interest from researchers over the past decade due to the potential use of the technology for biomedical applications. Acoustic tweezers are a powerful tool for contactless cell sorting, patterning, lysing, and mixing at small scales. However, several challenges issues must be overcome for the technology to be viable for commercial applications.

One of these challenges is the fact that the high-frequency surface acoustic waves (SAW) used in conventional solutions are difficult to generate and decay rapidly, which makes implementation difficult. We decided to address this challenge by using evanescent waves—a strategy that echoes what has been done with optical tweezers, which were initially obtained with propagative laser beams, but which evolved toward evanescent sources.

We reinvestigated observations made during previous research until

we gained a deeper understanding of the physics at play. We were then able to demonstrate the potency of evanescent sound waves to exert forces upon tiny particles without resorting to the use of high-frequency ultrasound. Specifically, we generated an evanescent Bessel beam in the low-frequency ultrasound range. The enhanced radiation force arising from the evanescent field makes it possible to pattern living organisms as small as bacteria along concentric circles on a simple substrate, for example.

The solution is simple and cost-effective to produce in non-cleanroom environments, is more energy-efficient and easier to implement than conventional SAW, and, because the energy is confined in the vicinity of the emitter, the required sample volume is lower, which is an advantage for biological applications.

Next, we will investigate breaking the Bessel beam symmetry to be able to apply both force and torque with the same beam to be able to rotate individual objects.





# Disabled patient moves thanks to brain-controlled exoskeleton powered by Leti technology

Guillaume Charvet  
Leti scientist

The Brain-Computer Interface (BCI) project at Clinattec (Leti's biomedical research lab operated in conjunction with Grenoble-Alpes University Medical Center) reached a major milestone with a successful proof-of-concept that enabled a tetraplegic patient to control all four limbs via a brain implant—a world first.

**THE BREAKTHROUGH:** The first-ever proof-of-concept of a four-limb exoskeleton controlled via a brain-computer interface.

**WHY IT MATTERS:** Advances in brain-controlled devices could compensate for motor disabilities and allow patients to live more independently.

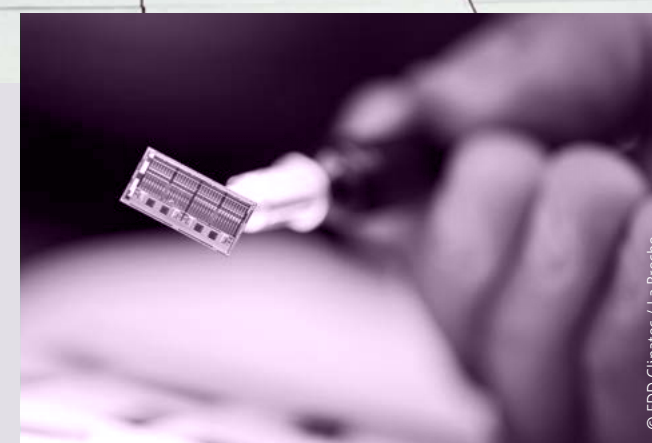
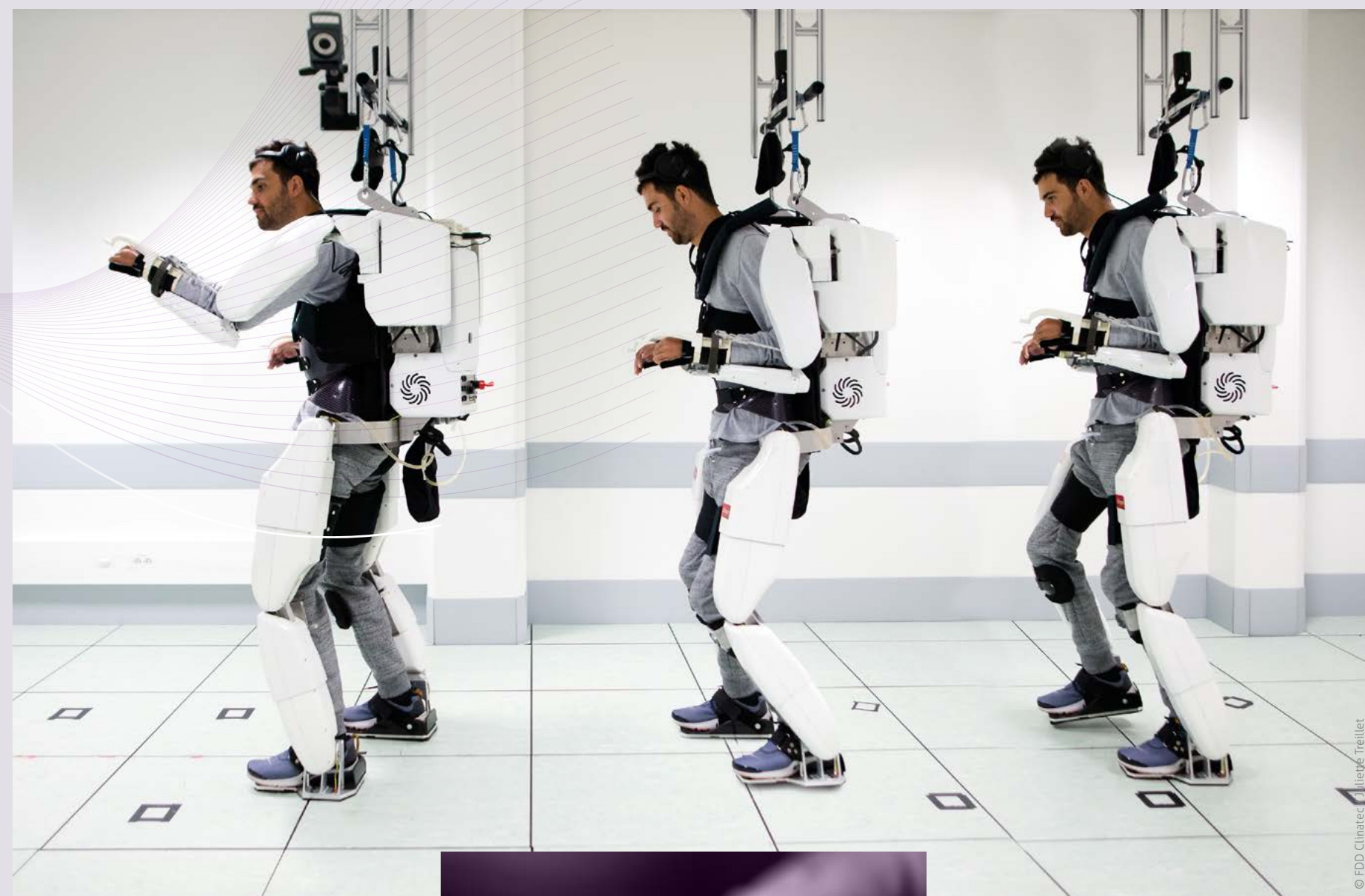
**NEXT STEPS:** Develop more precise and robust algorithms to enable more complex movements (holding objects) and integrate new effectors to address clinical applications other than paralysis.

The purpose of Clinattec's Brain-Computer Interface (BCI) project is to demonstrate that, with training, patients with severe motor disabilities (tetraplegic patients) can control complex functional substitution devices (a four-limb exoskeleton in this study) by decoding the brain's electrical activity recorded via a fully implantable medical device.

The BCI project recently reached a major milestone that was published in *The Lancet Neurology*. For the first time ever, a tetraplegic subject was able to walk and control his arms using the WIMAGINE® implant, designed to record brain signals (ElectroCorticoGraphy, or ECoG) over the long term, and a four-limb exoskeleton. The system features Leti-designed electronic circuit boards that contain the ECoG acquisition and digitalization systems. Artificial intelligence (machine learning) algorithms and dedicated software were also developed to decode ECoG signals and translate them into commands to control the exoskeleton in real time.

In this groundbreaking clinical trial, two of the devices were implanted on the patient's brain. The patient then spent 27 months training the system and learning to control the exoskeleton, both in virtual environments at home, and with the actual exoskeleton at Clinattec. The patient successfully controlled eight degrees of freedom with bimanual control of the exoskeleton, more than ever before.

The successful clinical trial will open the door to new developments to modify the technology for out-of-lab use. Applications other than paralysis (communication for patients suffering from locked-in syndrome, post-stroke rehabilitation) are also on the drawing board.



Neural signal recording integrated circuit developed at Leti.

**RESEARCH PARTNERS:** Grenoble-Alpes University Medical Center; Grenoble-Alpes University; List, a CEA Tech institute.

Further reading: • "An exoskeleton controlled by an epidural wireless brain-machine interface in a tetraplegic patient: a proof-of-concept demonstration," *The Lancet Neurology*, 2019. Alim-Louis Benabid et al.

• "Recursive exponentially weighted n-way partial least squares regression with recursive-validation of hyper-parameters in brain-computer interface applications," *Scientific Reports*, 2017. Andrey Eliseyev, Vincent Aboiroux, Thomas Costecalde, Lilia Langar, Guillaume Charvet, Corinne Mestais, Tetiana Aksanova, Alim-Louis Benabid.



## Microfluidics automates blood sample preparation, bringing proteomics to the patient bedside

Marie-Line Cosnier  
Leti scientist



Work on blood samples in L2 biosafety lab.

Disposable microfluidic cartridge.

**Proteomics is heralded as the new genomics for its capacity to speed up both the diagnosis and treatment of diseases like cancer. Using proteomics in clinical settings has, however, proven to be a challenge. Leti scientists have developed a solution that makes blood sample preparation fast, reliable, and portable—ideal for personalized and point-of-care applications.**

Personalized medicine and point-of-care diagnostics are two of the major trends shaping the healthcare industry. Mass-spectrometry-based proteomics holds great promise in both of these fields. Currently, however, preparing a blood sample for proteomic biomarker analysis can take up to two days, with a number of manual steps that must be performed by a highly-qualified lab technician with special training.

We worked with Clinatéc, IRIG, and DIP to design and prototype a transportable microfluidics laboratory that integrates and automates all of the steps involved in sample preparation: injection of whole blood, separation of red blood cells, calibration of the plasma volume, depletion of albumin, digestion of proteins, and purification and storage of peptides. The system, called PEP's, consists of a disposable microfluidics card and the associated instrumentation. Leti's expertise in biological process integration, instrumentation, microfluidics, and

microtechnology and the associated manufacturing processes played an important role in our research.

The prototype successfully automated management of the blood sample, reducing the process time from two days down to two hours. The quality of the plasma and peptides obtained was high, and the quantity of peptides was sufficient for 5 analyses using targeted mass spectrometry and for 50 analyses using discovery mass spectrometry. Specifically, we achieved complete integration and automation of all of the process steps necessary for whole-blood-sample preparation prior to MS analysis directly at the patient's bedside.

Sample preparation is one of the bottlenecks hindering the widespread development of personalized medicine. Our advance will bring a level of quality and reproducibility to blood proteomics that should facilitate the use of the technique in point-of-care and personalized medicine.

**RESEARCH PARTNERS:**  
Clinatéc and IRIG (proteomics for biomedical applications, cutting-edge mass spectrometry facility, biochemical preparation of clinical samples); DIP (modular architecture design, market research, 3D printing).

Further reading: One article forthcoming; • "Innovation Best Team Practices 2019" award from the Paris Innovation Directors' Club.

### THE BREAKTHROUGH:

An automated sample-preparation solution that will speed up proteomics analysis.

### WHY IT MATTERS:

This advance will promote the use of proteomics in clinical settings by enabling the automation and integration of all pre-analytical blood sample preparation steps at the patient bedside.

**NEXT STEPS:** Scale up the technology and transfer it to a manufacturer.

## Pep's advances point-of-care diagnostics and personalized medicine



Leti Senior Researcher and Project Manager Marie-Line Cosnier brought the "Innovation Team Best Practices Award" home from the Paris Innovation Directors' Club on September 5, 2019. The award recognizes a noteworthy advance in point-of-care diagnostics achieved thanks in part to funding from the Carnot Network. Marie-Line Cosnier and her team developed Pep's (Peptide Saver), an integrated and automated microfluidic instrument for whole blood sample preparation in proteomics analysis. Pep's reduces the time it takes to prepare a sample for mass spectrometry from two days to just two hours, opening up new possibilities in point-of-care diagnostics and personalized medicine. Marie-Line Cosnier said that the award recognizes the contributions of all partners\* and highlights the results of exemplary teamwork.

\*Biological protocol integration: Myriam Cubizolles, Patricia Laurent, and Mathilde Louwagie.

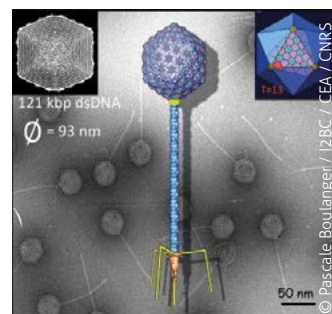
Microfluidic and instrumentation development: Remco den Dulk, Camille Echampt, Frédéric Revol-Cavalier, and Manuel Alessio.

Proteomics: Virginie Brun, Benoît Gilquin, Yohann Couté, and Annie Adrait.

Design and electronics development: Charles-Elie Goujon, Gorka Arrizabalaga.

Project management: Fabrice Navarro and Marie-Line Cosnier.





The “nano-weighing” system published in Science was tested to measure the mass of a virus capsid, the bacteriophage T5, whose theoretical mass could only be estimated previously. With a size of 93 nm, this viral capsid weighs ~ 105 megadaltons.

## Nanoresonators go where mass spectrometers can't in the analysis of particles of biomedical interest

Sébastien Hentz  
Leti scientist

**Leti researchers have eliminated ionization from nanomechanical mass spectrometry, enabling the characterization of biological particles like “bacteria-eating” viruses for the first time ever. The advance will fuel progress toward alternatives to antibiotics.**

### THE BREAKTHROUGH:

Measurement of the highest molecular mass ever measured (an entire bacteriophage virus capsid).

### WHY IT MATTERS:

This advance overcomes one of the challenges hindering the development of phage therapy by providing new analysis capabilities.

**NEXT STEPS:** Improve the instrument's sensitivity, speed, and resolution and miniaturize the system.

Tomorrow's medical treatments will require very advanced characterization techniques capable of controlling the quality of drugs produced before the drugs can be used. Phage therapy, which uses viruses to infect and fight pathogenic bacteria, is one example. New techniques will also be required to analyze the nanoparticles used in targeted drug delivery. The methods currently used to characterize these particles are based on size—they cannot provide functional or structural information. Mass is a more useful measurement, because it can identify specific species. But today's mass spectrometers, which use ionization to sort particles with electromagnetic fields, cannot weigh objects in the intermediate range. Unfortunately, this applies to many objects of biomedical significance, including viruses.

Leti has developed and fabricated nanomechanical resonators that are ideal for objects in this intermediate

mass range. They do not require ionization to measure mass: Like a guitar string that changes tone when a finger is placed on it, the vibration frequency of a resonator changes when a mass lands on it. We utilized these tiny nanoresonators, which are 150 times smaller than the width of a human hair—to develop the first-ever instrument that can quickly and efficiently analyze species in the MDa to GDa mass range.

Entirely devoid of ionization, the instrument nebulizes the particles in solution, aspirates them into the system under vacuum, and, using an aerodynamic lens, focuses the particles onto an array of 20 nanoresonators. This system is vastly more efficient and faster than previous nanoresonator-based systems, analyzing a sample in just a few hours rather than a few weeks. The system was able to measure the mass of a bacteriophage T5 capsid—a virus that holds promise as a future alternative to antibiotics.

### RESEARCH PARTNERS:

**CEA Science, BIG, IIRIG (mass spectrometry, sample preparation, nebulization of particles in solution); CNRS-I2BC (T5 assembly).**

Further reading: • “Single-particle mass spectrometry with arrays of frequency-addressed nanomechanical resonators”, *Nature Communications* 9 (2018).

Eric Sage, Marc Sansa, Shawn Fostner, Martial Defoort, Marc Gély, Akshay K. Naik, Robert Morel, Laurent Duraffourg, Michael L. Roukes, Thomas Alava, Guillaume Jourdan, Eric Colinet, Christophe Masselon, Ariel Brenac, Sébastien Hentz.

• “Neutral mass spectrometry of virus capsids above 100 megadaltons with nanomechanical resonators”, *Science* 23 (2018).

Sergio Dominguez-Medina, Shawn Fostner, Martial Defoort, Marc Sansa, Ann-Kathrin Stark, Mohammad Abdul Halim, Emeline Vernhes, Marc Gely, Guillaume Jourdan, Thomas Alava, Pascale Boulanger, Christophe Masselon, Sébastien Hentz.

A network of 20 silicon nano resonators connected by metallic lines. Successive zoom in on an individual resonator (typically about ten microns long and a hundred nm thick).

## Innovative biological particle separation technology to benefit medical diagnostics

Eloïse Pariset,  
Aurélien Thuaire,  
Vincent Agache  
Leti scientists

**Leti's microelectronics, microfluidics, and advanced materials know-how contributed to a major advance in biological sample preparation for medical diagnostics. Our researchers used cascaded deterministic lateral displacement to sort complex biological samples into sub-populations based on size.**

### THE BREAKTHROUGH:

Separation of biological particles in a modular platform of cascaded DLD modules.

### WHY IT MATTERS:

The capacity to isolate biological particles has potential applications in diagnosing sepsis and isolating nanoparticles like viruses and exosomes, also for diagnostic purposes.

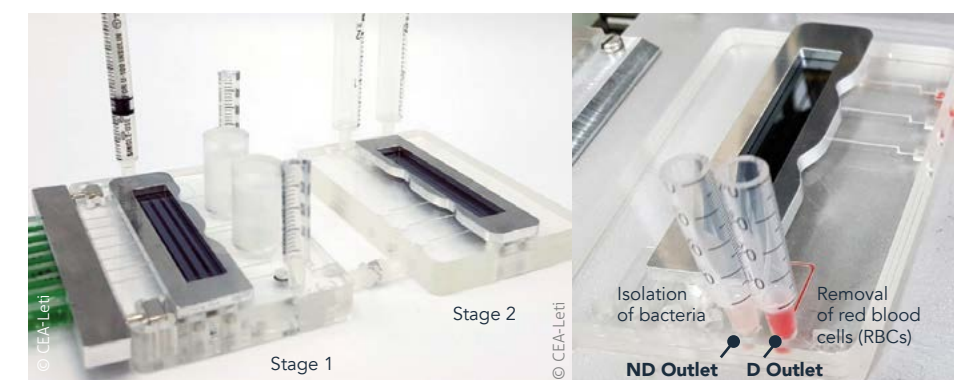
**NEXT STEPS:** Test the modular platform on the isolation of specific particles and improve dynamic range and throughput.

The detection of nanoparticles like viruses and exosomes is useful for a broad range of medical diagnostics. The aim of our research was to develop a new modular approach to purify complex biological samples and fractionate the particles in the sample by size into several sub-populations. Specifically, we implemented deterministic lateral displacement (DLD), a passive microfluidic technique that utilizes a slanted pillar array, to sort the particles in a sample.

DLD is a widely-used sample preparation technique, primarily at the micrometer scale, where it can be used to detect cells and bacteria, for example. And, at the nanometer scale, DLD can detect exosomes. However, the fractionation of complex samples into several sub-populations remains a challenge. Effective fractionation requires connecting several DLD components in series while maintaining a constant flow velocity across the DLD outlets so as not to disturb the particles' trajectory.

We connected silicon-based DLD components designed and fabricated in Leti's 200 mm cleanrooms in series on an automated platform. The modules are temporarily isolated with valves and deformable chambers built using membranes previously developed at Leti so that they can operate independently, one after the other. We validated the approach on a model sample, and then tested it on the isolation of bacteria from a complex blood sample containing cancer cells.

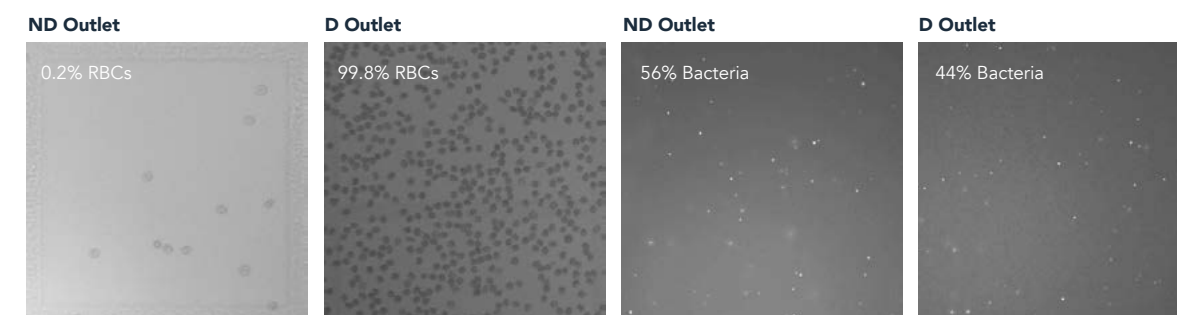
Now that the proof-of-concept has been validated, the next steps will be to test it on the target applications. We have already obtained a dynamic range of 4; this could be improved to isolate smaller particles like nanoparticles, for example. Finally, throughput must also be improved for faster sample preparation and to enable the processing of larger sample volumes, which would be useful in diagnosing sepsis, for instance.



Cascaded deterministic lateral displacement modules:

Stage 1: removal of cancer cells

Stage 2: removal of red blood cells (deviated outlet) and isolation of bacteria (non deviated outlet)





# Market news from our R&D partners

## Diabeloop completes record-breaking European fundraising effort with its autonomous diabetes management solutions

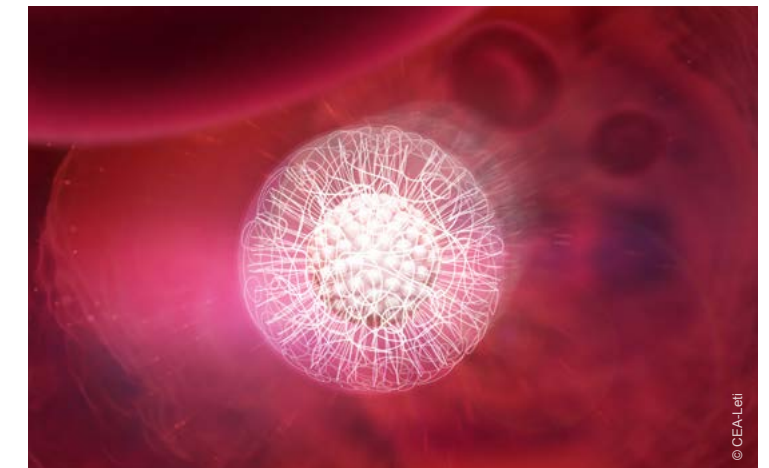
Diabeloop announced today that it has completed a €31-million Series B round of funding, setting a European fundraising record in the area of therapeutic artificial intelligence. This funding will allow Diabeloop to accelerate its international commercial deployment in both Europe and the US, and will support the award-winning company's innovative programs.

The solutions developed by Diabeloop leverage artificial intelligence to automate and personalize diabetes management.

The core of the company's first Automated Insulin Delivery (AID) system is a self-learning algorithm hosted in a dedicated handset. In combination with a continuous glucose measurement system and an insulin pump, the device – a breakthrough technological innovation – almost completely automates the treatment of Type 1 diabetes.



Learn more:  
<https://bit.ly/34cEAVE>



## CEA-Leti breakthrough opens path to new vaccine for HIV using lipid-nanoparticle-delivery technology

**GRENOBLE, France – Feb. 27, 2019 –** Leti, a research institute of CEA Tech, in collaboration with CEA's Fundamental Research Division, has developed a new vaccine approach for HIV based on engineered lipid nanoparticles that deliver p24 - a viral protein that is key to an HIV vaccine- and optimize the CpG adjuvant's effect.

Until now, p24-based vaccines have shown limited effectiveness because of an insufficient immune response to this antigen in HIV patients. Based on its Lipidots® delivery platform, CEA-Leti's new approach improves immunogenicity against the p24 HIV protein by loading it and an immunostimulant agent onto nanostructured lipid carriers (NLCs). This may be a first step for a new HIV vaccine that also would include additional components of the virus.

Lipidots® is a versatile nano-delivery platform that encapsulates drugs and/or imaging agents in tiny droplets of oil and delivers them to targeted cells in the body for patient treatment or diagnosis. The small size of the Lipidots NLCs, approximately 100nm in diameter, allows them to enter the body's lymphatic vessels, which carry them to the lymph nodes where they trigger a stronger immune response.



Learn more:  
<https://bit.ly/37OqHjs>



# 04

## Innovative devices and architectures for a power-efficient society

The age of data is upon us. And, as the delivery of services in just about every field depends on the ability to access and utilize constantly-increasing volumes of data, issues like data protection and the efficient use of both energy and raw materials must be addressed urgently. Today's technology development is multi-scale, encompassing devices, systems, and architectures.

Leti is developing and scaling up innovative devices, systems, and architectures that will effectively respond to these challenges. Most notably, we are working on breakthrough memory technologies that will increase reliability and energy efficiency through advanced materials and tighter integration.

OTS selector technology for resistive crossbar memory brings brain-inspired computing within reach	58
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Simplified scheme of a Phase-Change Memory (PCM) co-integrated with an Ovonic Threshold Switching (OTS) selector developed and fabricated in Leti.

## OTS selector technology for resistive crossbar memory brings brain-inspired computing within reach

Gabriele Navarro  
Leti scientist

**Leti's know-how in materials played a major role in the engineering of an OTS material capable of improving the reliability of resistive crossbar memory. This advance will help fuel the development of tomorrow's computing and memory architectures.**

### THE BREAKTHROUGH:

Enhanced OTS selector materials and co-integration with resistive memory technologies for more reliable back-end crossbar arrays.

### WHY IT MATTERS:

Back-end resistive crossbar memory enables revolutionary architectures like storage-class memory and neuromorphic computing systems.

### NEXT STEPS:

Further improve OTS selector reliability, develop new OTS materials, explore innovative electric field activated OTS-based devices, and fabricate back-end high density crossbar arrays.

Resistive memory technologies are expected to power the next revolutions in computing and storage. To respond to the advanced neuromorphic systems integration requirements of tomorrow's brain inspired computers and deliver the real time processing and massive scalability that memory first database applications will demand, resistive crossbar memory (or RCM), with its intrinsic parallel structure and high density, offers high potential. And the future of RCM will depend on making the selector device more reliable.

We focused on GeSe-based ovonic threshold switching materials (amorphous chalcogenides) to make more reliable back-end selectors and enable their integration into RCM architectures.

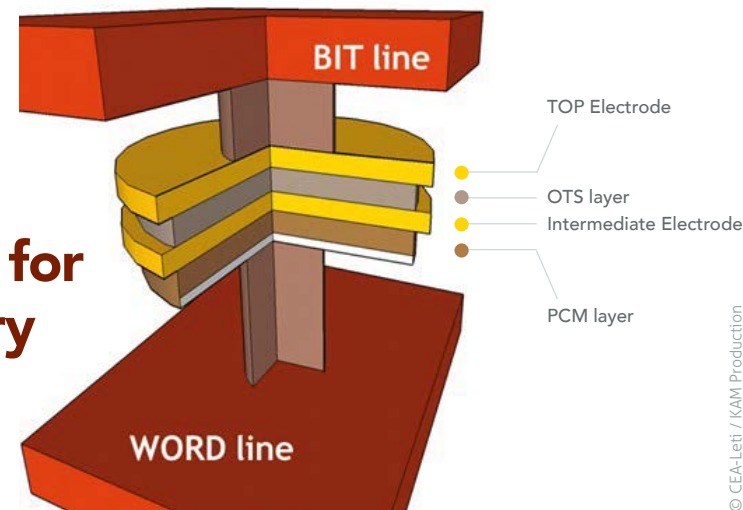
The OTS material we engineered led to enhanced RCM device programming and read endurance—crucial to reliably accessing the stored information. We also improved the OTS material's robustness under temperatures typical of CMOS back-end fabrication processes to

increase the material's compatibility with different applications. We studied leakage current and threshold voltage—the main OTS electrical parameters—and gained new insights into the material's physics. We investigated the causes of endurance failures in OTS—material aging during cycling—and engineered a carbon-based electrode to delay failures. Finally, we demonstrated the feasibility of innovative co-integrations with different resistive memory devices (e.g. phase-change memory).

Leti's vast experience with chalcogenide characterization and deposition was vital to our research. We used a number of techniques available at the nanocharacterization platform (Raman and infrared spectroscopy, etc.) during the project. In addition, Leti's broad, deep knowledge of resistive memory devices—from physics through to manufacturing—played a major role in this advance. Our successful co-integration with resistive memory devices is evidence of the maturity of Leti's OTS technology and its readiness for prototyping and manufacturing.

### RESEARCH PARTNERS: STMicroelectronics

Further reading: G. Navarro et al., • "Innovative PCM+OTS device with high sub-threshold non-linearity for non-switching reading operations and higher endurance performance," 2017 Symposium on VLSI Technology, Kyoto, 2017, pp. T94-T95.  
A. Verdy et al. • "Optimized Reading Window for Crossbar Arrays Thanks to Ge-Se-Sb-N-based OTS Selectors" IEDM 2018.



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## Monolithic Noff GaN MIS HEMT now in the running for tomorrow's post-silicon power converters

Marc Plissonnier  
(Head of Power Component Laboratory) and Luca Perniola  
(Head of Power, Energy & Connectivity Component Section)

**Gallium nitride could be a more efficient replacement with respect to silicon for certain applications in the high-frequency domain of power electronics. Leti and its partners are pursuing an ambitious GaN on Si roadmap that encompasses the entire value chain from material to complete system.**

### THE BREAKTHROUGH:

Position MIS HEMT architectures in the GaN technology arena and help expand GaN technology penetration in a market dominated by silicon components.

### WHY IT MATTERS:

This research will help pave the way toward the commercialization of a more efficient replacement for silicon power conversion systems and enable the design of smaller, more efficient devices.

**NEXT STEPS:** Pursue our roadmap toward monolithic solutions and systems-in-package to achieve high switching frequency and higher power density than silicon using CMOS processes. The introduction of this new technology will lead to cost reductions at system level.

### RESEARCH PARTNERS:

DOCC Toulouse (functional and reliability testing); LTM; G2ELab; Ampere; LAAS; STMicroelectronics.

Further reading: • "The 2018 GaN Power Electronics Roadmap," Journal of Physics D: Applied Physics, 2018. Léa Di Cioccio et al.  
• "III-N Epitaxy on Si for Power Electronics," (book chapter) in High Mobility Materials for CMOS Applications, 2018. M. Charles

Electronic devices are ubiquitous in the lives of most consumers, and the IoT revolution is fueling continued growth. New "always on" devices are creating higher than ever demand for efficient power management technologies. Most of the power management systems integrated into today's electronic devices are based on Si and SiC technologies.

A new class of power components based on Gallium Nitride (GaN) has the capacity to deliver excellent power performance and could meet the need for smaller, more energy-efficient power converters that cost less to manufacture. In the quest to replace silicon technologies with something more efficient, several manufacturers have already developed GaN power devices. TSMC, Infineon, and Panasonic have developed their own proprietary solution based on a P-GaN gate architecture.

We chose to develop a MIS High-Electron-Mobility Transistor (MIS HEMT) GaN device architecture

in the Normally OFF (Noff) configuration. It offers features similar to those of a conventional silicon-based MOS, but with a better tradeoff between drive and leakage currents compared to a P-GaN gate architecture. We drew on a broad range of expertise available at Leti and, more broadly, the CEA, and work with outside partners like STMicroelectronics, LTM, G2ELab, Ampere, LAAS, and others, either directly or through the Labex GANEX initiative. Our research encompassed the entire value chain from material to system, with work on GaN epitaxy, device and packaging technologies, integrated circuits, system architecture, and functional and reliability testing.

We will pursue our GaN roadmap with further research on epitaxy, devices, passive components, co-integration, and system architectures to develop a GaN technology that allows switching frequencies in the MHz and power densities ten times those of silicon—all using standard CMOS processes to keep costs down.



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# Leti and international partners develop new RRAM memory capable of supporting tomorrow's embedded AI

Elisa Vianello,  
Pascal Vivet  
Leti scientists

Leti, Stanford University, and Nanyang Technological University designed, fabricated, and validated a circuit that integrates multiple-bit non-volatile memory, giving edge-AI a needed boost in resiliency and capacity.

**THE BREAKTHROUGH:**  
A revolutionary RRAM chip for edge-AI.

**WHY IT MATTERS:**  
As artificial intelligence makes inroads into the Internet of Things, more resilient, higher-capacity memory will be needed to enable energy-efficient smart-sensor nodes.

**NEXT STEPS:**  
Develop domain-specific accelerators, bit-cost scalable 3D vertical RRAM, and monolithic 3D integration of multiple RRAM layers.

Resistive RAM, a type of non-volatile memory, has advanced by leaps and bounds in recent years. However, major challenges remain—such as the limited endurance of RRAM cells before a permanent write failure. For RRAM to work as an on-chip memory capable of supporting data-intensive deep learning, it must offer greater resilience and higher storage density.

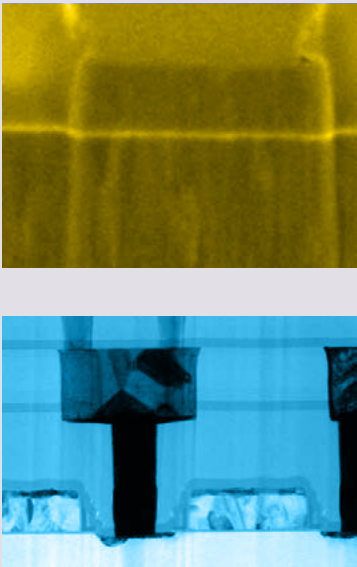
This innovation, which entailed monolithically integrating two heterogeneous technologies, grew out of the idea that combining RRAM programming and system-level resilience solutions could effectively solve density issues and improve RRAM resilience. The approach was validated for machine learning, control, and security applications on a proof-of-concept chip consisting of a non-volatile microcontroller with 18 KB of on-chip RRAM on a commercial 130 nm CMOS with a 16-bit general-purpose microcontroller core with 8 KB of SRAM.

This world-first is the fruit of an international collaboration of partners whose expertise spans technology, circuits, architecture, and applications: Stanford University designed the chip; Nanyang Technological University in Singapore helped determine which techniques would make the best

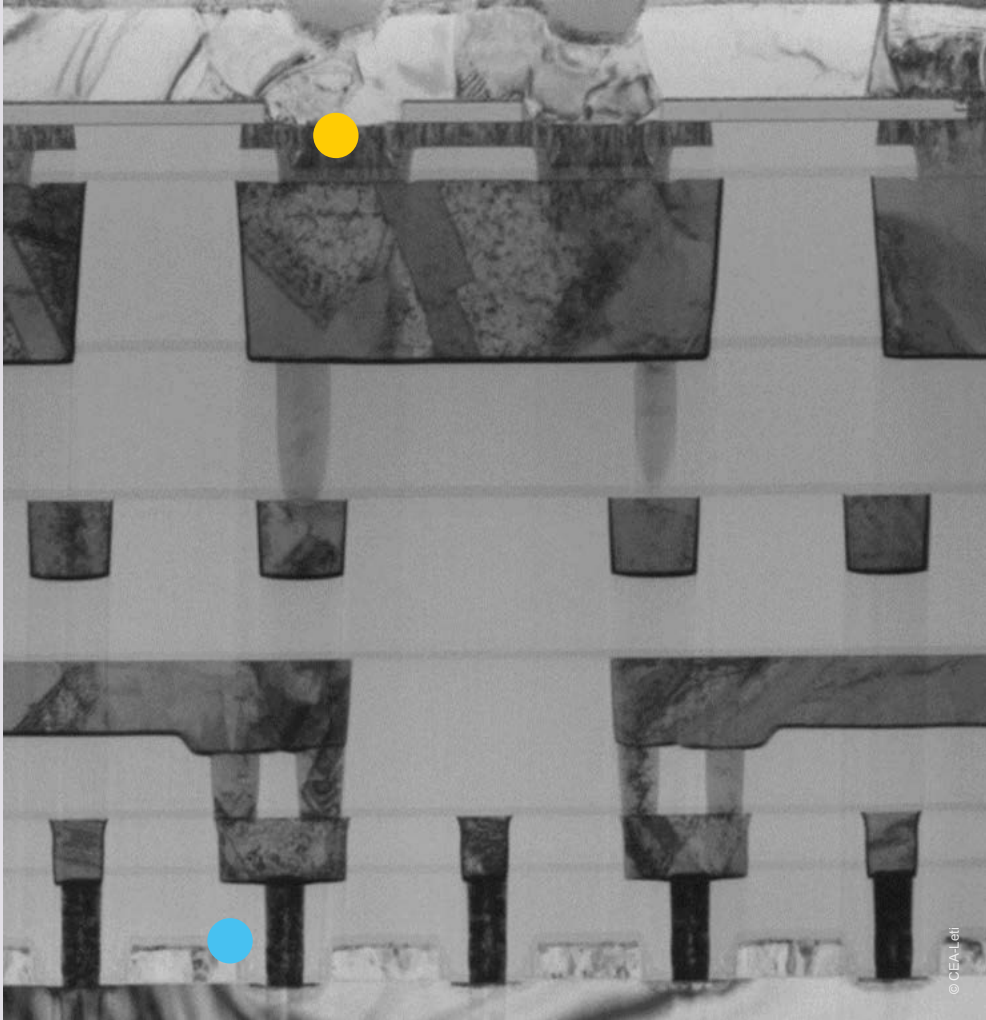
use of RRAM features and led the system-level simulations; and Leti contributed its Memory Advanced Demonstrator (MAD200), a testing platform that brings versatility and robustness to component and interface assessment and that allows researchers to explore memory performance from both design and technology angles.

The highly-resilient multiple-bit RRAM offers 2.5 times the capacity of current RRAM with energy consumption five times lower than that of standard embedded flash memory. In addition to enabling a ten-year lifetime for neural network inference applications, the chip also improves neural network inference accuracy, essential to artificial intelligence. The technology can currently be purchased through Multi-Project Circuit (CMP), a nonprofit prototyping and low-volume production service provider.

**RESEARCH PARTNERS:**  
Stanford University (chip design); Nanyang Technological University (system-level simulations)



RRAM integrated on silicon CMOS



Further reading: • “Resistive RAM Endurance: Array-Level Characterization and Correction Techniques Targeting Deep Learning Applications”, IEEE Transactions on Electron Devices, Year: 2019 Volume: 66, Issue: 3, Pages: 1281–1288.  
Alessandro Grossi, Elisa Vianello, Mohamed M. Sabry, Marios Barlas, Laurent Grenouillet, Jean Coignus, Edith Beigne, Tony Wu, Binh Q. Le, Mary K. Wootters, Cristian Zambelli, Etienne Nowak, Subhasish Mitra.  
• “Resistive RAM With Multiple Bits Per Cell: Array-Level Demonstration of 3 Bits Per Cell,” IEEE Transactions on Electron Devices, Year: 2019 Volume: 66, Issue: 1, Pages: 641–646.  
Binh Q. Le, Alessandro Grossi, Elisa Vianello, Tony Wu, Giusy Lama, Edith Beigne, H.-S. Philip Wong, Subhasish Mitra.  
• “14.3 A 43pJ/Cycle Non-Volatile Microcontroller with 4.7μs Shutdown/Wake-up Integrating 2.3-bit/Cell Resistive RAM and Resilience Techniques,” 2019 IEEE International Solid-State Circuits Conference (ISSCC).  
Tony F. Wu, Binh Q. Le, Robert Radway, Andrew Bartolo, William Hwang, Seungbin Jeong, Haitong Li, Pulkit Tandon, Elisa Vianello, Pascal Vivet, Etienne Nowak, Mary K. Wootters, H.-S. Philip Wong, Mohamed M. Sabry Aly, Edith Beigne, Subhasish Mitra.



# Gate-reflectometry-based dispersive spin readout holds promise for scalable quantum computing

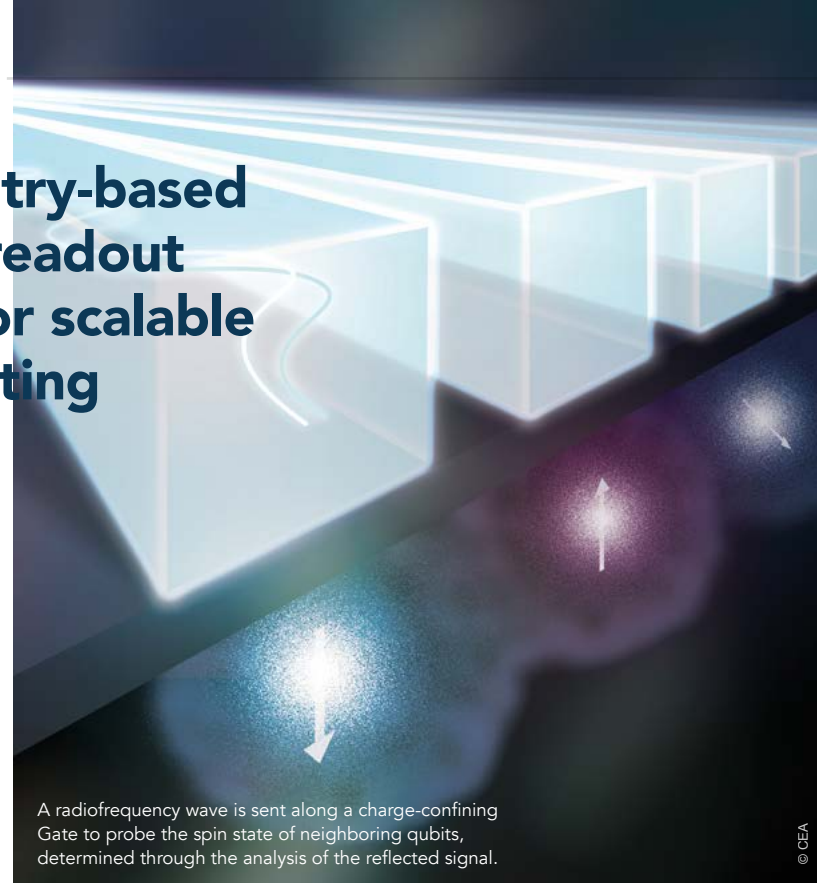
Louis Hutin, Gaël Pillonnet  
Leti scientists

**When it comes to quantum computing, high speed and reliability are paramount to running fault-tolerant calculations. Gate-based reflectometry spin readout was implemented by IRIG and Institut Néel on Si MOS qubits fabricated by Leti with results that bode well for the future of QC.**

**THE BREAKTHROUGH:** Successful implementation of gate-reflectometry-based spin readout schemes on Si MOS qubit devices.

**WHY IT MATTERS:** A potentially-scalable solution to reliably read large-scale qubit registers.

**NEXT STEPS:** Further improve speed and fidelity and achieve fully-integrated large qubit arrays and control/readout electronics.



A radiofrequency wave is sent along a charge-confining Gate to probe the spin state of neighboring qubits, determined through the analysis of the reflected signal.

Si-based quantum computing research is still a relatively new field. We are currently hoping to obtain fault-tolerant, universal gate-based quantum computers capable of offering exponentially higher speeds than conventional computers on some classes of algorithms.

Although the fundamental and engineering limits to Si quantum computer size and power are not yet known, our aim is to engineer devices for the coherent manipulation of information encoded as a quantum superposition of basis states, or quantum bits. The state of a qubit is mapped to the spin of a charged particle confined in a quantum dot. We opted for electrostatic confinement by MOS gates in a silicon channel.

We implemented gate-based reflectometry on Si MOS qubit prototypes based on a slightly altered SOI nanowire MOSFET process flow

and fabricated on Leti's 300 mm line. The results were very encouraging in terms of fidelity (>98% for 0.5ms). Our technique analyzes a radiofrequency signal reflected off the qubit or an auxiliary quantum dot. The implementation offered the low power dissipation and minimal thermal noise required at energy scales this small.

In addition to Leti's resources, we drew on our long-standing partnerships with IRIG and Institut Néel to make the necessary adaptations to the dimensions and materials of the nano-objects, which were initially designed to operate at room temperature, and to refine our approach and obtain quantum dots that perform well at low temperatures.

As we continue to explore the limits of what quantum computing can do, we will pursue further improvements to our scalable readout method, a must for expandable QC architectures.

## A PORTFOLIO OF CRYOGENIC INTEGRATED CIRCUITS TO SUPPORT LETI'S QUANTUM COMPUTING PROGRAM

Leti's goal is to design a large portfolio of cryogenic integrated circuits to support massive quantum device characterization and address the challenge of qubit matrix readout. Specifically, we are investigating tradeoffs between power consumption, bandwidth, and noise to maintain circuit operation below 1 Kelvin with a set of analog, RF, and digital functions. Finally, we are building a cryogenic design kit for FDSOI based on a novel sub-Kelvin cryogenic MOS characterization platform.

### RESEARCH PARTNERS: IRIG and Institut Néel (modeling, simulation, cryogenics, spin physics).

Further reading: • "Gate-reflectometry dispersive readout of a spin qubit in silicon," *Nature Communications* (accepted), 2019A. Crippa, R. Ezzouch, A. Aprà, A. Amisse, L. Hutin, B. Bertrand, M. Vinet, M. Urdampilleta, T. Meunier, M. Sanquer, X. Jehl, R. Maurand, S. De Franceschi.  
• "Gate-based high fidelity spin readout in a CMOS device," *Nature Nanotechnology* (accepted), 2019. M. Urdampilleta, D. Niegemann, E. Chanrion, B. Jadot, C. Spence, P.-A. Mortemousque, C. Bäuerle, L. Hutin, B. Bertrand, S. Barraud, R. Maurand, M. Sanquer, X. Jehl, S. De Franceschi, M. Vinet, T. Meunier.

# Self-powering sensors could soon benefit from compact, robust vibration energy harvesters

Gaël Pillonnet  
Leti scientist

**Vibration energy harvesters turn ambient vibration into electrical energy, making them ideal for self-powering devices like sensors. Leti researchers have recently made an advance that will enable harvesters that are more compact and that can operate efficiently in fluctuating conditions.**

### THE BREAKTHROUGH:

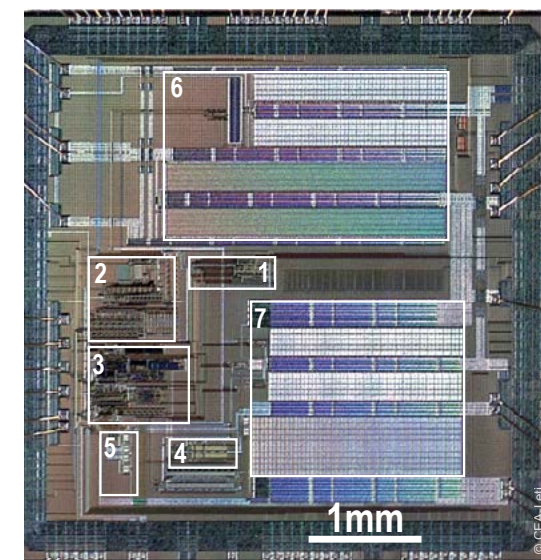
The indirect piezoelectric coupling effect and controlled short-circuit phase were used to tune the mechanical dynamic of a vibration energy harvester.

### WHY IT MATTERS:

This overcomes the main hurdle to implementing vibration energy harvesters in self-powering sensors.

### NEXT STEPS:

Test the limitations of the technology on very-low-power ambient energy and apply the technology to other types of energy harvesters.



1\_Digital  
2\_MPPT  
3\_Analog  
4\_Drivers  
5\_Bulk reg.  
6\_Cold start

Energy harvesters will be crucial to many of tomorrow's self-powering electronic devices and, especially, sensors. Our research set out to overcome one of the main hurdles to using vibration energy harvesters in sensors: narrow frequency bandwidth. Harvesters with larger frequency bandwidths would operate more effectively amid fluctuating ambient vibration and be more resilient to dynamic shift due to aging and temperature changes. Another challenge facing energy harvesters is compactness. We posited that electrical tuning could be used to control an easy-to-implement short-circuit phase, eliminating bulky mechanical tuning systems.

We developed a novel energy extraction strategy called SC-SECE (Short-Circuit Synchronous Electric Charge Extraction) to maximize the energy extraction of piezoelectric-based harvesters over a large frequency bandwidth. Existing vibration energy harvester systems suffer from low mechanical-to-electrical power transfer if there is

a mismatch between the frequency of the harvester resonance and the environmental vibration excitation (due to aging, temperature changes, or unpredictable ambient vibration). We drew on Leti's know-how in electromechanical coupling modelling for energy harvesting applications and developed high-coupling piezoelectric harvesters that get maximum efficiency out of our strategy. The figure of merit (which includes power density and bandwidth) we obtained is the best ever reported in lab conditions.

The next step is to explore the limitations of our strategy with very low ambient energy. We have since developed a custom low-power integrated circuit with a positive energy harvesting point below 1  $\mu$ W. The circuit is currently being tested. Our strategy could also be applied to electrodynamic or electrostatic vibration energy harvesters. Finally, a PhD research project is investigating an improved mechanical design to increase coupling without the need for high-coupled piezoelectric materials.

### RESEARCH PARTNERS: SYMME Lab, Savoie Mont Blanc University; Elie Lefevre, Paris Sud University, DSYS (Leti).

Further reading: • "Frequency tuning of piezoelectric energy harvesters thanks to a short-circuit synchronous electric charge extraction", *Smart Materials and Structures*, 2018. Adrien Morel, Gaël Pillonnet, Pierre Gasnier, Elie Lefevre, Adrien Badel.  
• "Short Circuit Synchronous Electric Charge Extraction (SC-SECE) Strategy for wideband vibration energy harvesting", *IEEE International Symposium on Circuits and Systems*, 2018. Adrien Morel, Pierre Gasnier, Yohan Wanderoild, Gaël Pillonnet, Adrien Badel.



# Power efficient computing: Novel manycore architecture enables up to 1,000 processor cores

Séverine Cheramy,  
Eric Guthmuller  
Leti scientists

**A chiplet developed by Leti and academic and industrial partners will pave the way to more powerful, energy-efficient, cost-competitive processing solutions for high-performance computing.**

## THE BREAKTHROUGH:

The first-ever implementation of a chiplet with 3D-ready scalable cache coherent processor architecture.

## WHY IT MATTERS:

As we move toward exascale computing, this advance demonstrates the maturity of both 3D technologies and 3D design tools to meet tomorrow's power-efficiency and high-performance computing needs.

**NEXT STEPS:** Integrate the chiplet onto an active interposer to build a 3D manycore processor leveraging Leti's 3D technology portfolio.

The expansion of high-performance computing to data centers around the globe is spurring demand for high-performance processors for applications from physics to finance. To overcome the power and frequency limitations of mono-core processors, today's processors are manycore.

Our research was conducted under the IRT Nanoelec 3D integration program in conjunction with STMicroelectronics; Mentor, a Siemens Business; EVG; SET; and the Pierre and Marie Curie University LIP6 laboratory. We also drew on Leti's expertise in 3D circuit design. Our goal was to demonstrate the feasibility of a scalable cache coherent 3D architecture using state of the art 3D technologies developed by Leti and improve 3D circuit design tools, with Mentor in

particular contributing to our work on the CAD flow for 3D testability.

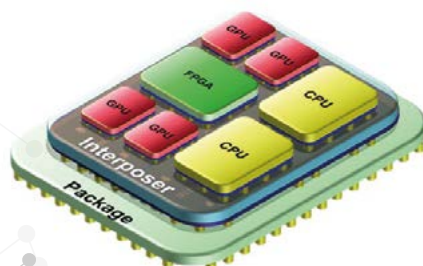
We came up with an architecture capable of supporting up to a thousand cores, improving the energy efficiency and performance of general-purpose computing. And, by using 3D technologies, we were able to bring costs down, add larger caches, and improve power delivery.

The research will feed into the EU Horizon 2020 European Processor Initiative to develop a processor for exascale-level European high-performance computing. The chiplet will be integrated onto an active interposer to build a 3D manycore processor. Later, as we move to finer pitches, we will need to develop new 3D stacking technologies like hybrid bonding. This could help achieve much higher 3D connection densities.

## RESEARCH PARTNERS: Pierre and Marie Curie University LIP6 Laboratory; STMicroelectronics; Mentor, a Siemens Business; EVG; SET

Further reading: • "A 29 Gops/Watt 3D-ready 16-core computing fabric with scalable cache coherent architecture using distributed L2 and adaptive L3 caches," ESSCIRC 2018-IEEE 44th European Solid State Circuits Conference (ESSCIRC). IEEE, 2018.  
E. Guthmuller, C. Fuguet, P. Vivet, C. Bernard, I. Miro-Panades, J. Durupt, E. Beigne, D. Lattard, S. Cheramy, A. Greiner, Q. Meunier, P. Bazargan Sabet.

• "Active Interposer Technology for Chiplet-Based Advanced 3D System Architectures," 2019 IEEE 69th Electronic Components and Technology Conference (ECTC). IEEE, 2019.  
P. Coudrain, J. Charbonnier, R. Vélard, A. Garnier, D. Lattard, P. Vivet, F. Ponthenier, T. Mourier, A. Farcy, J. Beltritt, D. Campos.





# Market news from our R&D partners

## CEA-Leti moves 3d sequential integration closer to commercialization

**SAN FRANCISCO – Dec. 4, 2018 –** Leti, a research institute at CEA Tech, has reported breakthroughs in six 3D-sequential-integration process steps that previously were considered showstoppers in terms of manufacturability, reliability, performance or cost.

CoolCube™, CEA-Leti's 3D monolithic or 3D sequential CMOS technology allows vertically stacking several layers of devices with a unique connecting-via density above tens of million/mm². This More Moore technology decreases dice area by a factor of two, while providing a 26 percent gain in power. The wire-length reduction enabled by CoolCube™ also improves yield and lowers costs. In addition to power savings, this true 3D integration opens diversification perspectives thanks to more integration of functions. From a performance optimization and manufacturing-enablement perspective, processing the top layer in a front end of line (FEOL) environment with a restricted thermal budget requires process modules optimization.



© CEA / Pierre Jayet

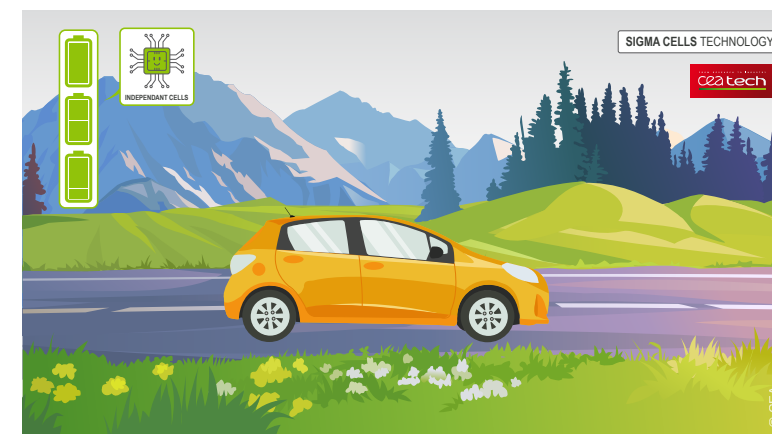


Learn more:  
<https://bit.ly/2DeV8RN>

## SIGMA CELLS AT CES: smart battery for electric cars, bikes, robots & smartphones powers on even when cell fails

**GRENOBLE, France – Dec. 5, 2018 –** The standard multi-cell battery has had a critical makeover: No longer will the battery fail if a cell fails.

CEA-Leti and CEA-Liten's Sigma Cells battery, which will be demonstrated at CES 2019 – CEA Tech booth - can be used for electric equipment ranging from laptop to an electric vehicle and is the world's first three-in-one battery solution with integrated inverter, charging and battery-management functions. This revolutionary technology serves as the battery's brain, governing the smart use of battery cells. If a cell is about to fail, Sigma Cells finds an alternative pathway, activating the "best" cells and, in the process, preventing downtime.



Learn more:  
<https://bit.ly/2QUgTOG>

## Weebit Nano and CEA-Leti to demonstrate brain-inspired neuromorphic demo

**18 July 2019 –** Weebit Nano (ASX: WBT), the Israel-based semiconductor company seeking to develop and commercialize the next generation of memory technology, and CEA-Leti, a global leader in miniaturization technologies enabling smart, energy-efficient and secure solutions for industry, will demonstrate a new neuromorphic demo able to perform precise object recognition tasks in an energy-efficient manner at Flash Memory Summit 2019.

Flash Memory Summit, held annually in Silicon Valley, is the world's premiere flash memory conference and expo. It showcases the mainstream applications, technologies, vendors and innovations in the multi-billion dollar non-volatile memory and SSD markets that include demanding enterprise storage applications, smartphones, tablets, and mobile and embedded systems.



Learn more:  
<https://bit.ly/2sc5z6a>





# 05

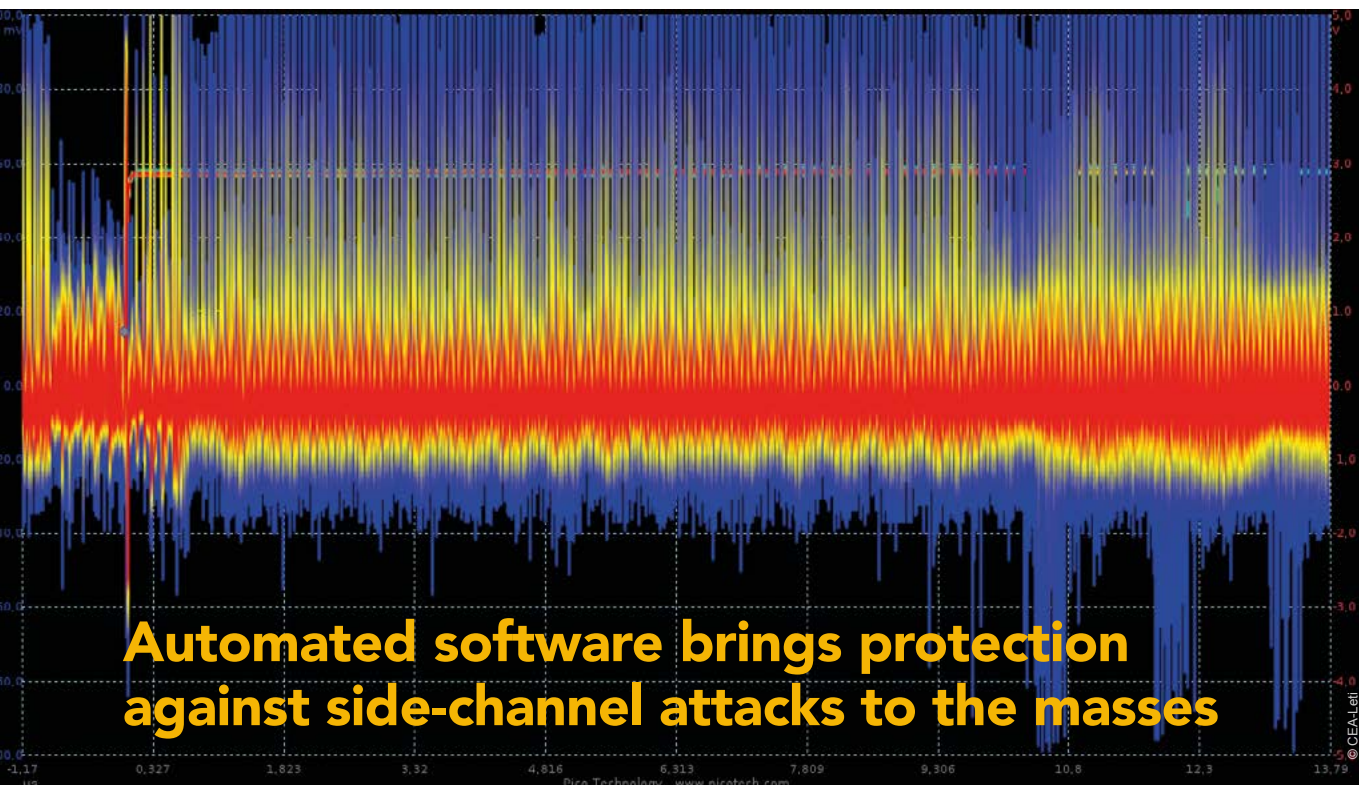
## Efficient, reliable interaction with complex systems

The digital world is now a tangible reality. Users are at the center of a brain-like ecosystem that offers virtually-zero-latency services, unlimited storage, and massive cognition capabilities. The widespread growth of this digital world will depend on the ability to efficiently connect humans, objects, machines, intelligence, and the environment and deliver reliable, resilient, and secure solutions.

Leti's research is at the center of the digital world. Our scientists have developed an ultra-fast imager for specific applications, multi-sensor fusion algorithms implemented on micro-controllers for the next generation in automotive perception, and a fully -automated generic compiler framework to protect software against side channel attacks. We are also working on IoT-empowered, robust low-capacity/long distance connectivity and innovative architectures for high-capacity/short distance communications. Finally, we are tackling the growing threat of cybersecurity to interconnected objects and their data, and on new security attacks and characterization tools.

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Electromagnetic signature of the execution of an AES encryption, with code polymorphism.

Damien Couroussé  
CEA-List scientist

#### THE BREAKTHROUGH:

A toolchain to automate the implementation of cybersecurity software to protect against side-channel attacks.

#### WHY IT MATTERS:

Demand for automated solutions to the problem of side-channel attacks against increasing numbers of electronic devices is high.

**NEXT STEPS:** Port the toolchain to the RISC-V architecture.

**Code polymorphism—the capacity of a program component to vary its observable behavior at runtime without altering its functional properties—effectively dissimulates information about a system’s physical properties from hackers trying to launch side-channel attacks. List has developed a toolchain to automate countermeasures against these attacks.**

In computer security, side-channel attacks gather information about a system’s physical parameters—power consumption, electromagnetic radiation emissions, execution times—and use the information to hack cryptographic algorithms. Many software and hardware countermeasures against side-channel attacks have been developed. However, most of them, like masking, are ad hoc and require additional development for the specific hardware or code they are designed to protect. Security components are now found in everything from computer bootloaders to household objects like light bulbs, creating a need for automated solutions to the problem of side-channel attacks that can be implemented anywhere.

We used code polymorphism to make a component’s behavior unpredictable to the attacker. Our work built on previous research conducted under two projects backed by the ANR (France’s national research agency): COGITO on runtime code generation to secure devices (2013-2017) and PROSECCO on formally-proven protections for secured compiled code (2015-2019). Here, we combined lightweight specialized runtime code generation with the optimization capabilities of static compilation to create a highly-configurable solution that can meet a variety of performance and security requirements. Test results showed that programs protected using this solution are very secure and meet the performance requirements of systems with very limited memory and processing power.

**RESEARCH PARTNERS:**  
Karine Heydemann, Associate Professor at the Sorbonne Université and Laboratoire d’informatique de Paris 6.

Further reading: • “Automated Software Protection for the Masses Against Side-Channel Attacks”, ACM Transactions on Architecture and Code Optimization (TACO), 2019. Nicolas Belleville, Damien Couroussé, Karine Heydemann, Henri-Pierre Charles.

## PROSE delivers fast, easy cybersecurity testing to IoT devices

Thomas Maurin,  
Laurent-Frédéric Ducreux  
Leti scientists

**IoT devices can be vulnerable to cyberattacks. The PROSE integrated and automated test suite makes assessing the security of IoT devices fast and easy, even for non-experts. As the IoT grows, the market will need secure devices—with the tests to prove it—in order to gain consumers’ trust.**

#### THE BREAKTHROUGH:

Automated, repeatable, reproducible cybersecurity testing for mainstream IoT products.

#### WHY IT MATTERS:

This innovative test bench addresses a crucial gap in the development of connected devices—security—that is essential to gaining consumers’ trust.

**NEXT STEPS:** Continue to work with IoT device manufacturers and analyze emerging cybersecurity threats to effectively update the test suites in PROSE.

The manufacturers of IoT devices have typically focused their development efforts on features, energy efficiency, and communication capabilities—this can be to the detriment of security. Today, the IoT is present in everything from consumer electronics to industrial equipment to medical devices, making it more pressing than ever to effectively address the security vulnerabilities of connected electronic devices that exchange data over interconnected networks.

We drew on Leti’s knowledge of cybersecurity and embedded software and systems and its broad experience assessing the security of shared and/or secure hardware and embedded software to develop a dedicated (PROSE) test bench in cooperation with certification organization Bureau Veritas. What makes PROSE so innovative is that it seamlessly integrates security test suites for heterogeneous

communication channels (Bluetooth LE, ZigBee, Wi-Fi, and TCP/IP) and uses black-box testing to look at how a system behaves without knowledge of the system’s structure. In addition, PROSE tests are repeatable and reproducible and do not require expert knowledge of cybersecurity.

PROSE is designed to be both scalable and customizable, making it simple to integrate new interfaces, test suites, and Common Vulnerabilities and Exposures (CVE) test cases as needed. In its current form it can be used to scan for vulnerabilities, check security compliance, and measure the security of any connected object’s communication channels—the first line of defense.

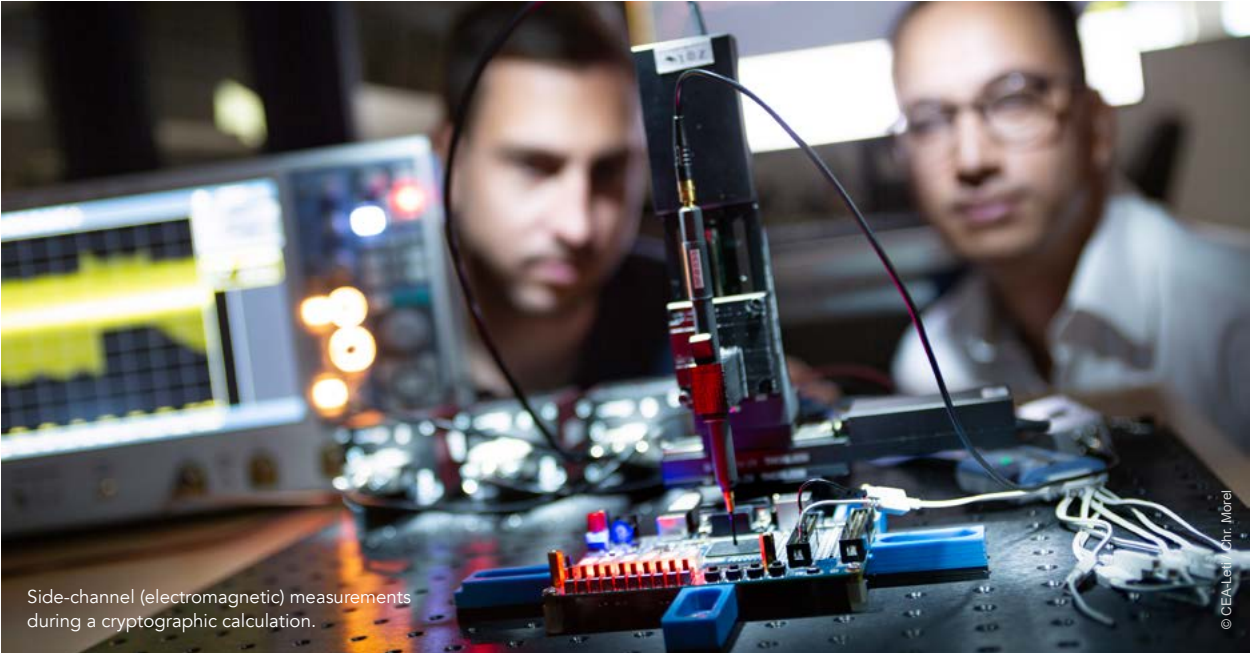
This solution is an example of the kind of tool and approach needed for emerging certification schemes as per the new European Cybersecurity Act.

**RESEARCH PARTNERS:**  
Bureau Veritas with LCIE and 7Layers.

Further reading: • “IoT security assessment through the interfaces P-SCAN test bench platform,” 2018 Design, Automation & Test in Europe Conference & Exhibition (DATE). Thomas Maurin, Laurent-Frédéric Ducreux, George Caraiman, Philippe Sissoko.







Side-channel (electromagnetic) measurements during a cryptographic calculation.

© CEA-Leti - J. M. Morel

# New Binary Edwards Curves provide IoT devices with “by design” protection against physical attacks

Antoine Loiseau,  
Jacques Fournier  
Leti scientists

**Elliptic Curves Cryptography is a fast, low-power, and secure technology capable of meeting the immediate security needs of the IoT—but only if it is inherently resistant to physical attacks.**

**THE BREAKTHROUGH:**  
New elliptic curves (Binary Edwards Curves) for asymmetric cryptography in IoT devices with limited computing resources.

**WHY IT MATTERS:**  
Low-power, high-performance cryptographic implementations for IoT devices will facilitate the widespread adoption of powerful cryptography to protect IoT systems.

**NEXT STEPS:**  
Improve the implementation of the technology to protect against new classes of side-channel attacks based on machine learning.

Elliptic Curves Cryptography (ECC) is perhaps best known for its recent use in the world of cryptocurrency. This type of cryptography, known as asymmetric, is utilized for public-key and digital signature protocols. Despite a rapidly-evolving environment shaped by advances in the mathematics that underpin elliptic curves and the advent of new physical attacks, ECC standards have remained pretty much the same for decades. In addition, ECC is computationally “slow” and does not meet the performance needs of IoT applications. To meet the growing security demands of the IoT and, specifically, the urgent need for fast, low-power, securely-implemented cryptography, we looked at a promising variation on elliptic curves: Binary Edwards Curves (BEC).

We drew on a broad range of know-how available at Leti to come up with a new set of Binary Edwards Curves capable of meeting the highest

security standards (284-bit security) and compatible with IoT devices with embedded 32-bit general-purpose processors. Specifically, we leveraged Leti’s expertise in algebra, number theory, and cryptography as well as knowledge of physical attacks like side channel and fault attacks. Leti’s expertise in embedding software on 32-bit processors was also crucial. Finally, Leti’s computing clusters were used to generate the new curves’ parameters. The BEC protocol developed offers the advantage of being intrinsically secure with regard to physical attacks.

We implemented the BEC protocol on RISC-V architectures. The next step will be to implement it on more mainstream ARM processors.

During the course of the research, we successfully tested a new type of attack based on machine learning for template analysis, which would suggest that new countermeasures are needed.

**RESEARCH PARTNERS:**  
N/A

Further reading: • “Binary Edwards Curves for intrinsically secure ECC implementations for the IoT,” *SECRYPT* 2018.  
Antoine Loiseau and Jacques J. A. Fournier.  
• “Méthode cryptographique sur courbes elliptiques binaires d’Edwards,” Patent: FR3071081, September 2017.  
Antoine Loiseau and Jacques J. A. Fournier.

# SIGMAFUSION™ brings real-time sensor fusion processing to automotive-certified Electronic Control Units for tomorrow’s autonomous vehicles

Tiana Rakotovoao  
Leti scientist

**Sensor fusion—crucial to automotive perception systems—is now compatible with the low-cost, low-power requirements of the automotive industry. SIGMAFUSION™ will make sensor fusion safer and tomorrow’s sensors smarter.**

**THE BREAKTHROUGH:**  
A patented mathematical and algorithmic framework for processing sensor fusion data in real time.

**WHY IT MATTERS:**  
SIGMAFUSION™ will make hardware and software integration safe, crucial to the future of automotive perception systems.

**NEXT STEPS:**  
Develop additional functions like free space assessment, safety zone estimation, and estimation of obstacle dynamics; make sensors “smarter” by increasing sensor/computing integration.

As autonomous vehicles gain traction, automotive perception systems are garnering increased interest from researchers and manufacturers alike. Crucial to safety, perception systems leverage sensors—LiDAR, radar, and cameras—to monitor the environment. Sensor fusion is used to process high-bandwidth data from these sensors in real time. However, until now, sensor fusion has only been implemented on desktops or high-end GPUs, which do not meet automotive safety requirements. To move autonomous vehicles forward, the automotive industry needs to bring these capabilities to low-cost, low-power hardware certified for automotive applications.

We developed SIGMAFUSION™, a patented mathematical and algorithmic framework that enables the real-time processing of sensor fusion on certified automotive Electronic Control Units (ECUs). We drew on Leti’s capacity to combine early-stage scientific research with

in-depth knowledge of embedded software and systems. Specifically, we were able to come up with a mathematical solution while factoring in the integration requirements of the target system. SIGMAFUSION™ can be integrated into low-cost, low-power automotive-certified hardware, where it enhances the safety of sensor fusion hardware and software integration.

We will now shift our focus to developing additional functions for tomorrow’s automotive perception systems with the goal of building a complete perception system based on SIGMAFUSION™. We will then move the system as close as possible to the sensors—enabling lower system costs and energy consumption. The closer the system is to the sensors, the “smarter” the sensors become: These smart sensors directly provide high-level information—like a kinematic analysis of obstacles in the environment—instead of raw data that must be processed to extract actionable information.



Further reading: • “General Inverse Sensor Model for Probabilistic Occupancy Grid Maps Using Multi-Target Sensors,” in *Proceedings of the Third International Symposium on Mathematical Theory of Networks and Systems (MTNS)*, 2018.  
R. Dia, S. Lesecq, J. Mottin, D. Puschini.  
• “Evaluation of Occupancy-Grid Resolution through a Novel Approach for Inverse Sensor Modeling,” 20th IFAC World Congress, 2017.  
R. Dia, J. Mottin, T. Rakotovoao, D. Puschini, S. Lesecq.



# Compact digital burst-image sensor delivers high frame rate, substantial storage, and energy efficiency

Laurent Millet  
Leti scientist

By doing away with the analog capacitances traditionally used to store burst-image sensor data, Leti researchers are enabling higher performance slow-motion video capture—a boon to research and industry.

**THE BREAKTHROUGH:** First-ever burst-image sensor with integrated digital storage.

**WHY IT MATTERS:** At five million frames per second, this advance will enable new analysis capabilities for research and enhance industrial productivity.

**NEXT STEPS:** Increase the sensor's frame rate and storage capacity.

Slow-motion video capture is useful in both research and industrial environments. It can be employed to observe and analyze high-speed physical events like cracks propagating or bubbles bursting, as well as in the study of plasma. Currently, however, the length of slow-motion video footage—captured at frame rates in excess of several millions images per second—is limited to what can be stored in memory embedded in the sensor.

We designed a novel 3D stacked burst-image sensor with integrated digital storage. This is the first-ever digital burst imager. Our innovation allows the use of digital memory like RAM, which is more compact than analog capacitance-based storage and provides much better immunity to parasite effects like signal leakage or photo-current reaching analog memory.

In conventional sensors the analog capacitances are either inside the pixel, where storage capacities—and thus video length—are restricted by space, or outside the pixel in peripheral memory. Peripheral memory offers more space, but creates data transmission issues that limit the frame rates of larger sensors. This architecture is also plagued by high power consumption.

Leti's multi-layer design, simulation, and verification capabilities and hybrid bonding technology positioned us to use 3D stacking: We designed a matrix of 50 μm x 50 μm photodiodes with a fill factor of 80% on the top tier, a per-pixel readout and ADC circuit to perform high-speed conversion, and data storage in the bottom tier.

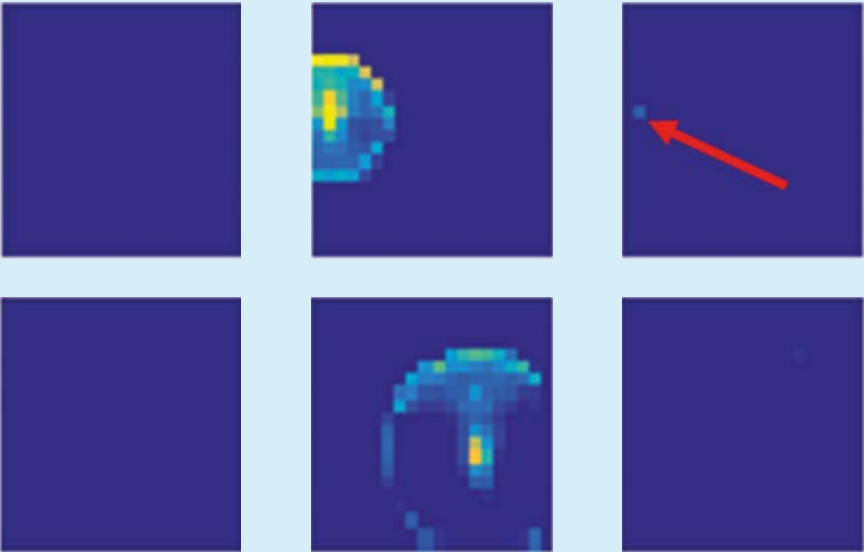
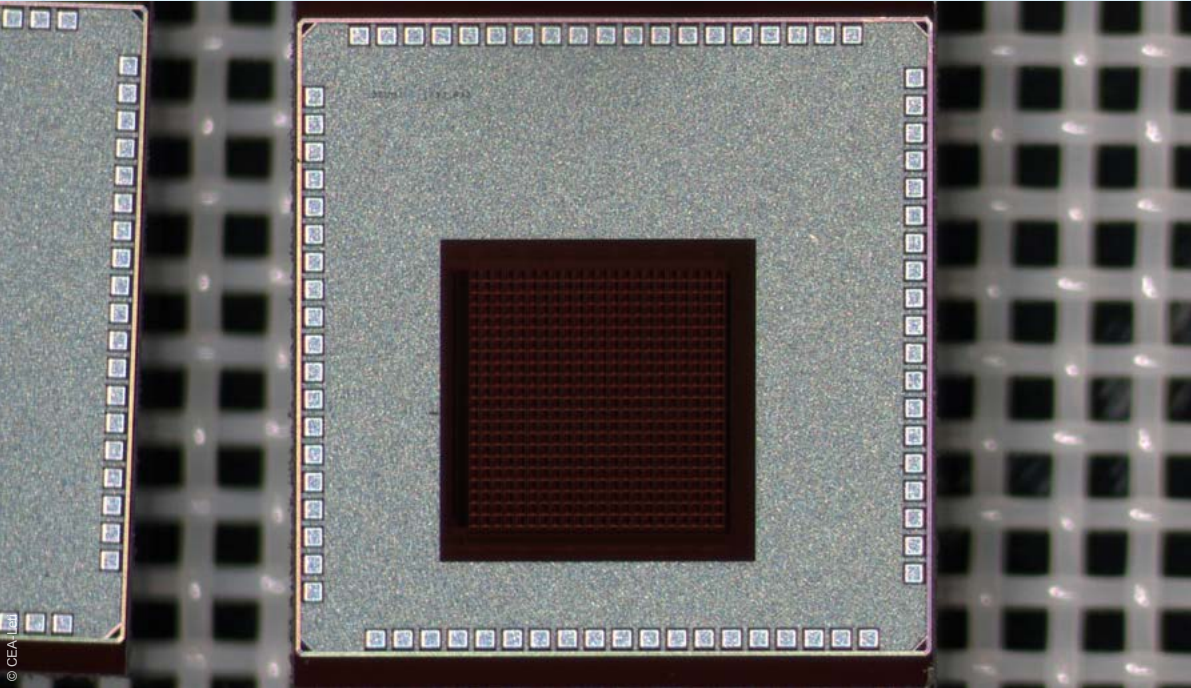
We completed an initial prototype and are now investigating ways to increase the sensor's frame rate and storage capacity—possibly by using digital signal compression.

**RESEARCH PARTNERS:** STMicroelectronics (imaging and advanced digital node); Icube (testing and optical characterization).

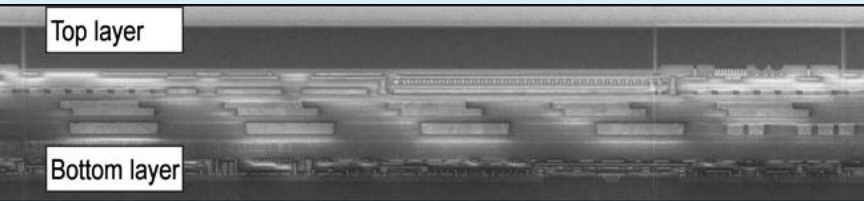
Further reading: • "A 5 Million Frames Per Second 3D Stacked Image Sensor with In-Pixel Digital Storage," IEEE ESSCIRC Conference 2018.

L. Millet, M. Vigier, G. Sicard, N. Margotat, F. Guellec, S. Martin, W. Uhring.

Microchip of the 3D stacked burst image sensor.



Two 3-frame sequences to evaluate beam persistence on A-type and B-type pixels, showing a small persistence on the A-type pixel.



Pixel cross-section detail, with the photodiode and readout circuits (top) and memories (bottom).





François Dehmas,  
Florian Wolf,  
Sébastien de Rivaz  
Leti scientists

## “Virtual” bandwidth brings precision radio positioning to IoT

**One of the challenges to radio-based positioning technology is a narrow bandwidth that limits ranging and, therefore, precision. Leti researchers came up with a novel solution for increasing bandwidth that delivers positioning accurate to within 10 meters.**

### THE BREAKTHROUGH:

A ranging estimation protocol and algorithm accurate to within 10 meters with a LPWA physical layer.

### WHY IT MATTERS:

This advance will create new opportunities in IoT and, especially, low-power indoor and outdoor positioning systems.

### NEXT STEPS:

Improve performance in harsh environments with multiple antennas.

Powerful positioning systems can bring a number of enhancements to IoT devices and open the door to completely new applications, from asset tracking and smart city solutions to wildlife, livestock, and environmental monitoring. Our research at the Smart Objects Communication Laboratory includes low-power wide-area (LPWA) networks and, specifically, radio-based positioning technology. One of the challenges presented by LPWA networks is the use of a narrow-band signal, which makes precise positioning difficult.

We developed a solution that exchanges a series of packets over different frequencies resulting in a

“virtual” bandwidth increase. And larger bandwidth means better ranging and positioning. Specifically, we determined the specifications for the physical layer in the target system, developed algorithms to receive the RF signal, and tested the system’s performance using a software-defined hardware platform modified for the experiment.

Our solution performed 20 times better than conventional time-based ranging, corresponding to a level of accuracy of around 10 meters. Now that our solution has been tested, we plan to explore multi-antenna systems that could improve ranging precision in harsh environments.

### RESEARCH PARTNERS:

Part of PhD research conducted by Florian Wolf, supervised by Jean-Pierre Cances of the University of Limoges.

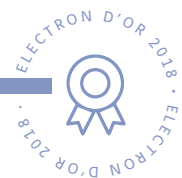
Further reading: • “Improved multi-channel ranging precision bound for narrowband LPWAN in multipath scenarios”, IEEE Wireless Communications and Networking Conference (WCNC), 2018.

Florian Wolf, Christophe Villien, Sébastien de Rivaz, François Dehmas, Jean-Pierre Cances.

• “Coherent Multi-Channel Ranging for Narrowband LPWAN: Simulation and Experimentation Results”, IEEE 15<sup>th</sup> Workshop on Positioning, Navigation and Communications (WPNC), 2018.

Florian Wolf, Jean-Baptiste Doré, Xavier Popon, Sébastien de Rivaz, François Dehmas, Jean-Pierre Cances.

## UNB transceiver wins top French electronics award in Connected Objects and Smart Buildings category



Leti scientist David Lachartre won an *Electron d'Or* (Gold Electron) award from French scientific journal *Electroniques* at a ceremony held on June 26, 2018 in Paris. The award, in the “Connected Objects and Smart Buildings” category, was presented by Frédéric Gilbert, who heads the French Directorate General for Enterprise Nanoelectronics Bureau. It recognized the contributions of Lachartre and his team\* to ultra-narrowband communications and, specifically, the development of an ultra-narrowband CMOS 65 nm transceiver for SigFox. The device solves several of the technical challenges that affect ultra-narrowband signaling: It is resistant to CFO offsets and drifts of  $\pm 75$  Hz (i.e. 150% of the 100 Hz channel) and 35 Hz/s, respectively, with sensitivity losses of just 1 dB, allowing the circuit to function without a TCXO. In DBPSK 100 b/s transmission mode, an error vector magnitude (EVM) better than 5% was measured for output powers up to 10 dBm. For Lachartre, the award is proof that years of teamwork with his Leti colleagues has paid off.



## 5G field tests at MINATEC and in Scotland confirm benefits of novel approaches

Jean-Baptiste Doré  
Leti scientist

**Leti is staying ahead of the state of the art in 5G telecommunications by developing new waveforms to enable multi-service scenarios. The institute drew on know-how covering the entire wireless transmission chain to successfully complete groundbreaking 5G field tests.**

### THE BREAKTHROUGH:

New insights into the entire wireless transmission chain spanning digital, analog, and antenna signal processing.

### WHY IT MATTERS:

5G telecommunications will be a key enabler on markets from the Factory of the Future to cars; the technology will be the silicon industry’s main growth driver.

**NEXT STEPS:** Explore new bands from millimeter-wave to THz to optical and new network paradigms including non-terrestrial access, satellite networks, and vehicular communications.

Tomorrow’s 5G access network will utilize spectrally-efficient waveforms and new (or new ways of using) spectra. In terms of waveforms, our research built on earlier work on filtered waveforms to develop a new BF-OFDM waveform to enable multiple-in, multiple-out (MIMO) communications with good frequency-localized waveforms. A thorough comparison of the waveforms proposed for 5G showed the interest of our proposed waveform for application to 5G services (very high bandwidth, low-latency communications and IoT). Our waveform was also implemented and deployed on the MINATEC campus, and the experiment confirmed the coexistence of the three types of services without using guard bands between the spectra allocated to the different services.

From a spectrum usage perspective, we completed design and implementation work on a communication system using the

unlicensed 5 GHz band to maximize throughput by aggregating carriers. Similarly, building on earlier cognitive radio research, the use of the BF-OFDM waveform in the 700 MHz band was studied for high-speed and long-range communications. A transmission, performed on a fragmented spectrum, was tested in Scotland at 700 MHz, where a range of 20 km was achieved.

Finally, we also explored millimeter waveforms, studying communication systems for terrestrial or satellite backhaul links in the 26 GHz to 28 GHz band. We kicked off a study of new architectures and modulations dedicated to the so-called sub-THz spectrum (90 GHz to 300 GHz) to fuel the design of communication systems that are inherently robust to spectral increase related to phase noise.

Some of this work has reached the prototyping stage, bringing us a major step closer to real signal experiments and commercialization.

### RESEARCH PARTNERS:

Supervision of a PhD candidate at CNAM Paris.

Further reading: • “Block-Filtered OFDM: A new promising waveform for multi-service scenarios”, Proc. IEEE International Conference on Communications (ICC), 2017.

Best paper award, wireless symposium.

Robin Gerzaguet, David Demmer, Jean-Baptiste Doré, Dimitri Kténas.

• “5G Multi-Service Field Trials with BF-OFDM”, IEEE Globecom Workshops, 2017.

Robin Gerzaguet, Simon Bicaïs, Patrick Rosson, Jeremy Estavoyer, Xavier Popon, David Dassonville, Jean-Baptiste Doré, Benoît Miscopein, Manuel Pezzin, David Miras, Dimitri Kténas.



# Market news from our R&D partners

## CEA's precise localization technology boosts quality control and efficiency in Desoutter's products

**GRENOBLE, France – June 26, 2019** – Desoutter Industrial Tools and CEA-Leti today announced a precise, new indoor-location system that enables factories to monitor tools in real time and help manage their use by workers to improve efficiency, safety, security and quality control on assembly lines.

Based on a CEA-Leti algorithm, embedded receptor architecture and ultra-wide-band (UWB) technology, the system has been optimized and customized for a variety of essential factory-floor jobs supported by Desoutter, a global leader in industrial electric and pneumatic assembly tools and other equipment. Easy to use deployment efforts have been significantly reduced with optimized automated functions compared to competing systems.



[Learn more:](https://bit.ly/33o3L6Y)  
<https://bit.ly/33o3L6Y>

## CEA-Leti & Radiall to design innovative RF components for 5G networks and photonics components for harsh environments

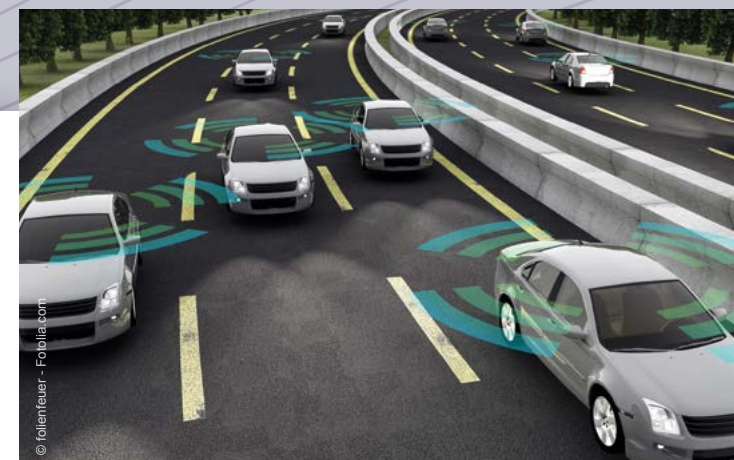
**GRENOBLE, France – June 26, 2019** – Leti, a research institute of CEA Tech, and Radiall, a global manufacturer of leading-edge interconnect solutions, announced a five-year common lab to design innovative antennas, radio frequency (RF) to meet infrastructure requirements of 5G networks and photonics components for harsh environments.

Announced during Leti Innovation Days in Grenoble, the common lab will develop low profile, millimeter-wave antenna solutions for backhaul/fronthaul applications. 5G networks require high-speed, point-to-point communication at millimeter-wave frequencies. The explosive increase in ultra-dense 5G infrastructure systems required to accommodate high-speed mobile data traffic and Internet of Things data is fueling a demand for low-cost, robust and reliable RF subsystems. These include compact and reconfigurable antennas that can be integrated on urban buildings and street furniture with minimal deployment cost.

[Learn more:](https://bit.ly/2DffKJE)  
<https://bit.ly/2DffKJE>

## CEA-Leti & EFI Automotive launch project to improve reliability and speed of low-cost electronic devices for autos

**GRENOBLE and BEYNOST, France – Sept. 18, 2018** – Leti, a research institute of CEA Tech, and EFI Automotive, a leading international supplier of sensors, actuators and embedded smart modules for the automotive industry, today announced a project to dramatically improve reliability and response time of low-cost automotive components by equipping the devices with sophisticated model predictive control techniques.



Model predictive control (MPC) is an advanced method of process control that makes use of a model of the system to predict its behavior. The control law is based on an optimization technique that computes the system inputs, taking into account the reference that the system output has to follow, together with the effort (energy) that is applied on the system inputs and some constraints that may exist within the system, typically saturation of the system inputs.

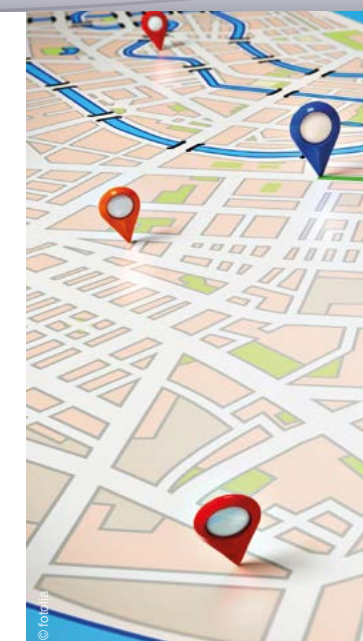
[Learn more:](https://bit.ly/2KTLmIM)  
<https://bit.ly/2KTLmIM>

## CEA-Leti and Orolia announce FlexFusion, a powerful positioning & navigation technology

**GRENOBLE, France – June 26, 2019** – Leti, a research institute of CEA Tech, and Orolia, a leader in accuracy and performance for terrestrial, aeronautic and naval transportation positioning, navigation & timing applications, today announced a new sensor-data-fusion engine that ensures resilient positioning and navigation even in cases of global navigation satellite system (GNSS) jamming or spoofing.

Called FlexFusion, the algorithm technology processes data from GNSS, inertial management units (IMU) and odometers to provide precise positioning in all conditions.

[Learn more:](https://bit.ly/2XLt5Tq)  
<https://bit.ly/2XLt5Tq>





# People

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## Awards



### High-density memory research wins Best Poster Award at NVMTS2018 in Japan

Leti PhD candidate **Rana Alhalabi** won the Best Poster Award at the 18<sup>th</sup> Non-Volatile Memory Technology Symposium in October 2018 in Sendai, Japan. This high-level international event brings together leading memory technology experts to discuss the state of the art in FLASH, FeRAM, PCRAM, RRAM, and MRAM. The award-winning poster presented the development of a high-density SOT-MRAM memory array using a single transistor by Alhalabi and her team\*. They replaced one of the usual two transistors with a unidirectional diode. This improved the area density by 20% and required less control logic, making the array suitable for high-density memory architectures. Alhalabi, who is investigating logic circuits and memory design with Spintec and Leti, came to the CEA to pursue her PhD after completing a Master's degree in Nanoelectronics and Nanotechnology at Grenoble-Alpes University.

\*Etienne Nowak, Ioan-Lucian Prejbeanu, and Gregory di Pendina

### ERC Consolidator Grant will drive advances in in-memory computing at Leti



European Research Council Consolidator Grants provide investigator-led funding to mid-career researchers with the goal of boosting the impact of their work and, ultimately, fueling innovation in Europe. Leti scientist **François Andrieu**, who leads the institute's advanced CMOS lab, was awarded a Consolidator Grant in 2018 for his My-CUBE project on 3D integration of a logic/memory cube for in-memory computing. His research will leverage non-volatile resistive memory, new energy-efficient nanowire transistors, and 3D monolithic technology to develop a functionality-enhanced system with advanced integration of logic and memory. The capacity to bring logic to memory/storage will be a game changer for artificial intelligence, machine learning, data analytics, and any data-abundant computing system. More broadly, it will serve as a key computational kernel for the next generation of low-power, energy-efficient integrated circuits developed in Europe. Just 12% of the proposals received by the ERC were selected for funding in 2018, proof that Leti research is at the head of the class in Europe.



### Leti engineer helps bring greater safety to the visually impaired

The Design Automation Conference (DAC) has been bringing the IC chip design and design automation community together for five decades. Held in San Francisco, DAC 2018 featured sessions on design, of course, but also on embedded software and systems and automotive technology, security and privacy, IoT, design infrastructure, and smart systems. Leti engineer **Olivier Debicki** brought home the 2018 Designer Track Best Presentation Award for his talk on the EU H2020 project INSPEX, which applies multi-sensor obstacle detection technologies originally developed for automotive applications to navigation for the visually impaired. The CEA's SigmaFusion<sup>TM</sup> sensor fusion technology was used to develop a model of the environment from LiDAR, radar, and ultrasound sensors on a white cane, effectively creating a buffer zone to keep the user safe. Assisted living solutions for the disabled are not something you encounter every day at tech conferences. The entire project team can be proud not only of the award, but also of contributing to a project that will make a positive impact on the lives of the visually impaired.

**"Integrated Portable Multi-sensor Obstacle Detection Device. Application to Navigation for Visually Impaired People."**

Olivier Debicki, Nicolas Mareau, Laurent Ouvry, Julie Foucault, Suzanne Lesecq, Gabriela Dudnik, Marc Correvon.

### Nanocharacterization platform contributes to tomorrow's non-volatile memory



The latest advances in materials science were spotlighted at the European Materials Research Society's E-MRS 2018 Spring Meeting in Strasbourg, France. E-MRS meetings stand out for their multidisciplinary philosophy and international positioning. The organization also actively supports innovation and achievement through awards, one of which went to **MunIQUE Kazar Mendes**, who was completing her PhD at Leti at the time of the award. She came in second in the Solid State Ionics Symposium Best Poster competition for her research on the electrochemistry of resistivity changes in Te-based conductive-bridge memories. The overriding purpose of her work is to pave the way for conductive bridge resistive memories (CBRAMs), currently in the running for the next generation of non-volatile memory. Kazar Mendes came to Grenoble from Brazil to complete her Master's in Electrochemistry at Grenoble Institute of Technology (2015) and her PhD at Leti (2018). Her thesis on subquantum resistive memories investigated the electrochemical reactions and ionic transport involved in resistive switching. According to Kazar Mendes, the Nanocharacterization Platform's ability to perform advanced analyses of complex structures like resistive memories helped position her research as a major contribution to the development and optimization of this technology.

**"Electrochemistry of resistivity changes in Te-based conductive-bridge memories."**

MunIQUE Kazar Mendes, Eugénie Martinez, Olivier Renault, Rémy Gassilloud, M. Bernard, J.M. Ablett, N. Barrett.



## Awards



### Novel research on nanopillar growth wins student award at international conference

The Americas International Meeting on Electrochemistry and Solid State Science (AiMES 2018), a joint conference of the 234<sup>th</sup> Meeting of the Electrochemical Society (ECS) and the XXXIII Congreso de la Sociedad Mexicana de Electroquímica (SMEQ) was held in Cancun, Mexico. AiMES meetings provide a valuable opportunity for researchers from government labs, academic institutions, and industry to share their latest results in a unique environment at the crossroads of electrochemical and solid state science. **Marouane Mastari** won the Best Student Presentation Award at the SiGe, Ge, and Related Compounds: Materials, Processing, and Devices Symposium for his research on the coalescence of SiGe nano-pillars. Mastari took advantage of the wide range of state-of-the-art resources at Leti to characterize SiGe pillars grown on a SiO<sub>2</sub> based nano-template at different stages of the coalescence process. This type of characterization at the very early stages of growth had not been done previously, and the insights gained could help improve semiconductor-industry processes.

#### "Nano-Heteroepitaxy: An Investigation of SiGe Nano-Pillars Coalescence."

Marouane Mastari, Matthew Charles, Yann Bogumilowicz, Patricia Pimenta-Barros, Maxime Argoud, R. Tiron, Anne-Marie Papon, Denise Muiyard, Nicolas Chevalier, Didier Landru, Youngpil Kim, Jean-Michel Hartmann.

### International junction technology community recognizes Leti advances in materials

Leti research won one of two Best Paper Awards at the 19<sup>th</sup> International Workshop on Junction Technology 2019. IWJT is a high-level international event showcasing the latest advances in research on junction formation technology for semiconductor applications. Leti's **Philippe Rodriguez** and his team explored the impact of alloying elements Co and Pt on Ni-based contact technology with the goal of increasing the thermal stability of Ni-GeSn contacts. In particular, they studied the effects on the solid-state reaction and on surface roughness and electrical properties. Rodriguez attributes the win to the relentless determination, investment, and talent of PhD candidate **Andrea Quintero**, who joined Rodriguez's team in April 2017. Rodriguez was in good company at IWJT: the other Best Paper Award went to acclaimed international advanced materials scientist Sigefusa Chichibu of Tohoku University.

#### "Effects of alloying elements (Pt or Co) on nickel-based contact technology for GeSn layers."

Andrea Quintero, Patrice Gergaud, Jean-Michel Hartmann, Vincent Reboud, Eric Cassan, Philippe Rodriguez.



### Leti and STMicroelectronics support award-winning PhD research

The SPIE Advanced Lithography conference is the leading global lithography event, showcasing a comprehensive lineup of lithography and patterning topics crucial to the future of many technologies. **Charles Valade** brought home the Karel Urbanek Best Student Paper Award, sponsored by KLA Corporation, from the 2019 SPIE Advanced Lithography conference (Metrology, Inspection, and Process Control for Microlithography session) in San Jose, California. Valade, who is currently completing his PhD in 3D SEM computational metrology with Leti's Computational Lithography Group and STMicroelectronics' Resolution Enhancement Techniques team, developed a model to improve the 3D reconstruction of images captured using tilt-beam SEM. The results were coherent with conventional 3D measurement techniques and reliable reconstructions on patterns of various heights were completed using a single calibrated model. This award is proof that the kind of cooperation between scientific research and industrial R&D that Leti is known for is an effective strategy. As a young researcher at Leti, Valade is already making a name for himself in the international lithography community.

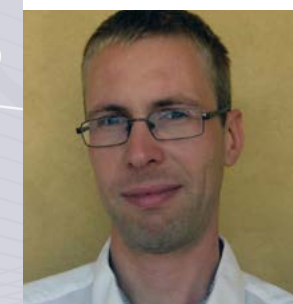
#### "Tilted beam SEM, 3D metrology for industry."

Charles Valade, Jérôme Hazart, Sébastien Bérard-Bergery, Elodie Sungauer, Maxime Besacier, Cécile Gourgon.



### Grenoble's quantum computing ecosystem earns recognition from the European Research Council

Leti's **Maud Vinet**, IRIG's Silvano De Franceschi, and Institut Néel's Tristan Meunier won a European Research Council (ERC) Synergy Grant for their QuCube project to develop a quantum processor. The award-winning principal investigators' home institutions will receive ERC funding of up to €14 million over a maximum of six years starting in 2019. The team will pursue their groundbreaking work scaling up the single Si CMOS qubit they developed in 2016. To do so, they will draw on the wide array of interdisciplinary skills available in Grenoble's renowned sci-tech community. Leti will provide access to VLSI technology and vertical CMOS integration at the nanoscale. IRIG, which has been studying the quantum properties of Leti devices for fifteen years, will contribute knowledge of the physics of electrons. Finally, Institut Néel, which has been a pioneer since the early days of electron spin qubits, will bring expertise in electron spin qubit manipulation in semiconductors. For Vinet, the ERC Synergy Grant will provide an opportunity to broaden her scientific scope and, especially, collaborate with basic research scientists.



### Leti PhD candidate breaks new ground in positioning technology for IoT applications

The 2018 15<sup>th</sup> Workshop on Positioning, Navigation and Communications (WPNC) brought together stakeholders spanning industry and academia to discuss hot tech topics like IoT, Industry 4.0, autonomous vehicles, and 5G communications. **Florian Wolf**, a PhD candidate at Leti, received the WPNC Best Paper Award for research that could lead to an alternative to Global Navigation Satellite System positioning for a wide range of IoT applications. The joint award recognized research Wolf conducted with Jean-Baptiste Doré, Xavier Popon, Sébastien de Rivaz, François Dehmas (Leti), and Jean-Pierre Cances (the University of Limoges) on a new location technique that utilizes phase-coherent multi-channel processing of narrowband signals. According to Wolf, Leti's capacity to innovate at all stages, from theoretical research through to proof-of-concept implementations, was instrumental in this award-winning work.

#### "Coherent Multi-Channel Ranging for Narrowband LPWAN: Simulation and Experimentation Results."

F. Wolf, J.-B. Doré, X. Popon, S. de Rivaz, F. Dehmas, J.-P. Cances.





# Management



**Emmanuel Sabonnadière**  
Chief Executive Officer



**Jean-René Lèguepeys**  
Deputy Director - Chief Technology Officer  
Head of the Architecture and IC Design Embedded Software Division



**Ludovic Poupinet**  
Deputy Director - Chief Operating Officer



**Laurent Clavier**  
Executive VP – Chief Platform Officer  
Head of the Technical Platform Division



**Thomas Ernst**  
VP for Science and Technology



**Laurent Hérault**  
VP for Europe



**Éric Dupont-Nivet**  
VP for Institutional Relations



**Olivier Faynot**  
Head of the Silicon Components Division



**Agnès Arnaud**  
Head of the Optics and Photonics Division



**Sébastien Dauvé**  
Head of the Systems Division



**Patrick Chaton**  
Head of the Health Division



**Jean-Claude Royer**  
Head of Clinathec



**Catherine Ogier**  
Communications Manager



**Hughes Metras**  
IRT Nanoelec



**Carlo Reita**  
Director, strategic partnerships and planning, CTO office



**Michael Tchagaspian**  
Executive VP Sales & Technical Marketing



**Thomas Signamarcheix**  
VP Strategic development, CTO office



**Fabrice Geiger**  
Head of Investment and Supplier Partnership Group



**Thierry Bosc**  
Clinathec Endowment Fund



**Philippe Ruffin**  
Startup Program Manager



# PhD research at Leti

Leti, a partner of Grenoble-Alpes University, welcomes young scientists with a passion for research and a desire to advance knowledge and make a positive impact on society. PhD students from around the world come to Leti for the opportunity to embrace disruptive scientific inquiry and develop breakthrough concepts for real-world applications.

At Leti, PhD students work alongside some of the best minds in science and collaborate with global tech companies in an international environment. And, as the following testimonials from past and current Leti PhDs show, their experiences are as diverse as our research.

## Advanced materials research for future-generation CMOS devices



After completing a graduate degree in engineering, **Léa Dagault** was seeking a PhD opportunity that would allow her to pursue her growing interest in semiconductor materials. She wanted to do lab research, but in an environment with close ties to the microelectronics industry. Leti was the perfect match.

Nanosecond laser annealing is a fairly new method that brings the surface of a material to very high temperatures while maintaining the rest of the material at a low temperature, making it a promising option for future generations of CMOS devices. Leti PhD candidate Léa Dagault is investigating the formation and origins of defects in laser-annealed SiGe layers and the electrical activation and deactivation of dopants in SiGe layers subjected to nanosecond laser annealing. Depending on her findings, her research could contribute to the development of devices with laser-annealed SiGe.

Today, Dagault is taking advantage of the wide range of characterization equipment and multidisciplinary experts available at Leti to further her PhD research. And, because her research is co-supervised by a Leti scientist and a scientist from CNRS LAAS (the French National Research Agency's Laboratory for Systems Analysis and Architectures), she is able to address her work from basic and applied research perspectives. Dagault sees her future in new energy technologies. After she completes her PhD, she would like to move into R&D in a field that supports the energy transition, such as electronic-waste recycling or solar energy.

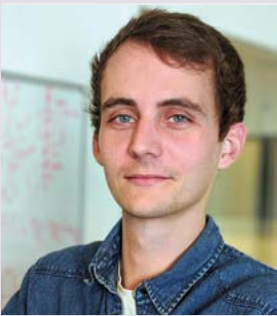
"I came to Leti for the wide range of materials characterization methods and expertise available, and what I found here lived up to my expectations!"



### LETI ADVANTAGES

- Co-supervision of PhD research by Leti scientist and CNRS scientist to address both fundamental physics and application-driven approaches
- Access to a wide range of advanced characterization equipment and multidisciplinary experts

## Interdisciplinary research for tomorrow's quantum computers



**Loïck Le Guevel** is currently doing his PhD research at Leti, where he is designing cryogenic-proof CMOS circuits fabricated at STMicroelectronics through CMP Grenoble, testing them on state-of-the-art equipment at CEA basic research lab LaTEQS, and applying them to co-integrated quantum devices like qubits. Leti's far-reaching research capabilities are preparing Le Guevel for a bright future in quantum computing.

After studying quantum mechanics and completing an internship in quantum information theory, Loïck Le Guevel was seeking an interdisciplinary environment for his PhD research. Leti fit the bill, providing opportunities for Le Guevel to deepen his knowledge of integrated electronics, industrial R&D, and CMOS fabrication processes. Today, he is working with scientists at Leti and IRIg who, together, cover all aspects of the fabrication, characterization, and study of FDSOI qubits.

Leti's partnerships have been particularly beneficial to Le Guevel's research. The circuits are designed at Leti department DACLE, co-integrated with quantum devices made at Leti department DCOS, and tested at IRIg—a level of coordination made possible by Quantum Silicon Grenoble, of which Leti is a member.

After he completes his PhD, Le Guevel would like to stay in research and be part of developing a quantum computer. Specifically, he would like to focus on new solutions like cryogenic electronics toolboxes, electronics-friendly cryogenic setups, and new readout processes and multiplexing schemes assisted by cryogenic electronics.

"Access to IRIg's state-of-the-art cryostats to test our circuits is exceptional in the field of microelectronics."



### LETI ADVANTAGES

- The availability of knowledge in virtually any field
- Experts willing to help with development processes and new platforms
- Opportunities to participate in Leti partnerships like Quantum Silicon Grenoble



From insect brains to advanced circuits



**Thomas Dalgaty** came to Leti to do his PhD research by chance—or maybe it was serendipity. A Leti partnership with researchers in Zurich is what ultimately led Thomas to Grenoble. Today, he is investigating technologically-plausible, insect-inspired neuromorphic computing at an institute with multidisciplinary know-how that has expanded his scientific horizons.

“The next computing revolution will be at the crossroads of technological plausibility, machine learning, and brain-inspired concepts, and I would like to be a part of it.”

With research at the interface between electronics, machine learning, and computational biology and day-to-day tasks that range from laying out circuits to performing electrophysiological analyses on crickets—PhD candidate Thomas Dalgaty’s work is nothing if not varied!

After earning his undergraduate and graduate degrees in Electronics Engineering with a focus on analog circuit design and machine learning at the

University of Glasgow and completing his Master’s thesis at ETH Zurich, Dalgaty came to Leti to conduct research for his PhD in neuromorphic computing and, specifically, to work on an advanced circuit design project. He didn’t know much about Leti then, but, after speaking with Leti scientists Elisa Vianello and Barbara de Salvo, he was won over by the multidisciplinary nature of the project and the opportunity of producing some innovative research.

While at Leti, Dalgaty has gained experience designing on a special wafer made by STMicroelectronics using standard CMOS processes, and then sent to Leti for integration of the resistive memory technology—something he feels he would not have had the opportunity to do elsewhere. He has also worked with Leti scientists in fields outside his own, like MEMS and cryptography.

Today, Dalgaty is fiercely passionate about what he does. He is starting to develop his own ideas about neuromorphic computing as a whole and fully intends to stick around to help shape the next big revolution in computing.

LETI ADVANTAGES

- Access to multidisciplinary know-how
- The ability to develop large-scale processes and implement them on chips using technologies not available elsewhere
- French language classes
- A high-quality living environment with a variety of mountain and outdoor activities

Former Leti PhD right at home at medtech startup



**Julie Oziat** knows how to seize opportunities when they arise. In fact, that’s exactly how she came to Leti for her PhD. After completing a student internship at DTBS, the CEA’s Department of Technology for Biology and Health, she knew she wanted to do research, and the CEA’s environment appealed to her. When another PhD candidate withdrew at the last minute, Oziat jumped right in.

Electrochemistry is not a very common topic in medtech R&D. But Julie Oziat found a home for her somewhat unusual PhD research—using an electrode to identify bacteria—at Leti. Her unique approach entailed growing bacteria in a specially-developed macroporous electrode. The electrode captures the electrochemically-active molecules that bacteria produce to communicate with each other. These molecules can then be used to identify the strains of bacteria present.

From developing the electrode to coming up with a protocol to detect the electrochemically-active molecules, Oziat found the support she needed among Leti’s interdisciplinary team at every stage of her project. After her PhD Oziat was very rapidly hired by medtech startup Bioserenity in February 2017 for a newly-created position. The fast-growing company develops and commercializes connected textiles for medical diagnostics. Oziat is doing R&D on the electrodes used to gather electrophysiological signals (ECG, EEG, EMG, etc.) in all of Bioserenity’s systems.

“During my PhD I learned about scientific methods and, more generally, how to conduct research. This has given me the confidence to hit the ground running in my new position at a medtech startup.”

LETI ADVANTAGES

- Access to multidisciplinary know-how and the wider CEA ecosystem (DSV, Cinatec, CEA List, CNRS labs at Grenoble-Alpes University)
- A big-picture view of the innovations being developed in Grenoble with lab meetings, MINATEC lunch talks, and the CEA Tech showroom.
- Experience relevant to conducting R&D for a medtech startup.

Leti is home to some of the greatest minds in microelectronics



Although he admits that he didn’t fully realize it back when he was a student, **Pierre-Emmanuel Gaillardon** rubbed shoulders with some of the world’s leading microelectronics researchers during his PhD at Leti. Now an Associate Professor at the University of Utah with two startups under his belt, Gaillardon looks back on the experience that helped start his very active and successful career.

Pierre-Emmanuel Gaillardon came to Leti to conduct his PhD research on reconfigurable logic architectures based on disruptive technologies. He took away much more, however!

In addition to working with world-class microelectronics researchers, Gaillardon collaborated with a wide range of junior and senior engineers, learned about patents and IP protection, and gained project management and leadership skills that have served him well in his subsequent roles in both academia and industry.

The expectations for scientific excellence were high at Leti and Gaillardon worked hard, of course. What made the biggest impression on him, however, was how he was immediately immersed in the lab activities.

After earning his PhD, Gaillardon went on to a research associate position at EPFL in Lausanne, Switzerland before starting his own lab at the University of Utah, where he manages a successful research program that investigates novel device technologies and design methodologies for computing and sensor systems. He also co-founded two startups to commercialize the results of his research.

“Everything we did at Leti was industry-focused, so I learned a broad range of non-scientific skills that have served me well, especially in my startup activities.”

LETI ADVANTAGES

- The credibility of the Leti name when defending your thesis
- An opportunity to learn project management and leadership skills you can use beyond the lab
- A work environment where you can form lasting friendships



# Collaborations







**Susana Bonnetier**  
VP of the Carnot Network  
Carnot Program Manager  
Leti Scientific Directorate

Learn more about  
the Carnot Network:  
[www.instituts-carnot.eu](http://www.instituts-carnot.eu)



## The French Carnot seal stands for scientific excellence and professionalism in R&D partnerships

**Leti is one of France's 30 Carnot Institutes. Membership in the Carnot Network is granted to government research organizations that successfully foster industrial innovation through R&D partnerships that help improve the competitiveness and growth of their business partners. Research organizations that earn the Carnot seal benefit from government funding aimed at maintaining their scientific excellence and developing their professionalism.**

With the ultimate goal of creating value through innovation, the French Carnot institutes establish research partnerships with industry, from start-ups and SMEs to large companies. Leti, a Carnot institute since the creation of the label in 2006, carries out R&D projects with approximately 220 enterprises of all sizes and sectors to develop breakthrough technologies that address the major economic and societal challenges of the 21<sup>st</sup> century's digital, energy and medical revolutions.

Since its creation in 1967, Leti's mission has been to co-develop novel technologies with academic and business partners aiming to increase industrial productivity in many different applicative fields. Today those fields include high performance computing, embedded artificial intelligence,

5G, cyber-physical systems and cybersecurity, power electronics and energy management systems, medical devices, connected health and personalized medicine.

To pursue this mission and prepare the next wave of disruptive technologies for industry, Leti uses its Carnot funding to encourage researchers to engage in early-stage research projects and ambitious scientific collaborations. Specifically, a biannual call for exploratory projects stimulates the upsurge of new ideas from our researchers, and regular auditions of top-down multidisciplinary proposals lead to the production of generic demonstrators that help mature technological concepts into tangible and transferable results. The Carnot chairs of Excellence and the international PhD internship program are two other R&D boosters made possible by Carnot funding.

### IN 2018, CARNOT PROJECTS OPENED NEW AVENUES OF RESEARCH IN:

- biodegradable electronics and thin film batteries,
- monolithically integrated lasers operating at room temperature in silicon CMOS wafers,
- drug releasing structural hydrogels able to significantly reduce brain tumor recurrence,
- bioinspired implementations of non-volatile memories to simulate human learning processes,
- new cybersecurity strategies made possible by the random nature of resistive memories.

These projects benefit from our numerous collaborations with national and international academic partners, among them CNRS-LTM, CEA basic research laboratories, Spintec, the Grenoble-Alpes University, other Carnot institutes, Stanford University, Caltech, MIT, ETHZ, EPFL, Paul Scherrer Institute, FZ Jülich, University of Twente, and Keio University, to name a few. Working in this way with some of the best teams in the world in our core research areas is strengthening Leti's scientific excellence and professionalism, while reinforcing an open mindset.



**Thierry Baron**  
Director, LTM



**Dr. Bassem Salem**  
Research scientist at LTM

## Partnership with LTM moves GeSn closer to nanoelectronics applications

**A long-standing Leti partner, LTM develops new etching processes for the microelectronics industry and explores innovative materials and integration approaches. The partners' research on surface treatments to enhance the structural and electrical properties of GeSn has earned them two publications in top-tier journals.**

**PARTNER:** LTM (*Laboratoire des technologies de la microélectronique*), a research unit of the French National Center for Scientific Research (CNRS) and Grenoble-Alpes University housed at Leti.

**OBJECTIVES:** Explore various surface preparation schemes on GeSn to obtain the optimal structural and electrical features and, ultimately, lay the groundwork for advances in optoelectronics and nanoelectronics.

**RESULTS:** The partners recently co-authored two papers (published in *ACS Applied Electronics Materials* and *Applied Physics Letters* in 2019) presenting their research.

A number of Leti departments have worked with LTM on silicon components and epitaxy since the partnership began in the early 2000s. Recently, the partners have turned their attention to GeSn alloys, which offer great promise for tomorrow's optoelectronic and nanoelectronic devices. Specifically, electron mobility is theoretically much higher in GeSn alloys than in bulk Ge. However, to effectively utilize the material's superior carrier mobility, its surface must be prepared properly to ensure optimal structural and electrical properties.

Leti scientist Jean-Michel Hartmann, who leads SiGeSn epitaxy research at Leti, is convinced of the benefits of partnerships with academic research labs like LTM. "Back in 2015 we were able to modify one of our epitaxy chambers for GeSn growth under a joint development agreement with Applied Materials, the manufacturer of the RP-CVD machine. Since then I have been investigating the potential for photonics offered by this new class of semiconductors. I feel that our partnership with LTM will position us to emulate these successes in the field of nanoelectronics."

The partners certainly appear to be on the right track, with some exciting developments to their credit. They have successfully tackled GeSn from several angles

(interfacial layers, surface cleaning, nanowire fabrication techniques) to enhance the material's electrical performance and structural properties. Leti's ability to achieve state-of-the-art results on the epitaxy of complex GeSn stacks—Leti provided the GeSn/Ge stacks used in the research—makes the institute a partner of choice for LTM. LTM Director Thierry Baron said, "Collaborating with Leti allows us to work on the development of prospective materials and technologies with the potential for transfer to industrial partners."

The partners will continue to collaborate moving forward as their research on GeSn gains momentum. Dr. Bassem Salem, a research scientist at LTM, said, "Working with Leti has also given us the opportunity to introduce new research topics, such as improving the performance of nanoelectronic devices by leveraging the unique properties of GeSn materials".





## A fruitful decade-long collaboration between Leti and the IRIG/Biomics research team

Dr. Xavier Gidrol

**Leti's Department of Technologies for Biology and Health has been working with the IRIG/Biomics research team for nearly a decade on a variety of topics from the design and testing of microfluidic systems for general and cellular biology, siRNA delivery, and organs-on-chip. Today, the partners are combining their efforts to develop a targeted nanotherapy for inflammatory bowel diseases in EU-funded research.**

### PARTNER:

Dr. Xavier Gidrol's IRIG/Biomics research team (CEA/Inserm/Grenoble-Alpes University).

### OBJECTIVES:

The partners are currently engaged in the EU NEW DEAL project (2017-2021) to develop an siRNA-based nanotherapy for patients suffering from inflammatory bowel diseases like Crohn's.

**RESULTS:** Over the past decade, the partners have co-authored a number of papers and patents on point-of-care diagnostics, microfluidic chips, and genetic screening and collaborated on joint projects funded by the French National Research Agency, the Carnot Network, and the EU.

Leti has been collaborating with the IRIG/Biomics research team for nearly a decade. One of the topics of Leti's work with Dr. Xavier Gidrol is siRNA delivery, which began back in 2011 with the joint supervision of a PhD dissertation, continued under the French National Research Agency Facsbio marker project and Carnot PANACHE organ-on-chip project, and is currently ongoing under the EU-funded NEW DEAL project to develop a highly-selective local siRNA-based nanotherapy for inflammatory bowel diseases. Gidrol said, "Our long and fruitful collaboration started when I first came at the request of the CEA Life Sciences Division. One of my missions was to work closely with Leti. So, there was a top-down element to it. However, there was a 'meeting of the minds' between me and Leti scientist Fabrice Navarro that has carried the partnership through its many iterations to the NEW DEAL project today."

Navarro is coordinating the NEW DEAL project for the CEA. "This type of therapy could result in a major advance in the treatment of IBD, which mainly affects young people.

The NEW DEAL concept combines a particularly efficient siRNA designed by Dr. Gidrol's team with a lipid carrier made by Leti. The carrier can transport the siRNA across biological barriers and deliver it locally to the target cells."

The NEW DEAL project is currently in the preclinical stage. Leti worked with Gidrol's team to design and characterize lipid nanoparticles that are more robust in biological environments; the delivery of siRNA using these lipid nanoparticles is being tested. Gidrol said, "Beyond investigating biology through the lens of technology, perhaps what interests me the most are the potential benefits for patients. Collaborating with Leti creates new opportunities to bring our work out of the lab and to take a more applied approach to our research."

This long-term collaboration illustrates Leti's capacity to effectively bring basic and applied research together to develop new medical technologies and has resulted in advances that will help structure Leti's medical technology roadmaps moving forward.



## Leti partnership to bring nanotechnology to breast cancer diagnostics

Professor Gilles Favre

**A collaboration with internationally-renowned cancer researcher Professor Gilles Favre of IUCT-Oncopole, Toulouse University's cancer center, will help bring Leti's proven Lipidots® nanocarrier platform to breast cancer diagnostics. The goal of the project is to get the technology to a TRL of 4 to 6 and produce marked batches for clinical trials in partnership with biotech startup VNano.**

### PARTNER:

Cancer researcher Professor Gilles Favre of IUCT-Oncopole.

### OBJECTIVES:

Develop the nanocargo (a novel bimodal tracer) for sentinel lymph node diagnostics and scale it up for batch fabrication in preparation for clinical trials.

**RESULTS:** A minimally-invasive, highly-selective, non-toxic, and economically-competitive diagnostic technique for breast cancer patients leveraging Leti's Lipidots® nanocarrier technology (see p. 46).

Leti began working with Professor Gilles Favre in 2017 to initiate a research partnership with IUCT-Oncopole, Toulouse University's cancer center. The idea was to bring Leti's Lipidots® nanocarrier technology to breast cancer diagnostics. Projects involving Leti, IUCT-Oncopole, and biotech startup VNano (and funded in part through government innovation financing instruments and by VNano) are now underway to prepare the technology for manufacturing and, ultimately, clinical trials.

The goal is to replace conventional sentinel lymph node diagnostic techniques based on isotopic and colorimetric labelling, which involve invasive surgeries and expose patients to radiation and toxic chemicals, with a nanocargo technique that will be both safer and more accurate. According to Leti scientist Pascal Mailley, who heads Leti's Health Research Division, "This project is a prime example of Professor Favre's instrumental role in bringing Leti technologies to healthcare, both in terms of building partnerships with the medical community and contributing to Leti scientific committees in charge of developing our healthcare roadmaps." Professor Favre said, "The first time I went to Leti in 2017 I saw what they

had been doing with Lipidots®. Leti had basically been working on the same thing we had imagined two decades ago with our nanovectors, which mimicked lipoproteins. They had successfully developed stable nanoparticles compatible with clinical applications. I immediately saw the potential."

Industrial transfer of the mature Lipidots® technology is well underway with VNano, which has invested heavily in a production facility to provide the nanocargo batches necessary for clinical trials. Research to develop the innovative Lipidots®-based bimodal tracer for sentinel lymph node diagnostics has been approved for government funding and is now in its early stages.

Professor Favre, who also founded France's first-ever nanomedicine startup, Biovector Therapeutics, in 1996, is a firm believer in the power of nanotechnology to revolutionize medicine. He said, "Partnerships with technology developers and startups are a key part of our strategy. Collaborating with institutes like Leti supports value creation. And the work we are doing on breast cancer is just the beginning. Lipidots® technology has the potential to improve the diagnosis and treatment of many other diseases."





## Better together: Leti and FZJ drive advances in laser technology

Dr. Detlev Grutzmacher

**Leti and Germany's Jülich Research Center are pursuing their long-standing partnership, joining forces in the race to achieve lasing in electrically-pumped MIR GeSn lasers at room temperature—an advance that would allow the lasers to be integrated into complex photonic circuits.**

### PARTNER:

Forschungszentrum Jülich (FZJ) GmbH, one of Europe's largest interdisciplinary research organizations, which focuses on groundbreaking research in energy, information technology, and the bioeconomy.

### OBJECTIVES:

Continue to improve the MIR lasers developed previously by lowering their lasing threshold and increasing their operating temperature; investigate a novel SiGe/Si gate-normal TFET with a pillar-shaped contact to the tunneling junction with the capacity to operate at ultra-low operating voltages with sharp on/off capabilities.

**RESULTS:** A truly prolific partnerships with more than 80 publications.

FZJ and Leti have been working together on Group IV semiconductors since 2005, first as partners in European research projects and later through their own partnership agreements.

Leti has been supplying samples to FZJ since the early days of the partnership. Leti's state-of-the-art 200 mm reduced pressure CVD cluster has a chamber for the high-temperature growth of Ge Strain Relaxed Buffers and SiGe/Si stacks. The institute can also grow complex epitaxial stacks on demand. Since 2013 Leti has been supplying thick Ge Strain Relaxed Buffers (SRBs) on Si(001) used as templates by FZJ for the epitaxial growth of complex GeSn/SiGeSn heterostructures for mid-infrared lasers and other devices.

Together, the partners have published prolifically. Among their more than 80 journal articles and conference papers is a 2015 *Nature Photonics* article that has been cited more than 500 times. According to FZJ's Detlev Grutzmacher, "Beyond the conference invitations and publications, this research has given our students an opportunity to graduate with outstanding results, win awards, and get their careers off to a strong start. For me, this has been one of the most satisfying outcomes of our partnership with Leti."

Today, the partners are ramping up their laser materials, design, and integration research. Recently, they combined high-Sn-content (and thus direct-bandgap) GeSn layers and

tensile strain (obtained by depositing SiN stressors on freestanding GeSn disks on Ge pillars) and yielded very low thresholds. An article on the research is currently under review for publication in *Nature Photonics*. They also investigated a multi-quantum-well design that achieved a lasing threshold almost ten times lower than that of bulk structures, demonstrating the potential of multi-quantum-well approaches for the next generation of CMOS-compatible Group IV lasers.

According to Leti scientist Jean-Michel Hartmann, conducting research with more academic-oriented labs is beneficial in several ways. "These labs can focus more on novel materials and architectures, whereas we tend to work more on devices that are past the proof-of-concept stage. They also work on pieces of wafers, which means that a single custom 200 mm wafer from Leti is a whole box of samples for FZJ. We also benefitted from FZJ's pioneering earlier-stage research on GeSn and SiGeSn for lasers to know which topics we should be investigating." And working with Leti has shaped the way FZJ sees the future of its research. Grutzmacher said, "Whether it is improving energy efficiency or enabling quantum and neuromorphic computing, today's silicon research is too complex for a single academic or government research lab to handle alone. This makes cooperative approaches involving partners at different levels fundamental. We knew that working with Leti had the potential to bring major benefits."



## Stanford and Leti take memory-centric computing nanosystems from concept to prototype

Professor Subhasish Mitra

**Leti has been working with Professor Subhasish Mitra of Stanford since 2017. The partnership brings together the research Mitra's group is doing on new computing concepts with Leti's advanced technologies and circuit demonstration capabilities. The goal is to shape the future of computing nanosystems.**

### PARTNER:

Professor Subhasish Mitra of Stanford University's Department of Electrical Engineering and Department of Computer Science.

### OBJECTIVES:

Shape the future of computing by coupling computing and memory more closely, inventing disruptive computing paradigms, and leveraging advanced More-than-Moore technologies to achieve tighter integration.

**RESULTS:** A revolutionary RRAM chip for edge-AI applications (see p. 60).

Leti has been collaborating with Stanford's Subhasish Mitra through a Carnot Chair of Excellence in NanoSystems since 2017. The Chair was established to bring the best minds in nanosystems research to Leti to provide scientific and strategic insights and engage directly in research with Leti teams. According to Mitra, "I am deeply interested in using new technology concepts to drastically improve the speed and energy of computing systems, so I immediately saw synergies with Leti. Over the past two years, our partnership has expanded to involve more researchers. We get to learn new things from these bright people and something magical happens—new ideas germinate. It's a virtuous circle."

Leti scientist Pascal Vivet feels that the partnership has been particularly beneficial. "I have personally gained a lot working with Stanford. Due to the groundbreaking nature of our joint research, I have improved how I formalize a new problem and become better at focusing on essential information in my academic writing. I have also become a stronger PhD supervisor." Mitra said, "The opportunity to be part of a collaboration that brings design and technology expertise together so effectively has been especially rewarding for me. The way Leti operates has facilitated this."

Today the partners are exploring

monolithic 3D (Leti's CoolCube™ technology) and non-volatile memory (RRAM) for ultra-dense and fine-grained integration of logic and memory to create new computing system architectures for coming generations of applications and, especially, AI. They have already produced a significant result, co-authoring a paper published at the 2019 IEEE International Solid-State Circuits Conference on a new computing system designed by Stanford and fabricated by Leti. Their work was also picked up by *Nature Electronics* for a special research highlight.

The partners' work on in-memory computing architectures is still underway, with collaborative Stanford-Leti PhD students. They will also create a joint research team to drive advances in-memory computing architectures, seek higher RRAM densities through both improvements in technology and design, and—ultimately—integrate RRAM into the memory-compute cube. Mitra said, "With the Chair, we are creating new ideas that I am confident will enable the next generation of computing systems essential for addressing global challenges such as the environment, energy, and healthcare. Getting people from diverse backgrounds working together is the first step, and that is exactly what the Stanford-Leti collaboration is doing."



## EU RTOs cooperation for next-gen computing

Encouraged by the European Commission, the three major European RTOs in microelectronics research and development, CEA-Leti, Fraunhofer/FMD and imec, are collaborating to create a strategic alliance to develop the necessary compute platforms enabling new applications in healthcare, industry, mobility etc. where technologies for artificial intelligence, high-performance computing and cybersecurity become indispensable.

This unique world-leading collaboration focuses on full technology and engineering development on 300mm wafers to realize the European hardware for the new compute infrastructure. This new initiative opens up an affordable, fast-track access for SMEs and systems houses in Europe.

## EU project TEMPO targets low-power chips for AI applications based on emerging memory technology



TEMPO project brings together the three top European RTOs, industrial fabrication facilities and leading application partners in the domain of neuromorphic computing, which features intense global competition towards the vision of intelligent machines. The objectives of TEMPO is to design and combine performing transistors and new emerging memories to realize new neural networks that will be able to analyse complex situation like object detection in real time (automotive, space, health,...multiple applications).

Emmanuel Sabonnadière, CEO at CEA-Leti: "It is our aim to sweep technology options, covering emerging memories, and attempt to pair them with contemporary (DNN) and exploratory (SNN) neuromorphic computing paradigms. The process- and design-compatibility of each technology option will be assessed with respect to established integration practices and meet our industrial partner roadmaps and needs to prepare the future market of Edge IA where Europe is well positioned with multiple disruptive technologies."

Prof. Hubert Lakner, Director of the Fraunhofer Institute for Photonic Microsystems (IPMS) and Chairman of the Board of Directors of

the Fraunhofer Group Microelectronics : "A key enabler for machine learning and pattern recognition is the capability of the algorithms to browse through large datasets. Which, in terms of hardware, means having rapid access to large memory blocks. Therefore, one of the key focal areas of TEMPO are energy efficient nonvolatile emerging memory technologies and novel ways to design and process memory and processing blocks on chip."

Luc Van den hove, CEO imec: "We are delighted to enter in such broad European collaboration effort on Edge Artificial Intelligence, gathering the relevant stakeholders in Europe, including CEA-Leti and Fraunhofer, two of our most renowned colleague research centers in Europe. Thanks to our combined expertise, we can scan more potential routes forward than what would be possible by each of us individually, and as such, position Europe in the driver seat for R&D on AI. Imec looks forward to the progress we can make together in the TEMPO project and hopes this will lead to more similar collaborations in the future. Behind the scenes, we are already defining more public and bilateral agreements with several of the partners involved."





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