Since its foundation in 1967, LETI has shaped its strategy around the main challenges arising from the evolution of society and from global economic and industrial landscapes.

Increasingly engaged in European and global industrial ecosystems, LETI is leveraging basic science results to actively stimulate the creation of startups and foster innovation and value creation in large, small and medium businesses. In doing so, LETI greatly contributes to improve the competitiveness of its economic partners and create opportunities for growth and employment. This solidly anchored experience developing disruptive technologies and pioneering differentiating solutions means LETI is able to understand the applications and use cases of its partners and provide the technical building blocks that will meet their system-level requirements.

LETI’s know-how and expertise is built on its scientific strategy which encourages true creativity and the discovery of new ideas and insights. Anticipating the arrival of new trends from many different origins, addressing issues that may arise during pre-industrial phases in a unique way, thinking large, seeing differently and demonstrating new solutions, this is our DNA.

“The best work is not what is most difficult for you, it is what you do best” said Jean-Paul Sartre, the French philosopher. What we do best is reported in these pages, often resulting from successful and long-term collaborations with academic and industrial partners, whom we greatly acknowledge for their solid contributions. Finally, I would like to praise the remarkable skills, dedication and integrity of LETI’s scientists: their outstanding commitment has been essential to creating these world-class successful results.

Before the discovery of Australia, people in the Old World assumed that all swans were white, an unassailable belief confirmed by empirical evidence. The sighting of the first black swan unsettled people’s expectations, derived from millennia of well-identified patterns believed to last forever. This single observation illustrates the ever expanding frontiers of human learning and knowledge.

At LETI, we praise incremental progress and we continuously challenge ourselves to look for the black swan in our research. Our strategy relies on highly creative investigation and recognition of non-conventional opportunities and innovative ideas. In this report, we would like to share some scientific highlights of our long-term exploratory research results, which have potential high technological and societal impact. These results will be presented along five strategic axes, aimed at capturing the complexity of today’s world:

- Advanced materials: A driver of opportunities;
- How novel imaging techniques will revolutionize life, environmental and material sciences;
- Towards kinder and smarter medical approaches;
- New generations of simulation, drug delivery technologies and monitoring systems;
- Energy efficiency at the device, chip, and board and system levels: ensuring the most efficient use of energy resources;
- Managing increasingly complex systems effectively and securely.

These results have been made possible thanks to the continuous efforts and authentic passion of our scientific experts and students. We also would like to acknowledge our academic partners for the many years of fruitful and fruitful collaboration.
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Leti is a technology research institute at CEA Tech and a recognized global leader in miniaturization technologies enabling smart, energy-efficient and secure systems. Our highly experienced teams are committed to developing innovative solutions that benefit our industrial partners.

By pioneering new technologies, Leti enables innovative solutions that ensure competitiveness in a wide range of markets, while creating jobs and improving people's lives. Leti tackles critical, global challenges such as the future of industry, clean and safe energies, health and wellness, sustainable transport, information and communication technologies, space exploration and safety & security.

Leti's multidisciplinary teams deliver solid expertise on micro- and nanotechnologies for applications ranging from sensors to data processing and computing solutions, leveraging world-class pre-industrialization facilities. Its pioneering technologies include low-power platforms for the IoT, low-cost multi-sensor solutions and 3D integration for cost-effective and low-power devices.

For 55 years, the institute has been building long-term relationships with its industrial partners – global companies, SMEs and startups – providing tailor-made solutions through bilateral projects, joint laboratories or collaborative research programs and a clear intellectual property policy. Leti's startup program actively supports the launching of new technology companies.

Over the years, Leti has collaborated with major research technology organizations and academic institutions to help bring upstream research to the marketplace.

Leti is a member of the Carnot institutes network*.

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

1. Challenging material choices to drive innovation

2. Seeing the world with novel imaging techniques

3. Technologies and smart systems to improve human health

4. Towards ultra-high energy efficiency at device and system level

5. Managing increasingly complex systems effectively and securely
1.

CHALLENGING MATERIAL CHOICES TO DRIVE INNOVATION

A Milestone in a Fundamental Transition: First 300 nm InGaAs-on-Insulator Wafer

10x Gain in Microdisplay Brightness with GaN

Supercritical Fluid Deposition for Fabricating Bio-sensing MEMS and NEMS

Silicon Photonics: III-V-on-SOI Tunable Lasers

Toward Lasers Made from Direct Bandgap Germanium-Tin Alloys Grown on Silicon
A MILESTONE IN A FUNDAMENTAL TRANSITION: FIRST 300 mm In GaAs–ON–INSULATOR WAFERS

How did researchers at Leti harness SmartCut™ technology to accelerate the use of high-mobility III-V materials?

Today, the semiconductor industry stands on the verge of a historic transition away from silicon. Its mainstream for almost 70 years. The high electron mobility and low electron effective mass values of III-V materials make them excellent candidates to become the new standard. But while several groups have produced InGaAs-on-insulator substrates by growing InGaAs layers on indium phosphide or silicon, these processes are complex and costly, and not always compatible with the industry standard 300 mm wafer diameter.

Our team took on the challenge by implementing a new MOCVD epitaxial deposition process and leveraging 20 years of experience with SmartCut silicon-on-insulator layer transfer and wafer bonding – and in 2016, created the world’s first 300 mm InGaAs-on-insulator substrates, opening an avenue to effective and economical volume production.

We achieved this milestone by demonstrating the ability to grow high-quality 25um-thick InGaAs layers directly on 300 mm silicon wafers, and successfully maintain their crystal quality while transferring them to wafers containing an insulating layer. At the same time, because SmartCut allows reuse of the expensive III-V donor wafer, the process has an intrinsic economic advantage.

What’s the potential for integrating InGaAs into advanced manufacturing processes?

The next challenge, which we are working on, is the ability to transfer III-V layers onto processed CMOS wafers using proprietary CoolCube™ technology, which preserves solid thermal budgets for subsequent processing. This would allow a single substrate to have a bottom SiGe layer containing low-cost pMOSFETs and a high-mobility III-V top layer with high performance nMOSFETs.

Leti’s ability to create this type of substrate would give designers and system developers a new paradigm for device scaling and dramatically increased CMOS power efficiency, along with the broader advantages of 3D integration (e.g., lower development costs, reduced circuit delay, less variation).

“First demonstration of 300 mm InGaAs–On–Insulator substrates fabricated using the SmartCut™ technology”

“300 mm InGaAs substrate fabrication using the SmartCut™ technology”
S. Widiez, J. Berton, M. Martin, O. Gaudin, F. Mazan, F. Faye.
100X GAIN IN MICRODISPLAY BRIGHTNESS WITH GaN

Very tiny yet extremely bright. How did you reach these results in micro-LED technology?

Most currently available microdisplays have fundamental technology limitations that prevent the design of high-brightness, compact, very low-weight and low-power products.

To overcome this problem, we combined our research on gallium-nitride-based (GaN) technologies for lighting applications, together with high-resolution emissive microdisplays and high-resolution small-pitch hybridization technologies. Our results show a very small size of the micro-LEDs (9 um) associated with extremely high-brightness — a ground-breaking change in this sector. In addition, the proposed technique is scalable and relies on a standard microelectronics large-scale fabrication process.

Our technology breakthrough features a brightness of more than 100 nits, which is several orders of magnitude higher than the ~10 nits obtained by state-of-art organic LED (OLED) microdisplays. We also demonstrated very high definition and the smallest pixel pitch for hybridized GaN microdisplays.

Other key innovations include micro-architecture of LED arrays (10 um pitches or smaller) with high efficiency, and 3D heterogeneous integration (hybridization) of the LED arrays on CMOS circuits.

Where will Leti’s micro-OLED expertise lead future research?

Leti has expertise on the full range of technologies to develop GaN microdisplays, from epitaxy, GaN array processing and hybridization to active-matrix design and display electronics.

Creating high brightness that can be achieved with such small pixel-pitch will first boost development of augmented reality systems and compact projectors. But these small-scale, high-power LED arrays are also of great interest for other applications, such as massless optical lithography and wide-band optical communications.

Awards:

Leti’s GaN microdisplay won an “Innovation Award” at TechConnect World 2015 as one of the top 25 most promising innovations.

SIMPLE DETAILS

Blue and Green 10 um pixel pitch GaN LED Arrays with very high brightness  

"Color conversion using red Quantum Dots integrated in a source on high-brightness blue GaN LED"  

SUPERCRITICAL FLUID DEPOSITION FOR FABRICATING BIO-SENSING MEMS AND NEMS

What is fundamentally eco-friendly about Leti’s new SFD process?

This is the first reported example of deposition of an organic silver using a supercritical fluid-deposition tool (SFD-200) that is automated and compatible with 200 mm wafers. This “green” process was used to coat silicon wafers with dicyanosulphide for bio-sensing applications and for coating mesoporous silica with inorganic catalysts for heterogeneous catalysts applications.

We have shown that this versatile, environmentally friendly method enables conformal deposition of nonvolatile organic molecules on microdevices with complex geometries. We also demonstrated the feasibility of industrializing the process for MEMS or NEMS fabrication.

How will this innovative chemical-deposition process change device fabrication?

Leti is developing SFD as a solvent-free methodology for chemical deposition, which for organic precursors is generally performed through liquid-phase methodologies. The problem is those processes involve large amounts of potentially toxic solvents and make it difficult to add innovative functions on microdevices or porous materials. SFD is the only methodology that can perform solvent-free chemical deposition for a large range of precursors.

The process offers many advantages over common methods in addition to eliminating solvents. It allows a controllable and thin film layer, and a shorter time reaction. Moreover, it offers the possibility of simultaneously or consecutively depositing different organic precursors to build complex organic structures.

Awards:

Leti’s SFD process was honored with the “2015 World’s Most Promising Innovation” award in the category “Advancing Materials and Manufacturing” at the World Technology Awards 2015.

SIMPLE DETAILS

“Functionalization of silica surface using supercritical fluid deposition of 3,4 epoxybenzothiazoylene for the immobilization of amino-modified dicyanosulphide”  

“Supercritical Fluid Deposition of epoxyamine on solid surface for biosensing and heterogeneous catalysts applications”  
G. Nguyen, G. Coste, C. Fontaine, C. Marchal, O. Marchal-Delpeyre, M. Nibouze, J. Rul  
EUROMAT 2015, Warsaw, Poland, 2015.

CHALLENGING MATERIAL CHOICES TO DRIVE INNOVATION

SUPERCRITICAL FLUID DEPOSITION (SFD)

BREAKTHROUGH

Coating silicon wafers to graft dicyanosulphide for bio-sensing applications, and for coating organic catalysts on mesoporous silica for heterogeneous catalysts applications.

WHY IT’S RELEVANT

The process enables new functionalities, and eliminates toxic solvents using standard CMOS processes.

MOVING FORWARD

Leti will integrate this new technique in a fabrication process for the microelectronics industry starting from MEMS and NEMS and extending toward MOFs applications.
SILICON PHOTONICS: III-V-on-SOI TUNABLE LASERS

What can you tell us about this innovation involving hybrid Si-photonics lasers?

In a joint project with French III-V lab, we developed a tunable hybrid III-V-on-SOI laser and its packaging in an optical module with electronic wavelength allocation control. We achieved a wavelength tunable range of 35 nm, a side-mode suppression ratio (SMSR) higher than 50 dB, and an optical output power level coupled into a monomode fiber in excess of 3 mW across the whole wavelength range. The measured laser linewidth falls in the range of 500 kHz to 5 MHz over the entire wavelength range. Eighty wavelength channels spaced by 50 GHz, as defined by the ITU grid for Dense Wavelength Division Multiplexing (DWDM) application, were allocated using an electronic control card.

In the hybrid laser, the III-V material is used to provide large gain, whereas all the optical elements of the laser cavity are fabricated in silicon, leading to a compact and low-loss architecture.

How will this breakthrough impact future development and use of tunable silicon photonics lasers?

The integration of these lasers on silicon paves the way for integration into more complex photonic ICs, such as transmitters and receivers for applications ranging from long-distance data communications to wideband optical transmission systems.

The competitive advantage is the integration of these laser sources in the silicon photonics technology, which is key to cutting power consumption. In addition, the integration of the laser source is vital for scaling silicon photonics transmitters circuits to a larger number of wavelengths for next-generation optical transceivers in datacenters, or for future optical networks-on-chip. It greatly simplifies the packaging, which accounts for the major part of the transmitter cost.

TOWARD LASERS MADE FROM DIRECT BANDGAP GERMANIUM-TIN ALLOYS GROWN ON SILICON

What combined contributions from FZJ and Leti led to this first-ever direct bandgap laser?

Monolithic integration of Si-based photonics and electronics as a key energy-efficient computing. Silicon-germanium-tin alloys, such as GeSn, Si$_2$Ge or Ge$_3$Sn$_4$, or germanium-tin III-V alloys such as GeSn or Ge$_3$Sn$_4$ are group-IV semiconductors of choice for the technology since band engineering allows the formation of direct bandgap materials. Not only passive optoelectronic components, but also light emitting devices like lasers and LEDs can strongly benefit from this intrinsic material property.

Leti’s partner, Forschungszentrum Jülich (FZJ), demonstrated for the first time over that a so-called direct bandgap, e.g. the energy difference between the top of the valence band and the bottom of the conduction, was achievable in group-IV semiconductors, using GeSn on Ge from Leti. This major finding shows that having a direct bandgap means, among other things, that light or a laser, emitted by that semiconductor will be re-absorbed compared to what can be obtained with regular silicon or germanium.

Leti provided 2.5 μm thick Ge buffers (on Si (001) substrates) for this research. Switching to Leti’s silicon-on-epitaxial Ge buffers enabled FZJ to significantly improve the structural and electronic quality of their stacks and reach much higher Sn content ~12-13 percent vs. a previous maximum of approximately 8 percent — which is a prerequisite to obtaining a direct bandgap and a laser. “Direct means that electrons, because of the peculiar band structure, will move from the conduction band down to the valence band without any photon (e.g. lattice vibration) involved. That is far more efficient for light emission.”

How will this breakthrough affect future R&D in direct-bandgap materials?

A group-IV laser could be monolithically integrated on top of CMOS devices and used as the light source of mid-infrared photodetectors, with SiGe waveguides and GeSn photo-detectors as receivers. Clock frequencies could then be distributed within and in between chips, reducing energy use at big data centers, for example. These are valuable features for the Internet of Things and applications that support the green economy. They also could be light sources for gas detection in industrial and defense applications.

Applications for this technology also include toxic gas detection and quantification in industry and for defense purposes.
2.

SEEING THE WORLD WITH NOVEL IMAGING TECHNIQUES

The Eyes of the Electronic World: Pixel-Level Packaging Advances IR Sensors / 22

Replacing 19th-Century Voice Coil Motors with Piezoelectric Varifocal Smartphone Camera Lenses / 23

Setting the Record for Infrared Light Cutoff Length / 24

Precession Electron Diffraction Provides Unprecedented Performance for Strain Mapping at Nanoscale Resolution / 25

Millimeter-Wave RFICs / 26

Non-Dispersive Infrared (NDIR) Technology / 27
THE EYES OF THE ELECTRONIC WORLD:
PIXEL-LEVEL PACKAGING ADVANCES IR SENSORS

How does Leti’s technology in improved surface micromachining help computers see the world around them?

Among the millions of silicon wafers being processed annually, Leti’s partner LISI ran a special kind – one that first used a new infrared (IR) sensor manufacturing technique capable of creating separate isolated vacuum chambers around thousands of individual pixels during front-end processing.

This pixel-level packaging (PLP) approach, the product of six years of research at Leti, is a game-changing advance for microbolometer sensor cost and performance. Combining these better IR sensors with modern computing horsepower will enable systems to better interact with the environment around them, “seeing” objects even in the dark.

Our process creates a cavity under vacuum around each microbolometer pixel by stacking thin-film layers. It’s a unique surface micromachining process, but uses standard microelectronic production techniques and equipment, and is ideal for high-volume production situations.

We created the first PLP image by projecting heat from a lamp through a handmade stencil, placed directly on a sensor that was still in its wafer. The image appeared immediately, much to our team’s delight – and the stencil is now a precious lab keepsake.

How will this influence the linking of computer platforms and sensors?

The PLP approach eliminates the need to create vacuum packaging by sealing a separate cap wafer onto the component wafer. While this works well for MEMS devices like accelerometers, its cost, complexity and quality issues increase as sensor pixel size decreases – and smaller pixels are key to achieving higher resolution and/or lower cost and power consumption.

Improvements in infrared sensing will enable applications in which computing systems gather knowledge of their physical surroundings. In the near term, this has uses in energy efficiency, security, defense, and industrial monitoring and control; going forward it will be essential for robotics and self-driving cars.

Because Leti’s research has been structured from the outset for low cost and easy adoption into volume manufacturing, our partners are able to quickly leverage the advances and bring new generations of devices to market.

STÉPHANE FAGET
Scientist

REPLACING 19TH-CENTURY VOICE COIL MOTORS WITH PIEZOELECTRIC VARIFOCAL SMARTPHONE CAMERA LENSES

How has Leti’s MEMS expertise brought lens quality in smartphones to state of the art?

Smartphones are masterpieces of modern engineering. Yet, relatively few people know that one of their components is virtually unchanged since the 1870s: the voice coil motors (VCM) used to focus smartphone camera lenses.

As scientists and engineers, we appreciate technology that endures, but the prospect of replacing these mechanisms with piezoelectric MEMS devices was very exciting because their greater precision enables true optical capabilities and the high-volume adoption of varifocal liquid lenses. Our innovative MEMS varifocal lens design, fabricated using standard production techniques, is a huge step forward, and because the camera function is one of the most-used smartphone capabilities, state-of-the-art lens technology is surely a key differentiator.

What design and production advances were needed for this breakthrough?

A 10-person team of piezoelectric materials experts, process-integration specialists, and MEMS designers used finite element modeling and extensive experimentation to design a deformable membrane-lens structure capable of encapsulating an optical oil, set in an embedded ring-shaped PZT piezoelectric actuator.

When a voltage is applied, the actuator displaces the oil and changes the shape of the lens, thus altering its focal length by up to 15 diopters. Just a few nanometers of current are needed, so power consumption is several orders of magnitude less than VCM designs, while response time is an order of magnitude faster. This technique produces very good optical quality that endures over millions of cycles.

High-volume production compatibility was essential, so while we developed a proprietary fabrication process, our team focused only on industry-standard tools and techniques. It utilizes multiple polymer layers, including one that provides very good bonding between the silicon base wafer and top-level glass wafer, both 200 mm. We worked very hard to create a recipe that does not generate bubbles in the optical cavity after bonding, and were very excited that our partner, Vaweirs, showcased a demonstration model at the 2015 Consumer Electronics Show in Las Vegas.

NICOLAS LIO SOON SHUN
Scientist

PIEZOELECTRIC VARIFOCAL SMARTPHONE CAMERA LENSES

BREAKTHROUGH: Creating a next generation of smartphone optics with an innovative MEMS varifocal lens design, fabricated using standard production techniques.

WHY IT’S RELEVANT: These optical autofocus capabilities are a powerful tool for smartphone users – and a market advantage for manufacturers.

MOVING FORWARD: Our partner, Vaweirs, is making the technology available commercially.

FOR MORE DETAILS
“Fabrication and Characterization of a New Vertical Liquid Lens with Embedded PZT Actuators for High Optical Performance”
SETTLING THE RECORD FOR INFRA-RED LIGHT CUTOFF LENGTH

**Nicolas Baier**
Scientist

**Infrared Light Detection**

**Breakthrough:** The cutoff wavelength of IR light detectors was pushed to 17 microns.

**Why it’s relevant:** This leading development boosts performance in IR light space, defense and security applications.

**Moving Forward:** Increased knowledge of the material fosters ideas for innovative improvements and applications for IR light detectors.

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**How does Leti’s innovation in focal plane arrays change IR light-detection performance?**

Our big breakthrough with Sofradir extended the cutoff wavelength of infrared light detectors past 15 µm, which was the project goal, to 17 µm, with a fully functional focal plane array. That has never been done before. Traditional detectors for security or defense applications on earth have cutoff wavelengths in the range 4.5-µm and 8.5-10 µm.

Leti’s infrared Lab is the only one in the world that demonstrates focal plane arrays (FPA) format with such cutoff wavelength and high-functional pixel yield. The second part of the breakthrough is a major gain in dark current, two orders of magnitude higher than existing technology. And the third aspect is the optimization of the pixels’ operability. This lowered the number of non-functional pixels (dark defects) and of pixels with temporal noise and/or with excess dark current.

Leti’s experience in this technology began 30 years ago, and includes the creation in 1988 of Sofradir, now the world leader in developing and manufacturing infrared sensors for military, space and commercial security applications.

This innovation combined Leti’s expertise in monocrystalline substrate growth, quality of a high-quality active layer, specific technological processes, characterization of electro-optical performances and physical modeling.

**What impact will this breakthrough have on future IR light detector R&D?**

By increasing our knowledge of the material, new ideas emerged to propose new improvements or to open novel potential applications for our detectors. Some recent technological developments can be reused in other processes to increase performance, or to open access to brand new processes.

For our industrial partner, this provides ways to increase production yield and detect performance, thereby strengthening its position as a world leader in this domain.

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**Prescission Electron Diffraction**

**Breakthrough:** A new transmission electron microscopy technique that provides unprecedented capabilities for mapping deformation in nanoscale devices.

**Why it’s relevant:** Strain is an important parameter in improving the performance of electronic devices. The ability to map strain with nm-scale resolution will allow the different processing steps to be optimized to provide the best performance.

**Moving Forward:** We continue to develop new characterization methods that can be used to support nanotechnology activities. One current direction is studying these devices at atomic resolution, while they are being operated in-situ in the electron microscope.

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**Precession Electron Diffraction provides unprecedented performance for strain mapping at nanoscale resolution**

Pushing the envelope in transmission electron microscopy techniques. What are the implications for mapping strain?

As part of Leti’s pursuit of innovative methods to improve the performance of SID device technology, we are continuously developing new techniques that induce local strain in FDSOI processes for next-generation circuits. The introduction of strain is a very cost-effective way of improving performance, boosting speed and lowering power consumption.

It is highly desirable, when developing new device technologies, to provide maps of the strain during the different processing steps. That way, we can interpret the electrical properties and determine whether these improvements are due to the introduction of strain, or not.

Developed with Insc, this new technique uses precession electron diffraction in an aberration-corrected transmission electron microscope to achieve better than 2 nm spatial resolution and 0.02 percent precision for strain mapping of semiconductor specimens. We then map the deformation in the latest generation of devices, where feature sizes may be in the order of a few nanometers.

Leti is the only laboratory in the world that today has access to these methods of measuring deformation with this combination of spatial resolution and precision.

**How will this breakthrough impact device manufacturing and what are the prospects for its further development?**

We are working with the high-performance-microscope supplier FEI to make this a standard strain-mapping technique available to the semiconductor industry. FEI is supplying software specialists to improve the speed and efficiency of the data collection, in which a single map may contain several GB of data.

We are also expanding on these ideas and have recently patented a method that can simultaneously measure electromagnetic fields, so that properties such as dopant potentials, photo-electricity and magnetism can all be mapped at nm-scale resolution.
**MILLIMETER-WAVE RFICS**

ALEXANDRE SILIGARIS  
Scientist

**How will Leti’s achievement in millimeter wave 300 GHz RFICs raise the bar for imaging?**

Leti’s RFIC circuit that operates near 300 GHz in a standard technology offers very good sensitivity and vectorial detection – double information on the scanned object – integrated in a single chip. The essential differentiator in Leti’s approach is that our receiver, or detector for imaging purposes, uses a heterodyne architecture with integrated oscillator. Moreover, the oscillator is locked by a stable signal at lower frequencies. Thus, the frequency synthesis is not carried out at 300 GHz, which is above the 200 GHz cut-off limit for transistors, but at much lower frequency, with higher performance. This approach greatly enhances image contrast.

Leti is the first to demonstrate that better image quality can be achieved if the oscillator is locked in a heterodyne imaging system.

**What new research possibilities will THz spectrum imaging open?**

As we approach the 300 GHz frequency, for which the wavelength is about 1 mm in free space, we can imagine detectors, like radars, which scan an object with 1 mm or less spatial resolution. With that capability, we can construct an image with good resolution in a frequency spectrum not yet available for these uses. Imaging exists today in the visible spectrum, the X-ray spectrum, the infrared spectrum and also in the RF spectrum, but not in the so-called THz spectrum. This spectrum can reveal new elements in biological materials since it behaves as a radio-frequency wave and has very interesting spatial resolution. Our work opens the THz spectrum for imaging, allowing new research in medical imaging, biology, material control, security and other fields.

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**NON-DISPERSIVE INFRARED (NDIR) TECHNOLOGY**

PIERRE BARRAUTAULT  
Scientist

**How will Leti’s breakthroughs in NDIR technology impact air-monitoring equipment?**

In the first of three major innovations, we took state-of-the-art blackbody IR source technology to a new level by using a water-level-packaging (WLP) source, fabricated on 200 mm wafers in CMOS processes. We copped each source under vacuum by positioning a second wafer above the water-source and sealing both wafers under vacuum (WLP). That eliminated the air surrounding the source and the thermal losses. As a result, the electrical-to-optical conversion efficiency is multiplied by 20.

The optical design, the second breakthrough, allows us to image the source on the IR detector within a compact optical cavity, while maintaining very high efficiency.

The third major innovation was the development of an IR pyro-electric detector to replace the standard detector used in our prototypes. The advantage is clearly to master the design and manufacturing of all the components used in the NDIR detector – source, optical cavity and detector – thus enabling an optimized design.

**How will the Leti startup, eLichens, put these innovations to work?**

eLichens’ technology, which detects, monitors and predicts air quality indoors and outdoors, is based on a portfolio of 20 Leti patents that reduce existing large and expensive sensors used in industrial applications to a size that fits in hand-held devices. These innovations will enable eLichens to improve performance and reduce power consumption with its products.

eLichens and Leti plan to develop CO2 NDIR sensors with an ultra low power consumption (a few mW) and a compact size (20x25x7 mm). CO2 will be the first targeted gas, with others to follow.

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*For more details:*

"A 370 to 300 GHz Sub-Harmonic Injection-Locked Oscillator for Frequency Synthesis in Sub-mmW Systems"

"A 371 GHz heterodyne receiver with on-chip antenna for THz imaging in 65 nm CMOS process"
3. TECHNOLOGIES AND SMART SYSTEMS TO IMPROVE HUMAN HEALTH

Wireless Brain-computer Interface Offers Mobility to Tetraplegic Patients / 30

Oximetry Sensor: a Wireless Conformable Patch for Treating Sleep Apnea / 31

Fighting Bio-Terrorism with Technology: a Mobile Ricin Detection System / 32

Giving Medicine a Closer Look with Spectrometric Image Detectors / 33
WIRELESS BRAIN-COMPUTER INTERFACE OFFERS MOBILITY TO TETRAPLEGIC PATIENTS

CORINNE MESTAS
AND GUILLAUME CHARVET
Scientists

OXIMETRY SENSOR: A WIRELESS CONFORMABLE PATCH FOR TREATING SLEEP APNEA

How does Leti’s novel technology for measuring oxygen saturation in the blood enhance existing techniques?

Combining expertise in wearable oximetry sensors and oximetry, Leti developed a less invasive and more reliable device to diagnose Obstructive Sleep Apnea (OSA) in patients affected by respiratory problems. This innovation is the result of a joint effort of Leti and its medical-industry partner to address a widespread pathology in adults.

The standard method of measuring oximetry is based on transcutaneous mode requiring small clamps attached to a finger and wired to a recorder integrating skin optics sensors and the Blue Tooth low-power protocol. Leti’s O2C wearable sensors monitor oxygen saturation in the blood in a reflectance mode on different locations on the body, such as the forehead and wrist, thereby eliminating the need for devices wired to patients.

Usual polytomography methods require a lot of sensors that cause abnormal sleep conditions, and therefore biased data, whereas Leti’s approach provides a compact, wireless and user-friendly solution.

This innovation resulted from our team’s combined expertise in optics, instrumentation, low-power electronics, simulation of light diffusion in the skin and embedded systems.

What research opportunities does this conformable patch breakthrough suggest for further medical benefits?

Obstructive sleep apnea (OSA) syndrome is an under-diagnosed pathology affecting up to 2 percent of adults, so there is a large group of potential beneficiaries.

Digital markers already identify for obstructive apneas and provide continuous monitoring and longitudinal analysis. Using this sensor will allow automated detection of several types of apneas and other respiratory problems.

Future R&D will address the complete development of the patch with other sensors, such as a PCO2 sensor (partial pressure of CO2 in the blood).
FIGHTING BIO-TERROISM WITH TECHNOLOGY: A MOBILE RICIN DETECTION SYSTEM

DOROTHÉE JARY
Scientist

What was the most challenging aspect of creating a mobile automated device to quickly evaluate exposure to the bio-toxin ricin?

When we accepted the challenge of producing a portable ricin detection system, our team knew it would require insight from many disciplines. Leti’s background in on-chip microfluidics for EWOD genetic analysis, particularly of individual cells, was essential to achieve rapid automatic detection. Our team was able to perform this in less than 90 minutes under field conditions. However, developing an integrated system also required a multidisciplinary expertise in biology, chemistry, material science, industrial design and instrumentation.

Using a PMMA material for the chip, rather than the PDMS traditionally used for toxicogenomics, provided a more robust device, suitable for point-of-care use, which could be easily produced in volume. Our interdisciplinary team designed an associated cartridge to hold reagents and control the process, including extraction of genetic material from a 10 μl blood sample and management of multiple parallel tests of RT-qPCR reactions. We also developed new competences in high-resolution machining of plastics, proprietary on-board micro-valve technologies and novel biological protocols.

The biggest advance in 2015 was on a task that sounds simple, and yet proved to be exceptionally difficult: evenly filling the bio-chip’s network of 28 micro-chambers with a precise mixture of the test subject’s mRNA and analytical materials. After struggles with uneven filling and bubbles created during heating steps, our team hit upon an audacious solution: using a short burst of relatively high pressure (up to 1 bar) to inject the mixture in less than one second. It was a great day when we achieved flawless filling and analysis!

How will this type of tool affect the health care field beyond first response to possible bio-weapon attacks?

By integrating a microfluidic system with innovative host-response analysis, our team has opened a wide range of biological analysis opportunities. One primary target is early point-of-care diagnosis of infectious diseases in biological fluids, through rapid and sensitive detection of molecular biomarkers. There are also a number of identified markets in the veterinary field, and in environmental monitoring applications such as food and water quality. Development is continuing, and our team is evaluating the creation of a startup company to commercialize these research achievements.

GIVING MEDICINE A CLOSER LOOK WITH SPECTROMETRIC IMAGE DETECTORS

MARKOPOULOS
Scientist

What will this innovation in dual-energy detectors mean for 2D X-ray imaging?

The energy of X-rays that are detected after going through an object depends on the composition of the object. Existing X-ray technology based on integrating detectors measures the mean X-ray absorption of the imaged objects without distinguishing the photons’ energy. Our early-stage, innovative detector design allows us to measure the energy of the X-rays it detects, i.e., it performs spectrometry.

For medical applications, comparing absorption levels at low and high energies distinguishes bones from soft tissues, as well as contrast media such as iodine or gadolinium.

The innovation we are working on also changes the format of detectors. Most present spectrometric or multi-energy detectors are either linear or small 2D detectors typically measuring 1 to 4 cm². These detectors generally use a photodetecting semiconductor X-ray absorber such as cadmium telluride (CdTe) coupled to a small silicon readout circuit.

Combining Leti’s expertise in global detector design, readout circuit design and characterization, image signal processing and other fields, we are working on a new solution compatible with large 2D detectors, e.g., 10x10 to 20x20 cm². For this, we are using a low-cost silicon readout circuit which detects X-rays of gamma rays and, at this time, a small 2D silicon readout circuit.

While the scintillator is cheaper than photoconductors, it is less sensitive, so our focus is on a detector with very low readout noise, e.g., 100 electrons. Because the detector will have a large 2D pixel matrix, we must make sure each pixel consumes very little power: less than 5 μW.

How will this breakthrough impact medical radiography?

If everything goes as planned, we will be able to develop a new solution compatible with large 2D detectors, which will significantly improve medical imaging.

For example, in traditional radiography, lung cancer nodules appear as bright spots that overlap the rib. This overlapping interferes with the detection of the nodules. By recognizing the X-ray energy, we see the patient’s rib, and we can remove them from the image. This provides a much better picture of the cancer nodules.

The technology could also be used outside of the medical field, e.g., for security or non-destructive testing applications.
TOWARDS ULTRA-HIGH ENERGY EFFICIENCY AT DEVICE AND SYSTEM LEVEL

COOLCUBE™
A LOW-TEMPERATURE ROUTE TO FURTHER 3D VLSI SCALING

How was Leti able to achieve first electrical results with CoolCube™ on 300 mm wafers?

As a reminder, 3D VLSI with a CoolCube™ Integration allows vertically stacking several layers of devices with a unique connecting-via density above a million/cm². To benefit from this via density and get improved IC performance, the top layer needs to be fabricated without impacting the electrical characteristics of the bottom one. As a consequence in order to achieve electrical results with CoolCube™, Leti had first to set up a fabrication flow for CMOS devices where the whole thermal budget was kept in the 600°C range.

We specifically focused on epitaxy, spacers, gate stack and junction annealing, harnessing the mainstream trend where process temperature tends to decrease. For dopant activation we relied on Solid Phase Epitaxy Regrowth to decrease the activation temperature from 1050°C down to 500°C. To achieve the 300mm demonstration we also had to elaborate a contamination containment strategy in order to guarantee Front-End-Of-Line wafer quality even after bonding for the top layer process.

How will this thermal budget breakthrough influence future CoolCube™ R&D?

This breakthrough validates the feasibility of CoolCube™ technology. We enter now in a new phase where we can focus on optimization of the performance and demonstrator fabrication. We can target applications and customize the top layers for their dedicated needs. As an example, CoolCube™ can be used to provide optimized CMOS partitioning where pMOS transistors are in the top layer whereas the digital part stays in the bottom one.

FOR MORE DETAILS

“3D VLSI CoolCube: An Alternative Path to Scaling”


“High Performance CMOS FDSOI Devices activated at Low Temperature”

DEMONSTRATING SILICON’S SUITABILITY FOR QUANTUM COMPUTING

MAUD VINET
Scientist

How were Leti and INAC able to demonstrate a quantum bit in SOI?

This world’s first demonstration of a qubit device on a foundry-compatible Si CMOS platform adopted SOI nanowire MOSFET technology to essentially fabricate a compact two-qubit JFET. The qubit was encoded in the spin degree of freedom of a two quantum dot placed under one of the gates. In order to demonstrate spin-state control, the classic analog of bit initialization or performing operations on a bit, we applied a RF electric field directly to the gate itself.

These results stem from more than a decade of research on using FDSOI silicon nanowire technologies to design devices with an accurate control of single charge. In 2015, we also demonstrated the design of quantum dots with diameters as small as 3.4 nm, and gate length in the 10 nm range. We very reliably controlled the charge state at room temperature, because of the large charging energy of the ultra-scaled quantum dots.

Quantum computing is widely regarded as representing a major new IT frontier. What will future R&D focus on?

Elementary silicon qubits devices made in academic research labs have already shown high-fidelity operation, in addition, transferring control and readout methods from GaAs spin qubits to Si-based structures has shown outstanding qubit performance in prototypical Si-Qubits, Si and 2DEG MOS qubits. But many challenges remain before industry will see a prototype computer. These include slow manipulation rates, low-fidelity two-qubit gate operations and, more generally, problems such as valley degeneracy, charge noise, nano-lithography control and device variability. These present a major hurdle for scaling.

We will continue our approach of leveraging the well-established device-processing and integration capabilities of industrial SOI technology. This offers industry-standard reliability and reproducibility, along with low-noise characteristics and low variation in device parameters - essential advantages for overcoming the main challenges.

FOR MORE DETAILS
1. Quantum Dot Made in Metal Clad Silicon Nanowire Field Effect Transistor Working at Room Temperature
2. “Si CMOS Platform for Quantum Information Processing”
   [IEEE VLSI Technology Symposium, Hawaii, USA, 2016].

MAINTAINING MOORE’S LAW WHEN LOW-POWER NANO DEVICES ARE PUSHED TO THEIR LIMITS

VALENTIN SAVIN
Scientist

Your i-RISC project proposed a unique approach to designing fault-tolerant nanoscale logic circuits with unreliable components. What can you tell us about that?

Nanoscale integration of reliable chips built with error-prone hardware is one of the most critical challenges for next-generation electronic circuit design. Our team in this EC FET Open project understood that fault-tolerant error correction could support innovative solutions for designing reliable systems even with unreliable components.

We also realized that this challenge called for a plan of attack that combined disciplines and techniques from many sources. We were the first team to pursue fault-tolerance by combining techniques from coding theory, graph-based multi-objective optimization and logic synthesis. We also leveraged ideas and techniques from a variety of research areas, such as communications and circuits/systems theory. The design approaches were also unique. For example, our team built effective error-correcting codes tailored to nano-era fault density and probability, and code architectures that provided reliable error protection even with faulty hardware. We also developed a design method that combines the code architecture with the hardware it protects, and optimized the design for energy consumption, latency and reliability.

The project even served up a few surprises. While prevailing opinion held that unreliable hardware is harmful, in some cases randomness from hardware noise actually improved the error-correction performance of some of the investigated decoders.

Our results paved the way toward reliable synthesis of logic circuits from unreliable components, as well as reliable storage and transfer of digital information throughout the chip.

How will these novel fault-tolerant design solutions influence future nanoelectronic circuit design?

The implications are both manifold and exciting. Reliable nanoscale integration of chips built with faulty hardware could lead to completely new solutions for next-generation, low-power electronic circuit design. This is especially important because the physical properties of nano devices are being pushed to their limits. The proposed fault-tolerance solutions may be particularly relevant to the design of low-power integrated circuits in the presence of deep submicron noise.

More generally, applying modern coding theory to the development of novel fault-tolerant devices provides a new measure of performance in memory and computing systems. In the future, the proposed techniques may be used in post-CMOS technologies, and the project opens a promising path to maintaining Moore’s Law.
VERTICAL RRAM TECHNOLOGY AND THE QUEST TO IMPLEMENT ARTIFICIAL SYNAPSES

ELISA VIANELLO AND GABRIEL MOLAS
Scientists

How does Leti’s new vertical RRAM development suggest a novel pathway to emulating synaptic behavior?

Emerging back-end resistive memory devices (RRAM) have been viewed as optimal candidates to emulate biologic synaptic behavior at nanometer scale, because their conductance can be easily modulated by applying very low biases. In addition, they can be easily integrated with CMOS-based neuron circuits.

Previous Leti projects proposed various RRAM technologies (PCM, CBRAM, OxRAM) and circuits to emulate the synaptic behavior in neuromorphic circuits. Recently, we proposed solutions based on a Vertical RRAM (VRAM) technology that offers significant area gain with respect to neural networks in planar configuration. Our VRAM solution allows one VRAM pillar per synapse and would integrate VRAM cells in a multi-layered, V-NAND-like structure. This is a simple and valuable 3D process to achieve high memory density.

How will this innovative combination of resistive memory and 3D integration affect future development in this field?

The next step is the fabrication of a full silicon demonstrator based on RRAM for synapses and advanced CMOS logic for the neurons. Right now, we have system-level simulation supported by data obtained with standard memory arrays. We demonstrated that neural network chips can be used for detecting patterns in complex data, and they are suitable for both visual and auditory data analysis.

RRAM technologies allow us to realize low-power circuits that are suitable for embedded systems. VRAM could be a cost-effective and competitive technology for future mass data-storage applications. Looking further ahead, neural network chips may be used to enable the design of future sensory processing or autonomous systems, such as a Brain Computer Interface making decisions based on real-time on-line processing for rehabilitation purposes.

MIMICKING THE BRAIN’S MEMORY-STORAGE CAPABILITY FOR BETTER POWER MANAGEMENT

What did your project discover about brain structure that can overcome power-management challenges in the Internet of Things?

Neural clique networks in the brain perform a powerful associative role in memory storage. Specific, cognitively significant images enable people to access detailed memories from snippets, such as remembering the end of a song after hearing its beginning.

Inspired by this highly efficient associative process in biology and brain structure, we partnered on a thesis project with a team from TELECOM Bretagne, which proposed a new kind of artificial neural network. We built on that concept, providing expertise in digital design and silicon technology.

Our innovation, which enables power efficiency in a small silicon footprint suitable for IoT applications, demonstrated that features of neural clique networks can provide quick, optimal power management in electronic devices. When a piece of information, a “key”, is fed into the network, the network recalls a corresponding, previously stored value in a few nanoseconds and with low power consumption.

This efficient “key-value” association makes it possible to dynamically retrieve an optimal power configuration even in a rapidly changing environment.

In fact, thanks to their brain-like properties, neural networks outperform traditional algorithms in some applications. The implementation in silicon of these wire-dominated systems created power-use challenges that Leti’s 3D-design expertise overcame by significantly reducing interconnect lengths.

How will this discovery influence future R&D?

Because this technology provides a new trade-off between power consumption, area and performance for associative memory, several applications fields may benefit from networks of neural cliques. Future research will explore different applications in the field of power-constraint devices or near-sensor data processing. There also are potential applications in deep learning, image classification and language processing.
5. MANAGING INCREASINGLY COMPLEX SYSTEMS EFFECTIVELY AND SECURELY

Filter-Bank Multi-Carrier Technology: Managing Explosive Growth in Wireless Data Traffic with TV White Space / 44

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A Novel Architecture for Mobile Devices? Stay Tuned / 49
FILTER-BANK MULTI-CARRIER TECHNOLOGY: MANAGING EXPLOSIVE GROWTH IN WIRELESS DATA TRAFFIC WITH TV WHITE SPACE

How will Leti's new cognitive radio technology ease the predicted bottlenecks in wireless data transfer?

Between 2016 and 2020, there will be a nearly eightfold increase in global mobile data traffic, according to forecasts from Cisco. In the absence of additional radio spectrum availability, we will have to rely on existing frequencies to meet that demand. Last year marked an important step towards meeting that challenge with TV White Space (TVWS). Through the adoption of Leti’s Filter-Bank Multi-Carrier (FBMC) technology, now implemented in an international standard.

We leveraged Leti’s large wireless communication IP portfolio, including expertise in cognitive radio that dates to 2006. That helped us develop, over four years, a flexible, efficient mechanism for utilizing available TVWS spectrum without interfering with television broadcasts. It’s rewarding to see our technology poised to be a potential fundamental enabler for implementation in rural broadband, campus-scale networking and wireless LANs worldwide.

The FBMC approach to flexible radio allows wireless devices to change communication parameters on the fly to utilize whatever chunks of TVWS spectrum happen to be available at any given moment. In addition to offering a 15 percent spectral-efficiency improvement over existing OFDM technology, FBMC has the even more important advantage of 89 percent less interference with adjacent channels. That means it can have at least twice the range of OFDM for the same transmit power, or it can increase spectral efficiency even more (two to three times) through larger constellations, thanks to better link budget.

So, could this innovative technology be part of 5G networks?

FBMC has been implemented in the wireless communication standard IEEE 1900.7–2015. There is currently a vigorous discussion about which air interface will be selected for future 5G communication networks, and FBMC is clearly a contender. We believe that having FBMC included in an IEEE standard will increase the appeal of this approach in the 3GPP discussions on 5G. FBMC shows a very good spectral efficiency and low interference profile, which is required as spectrum becomes more congested. In addition, the architecture designed at Leti, namely Frequency-Sampling FBMC (FS-FBMC), dramatically reduces the implementation footprint compared to classic FBMC approaches.

FOR MORE DETAILS

1. IEEE Standard 1900.7 for White Space Dynamic Spectrum Access Radio Systems

SHAPE CAPTURE SOLUTION TRACKS CHANGES IN CRITICAL INFRASTRUCTURE

How did Leti create a novel way to monitor structural health from the inside?

We developed an embedded, MEMS-based, inertial-sensor system that provides deformation and shape data in infrastructure such as pipes, bridges and wind turbines. Our technology and methods perform well even in harsh environmental conditions.

Building on this innovation, we worked with our industrial partner Technip to develop MorphoPie, an embedded shape-capture technology that provides 3D curvature monitoring in underwater pipes.

Our team used two fields of upstream research: signal processing and advanced geometrical and dual models that were part of three PhD and two postdoc projects; communication protocols: more sensors and higher acquisition frequency, from research work came out through internships and external initiatives.

How will this innovation impact R&D in structural health monitoring?

This new way to detect damage and improve safety for structural systems can be implemented either as a short-term monitoring tool in which our smart system is deployed for special test sessions, or as a long-term solution, in which sensors are integrated directly in the structures and provide regular data over their lifetime.

As an analytical tool, the sensors can detect and characterize damage or evolution of critical parameters within the infrastructure. This improves reliability and safety and lowers maintenance costs. In time, the sensors will provide a database of real measurements that will allow comparison with simulations or models, which will allow companies to modify and improve their models.

FOR MORE DETAILS


1. Dominique Noguet
2. Nathalie Sagun-Sprynski

COGNITIVE RADIO

BREAKTHROUGH: Achieving better performance than traditional OFDM technology -- without the need for costly and non-flexible filtering -- FBMC’s modulation is inherently spectrally localized, which reduces interference with adjacent bands.

WHY IT’S RELEVANT: As part of an IEEE standard, the FBMC technology serves a huge demand for the growing wireless data traffic, allowing very flexible channel allocation while fulfilling regulators’ rules.

MOVING FORWARD: Offering standardized, IP-protected implementations of FBMC-based flexible radio to network operators worldwide, while improving the MAC protocol of the IEEE 802.11 standard to provide better quality-of-service support.

STRUCTURAL HEALTH MONITORING

BREAKTHROUGH: Embedding MEMS-based, shape-capture systems in materials to monitor structural changes.

WHY IT’S RELEVANT: Improves infrastructure safety and provides data to compare performance with models, over time.

MOVING FORWARD: Use inertial-sensor networks distributed on a surface or in a closed space to continuously monitor the shape of 3D space.
**FIRST NEMS IN POLYSILICON FOR 3D SENSORS ON CMOS**

**ISSAM OUERGHI**
PhD Student

**BREAKTHROUGH:** Low-temperature fabrication of nanodevices with critical dimensions of ~50 nm, after back-end deposition and with back-end-compatible process flow.

**WHY IT’S RELEVANT:** This technology will enable highly dense populated sensors, of great importance for gas sensing and mass spectrometry, and replace expensive monitoring equipment with more sensitive, portable NEMS-based devices.

**MOVING FORWARD:** Integration of multifunctional sensors in various systems for embedded on-chip multisensor analyses or mass spectrometry, based on arrays of NEMS resonators.

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**FIRST NEMS IN POLYSILICON FOR 3D SENSORS ON CMOS**

ISSAM OUERGHI
PhD Student

**HAS LETI BROKEN NEW GROUND IN FABRICATING POLYSIL NEMS AT LOW TEMPERATURE?**

Current state-of-the-art polysil sensors are MEMS fabricated at higher temperatures, front-end compatible. Leti’s breakthrough is low-temperature fabrication of nanodevices with critical dimensions of ~50nm, after the CMOS back-end deposition.

Our team developed a back-end-compatible process flow because of the thermal budget restriction imposed by the CMOS process and the back-end.

Room-temperature PVO amorphous silicon deposition and laser annealing enabled fabricating NEMS at very low temperature. Laser annealing locally provides a very high temperature— the melting point of amorphous silicon — while maintaining a low temperature for the underlying layers. The temperature of the whole process does not exceed 400°C.

**HOW WILL LOW-TEMPERATURE MEMS FABRICATION IMPACT FUTURE DEVELOPMENT OF NANOSSENSORS?**

Leti believes 3D fabrication of NEMS following back-end deposition is a very effective and compact solution for manufacturing embedded nanosensors.

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**FOR MORE DETAILS**

“Polysilicon Nanowire MEMS fabricated at low temperature for above IC MEMS mass sensing applications”

“High-performance polysil NEMS fabricated at low temperature with UV laser annealing”

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**HOW CONTROL THEORY BOOSTS POWER MANAGEMENT IN SENSOR NETWORKS**

**SUZANNE LESEQ**
Scientist

**WHAT DOES LETI’S NEW APPLICATION OF CONTROL THEORY REVEAL ABOUT POWER USE IN SENSOR NETWORKS?**

New services for smart environments such as cities, buildings, transportation and agriculture require advanced technology and new sensor architectures—with the best compromise between the service and power consumption.

Nevertheless, today, the number of sensor nodes deployed in smart buildings is larger than needed, because of the lack of coordination in building automation systems. In other words, the independent building-automation systems don’t share data.

By taking on an application- and service perspective, we figured that some nodes could sleep, thus saving energy, with no drop in system performance. We thus worked on this optimization challenge using two approaches of cooperation: model predictive control (MPC) and hybrid dynamical system (HDS) control—and we found out that the service lifetime of the sensor networks could be extended by up to 30 percent.

These results suggest exciting possibilities for many application domains, especially smart farming or monitoring of natural environments, such as forests, where nodes are far apart and only rarely need to “wake up” and transmit.

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**FOR MORE DETAILS**

“Automatic assignment of sensor nodes using hybrid Dynamical System approach”


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**WHAT DOES THIS DISCOVERY SUGGEST FOR FUTURE R&D INVOLVING SENSOR NETWORKS?**

The energy-management strategies proposed provide a substantial increase in sensor-network battery lifetime, and, therefore, of service availability. These strategies also will provide breakthroughs at the sensor-node level. In fact, by implementing wake-up radio mechanisms at the node level, the nodes will be woken only when strictly required by the application. That would lead to a real “on-event” control in off-event sensor-node switching. As a result, the whole sensor network will be event-based, instead of sending data on a regular basis, with a huge power-efficiency gain.
A NOVEL ARCHITECTURE FOR MOBILE DEVICES? STAY TUNED

How did Leti researchers achieve this major advance on the true frequency-tuning front?

Tunable filters have been described as a “Holy Grail”. Indeed, the Bulk Acoustic Wave (BAW) or Surface Acoustic Wave (SAW) resonators making up the many passband filters located in the RF front-ends of mobile phones exploit mechanical vibrations of piezoelectric materials to generate electric resonances. This is exactly the operation of quartz resonators used for timing applications, but transferred here to G-Pi frequencies. The drawback is that mechanical resonances are intrinsically fixed-frequency. To overcome this physical limitation, we proposed resonator structures capable of exhibiting a tunable mechanical resonance frequency, through the use of the so-called “acoustoelectric” effect. This means that the velocity of sound in a piezoelectric material depends on which electrical circuit this material is connected to. In principle, we add a piezoelectric “tuning layer” to a conventional BAW resonator to extend the resonant cavity by a material with a tunable equivalent stiffness. In practice, this means building a resonator made of two piezoelectric layers, instead of only one for conventional devices.

Making such a new generation of RF resonators required integrating thin films exhibiting tuning piezoelectric properties. This is the breakthrough in which Leti scientists have been involved for more than 15 years. Leti has worked on bulk acoustic waves (BAW) resonators since 2003, which built a strong foundation in the design of acoustic components and the integration of piezoelectric materials. The actual fabrication of a demonstrator of tunable filters in 2015 leveraged the specialized know-how acquired over the past decade on the transfer of thin monocrystalline piezoelectric films.

Two specific fields of expertise that our team contributed were essential to our results. First, the ability to understand how acoustic resonators operate and to model and design complex acoustic resonators. Second, the capability to integrate and optimize thin piezoelectric films, particularly lithium niobate, which offers the outstanding piezoelectric properties required for true frequency tuning.

Building on the foundation of earlier research, we focused on developing a new generation of RF resonators that rely on bulk acoustic waves and leveraging lithium niobate’s piezoelectric properties. All came together in our transfer of two piezoelectric films.

The implications are significant for 4G and 5G networks. Where do we go from here?

Current mobile phones have more than 40 RF filters, based on acoustic resonators that are fixed-frequency. This number could more than double for 4G and 5G networks – except that’s just not realistic for size, cost and complexity.

We think filters capable of being tuned over a large range – say 15-20 percent of their center frequency – have the capability to totally reshape the way RF front-ends in mobile devices are built. They will not only reduce the number of components, but will also support a completely new architecture. It may also impact opportunistic radio systems, or enable efficient and low-power, software-defined radios, since it provides increased flexibility and re-configurability.

This advance could lead to communication systems with lower power consumption, higher signal-to-noise ratios and/or improved linearity.
PEOPLE

AWARDS

LETI’S RESEARCH DIRECTORS AND INTERNATIONAL EXPERTS
AWARDS

A SMART GAMMA CAMERA TO SPOT AND IDENTIFY RADIOACTIVE NUCLIDES
Guillaume Montferrand’s poster showing how Leti’s portable spectrometric gamma camera allows simultaneously locating and identifying radionuclides in the field of view won Best Poster Award at ANIMMA 2015 in Lisbon.

The camera is based on a unique detector technology that combines spectral and spatial resolution at low cost by using dedicated signal processing known as sub-pixel positioning. Sub-pixel positioning was first integrated in a gamma camera in 2013 at Leti.

DOCTORAL CANDIDATE WINS BEST PAPER AWARD
PhD candidate Natalija Jovanović won the 2015 Best Paper Award at the IEEE SOI-3D Subthreshold Conference. In the paper, she presents Leti’s investigation of the design architecture and the optimum resistance state values for high-endurance, high-speed energy-efficient OxRAM-based non-volatile flip-flops (IVFF) for ultra-low power applications in 28nm FD-SOI. The paper was co-authored by thesis supervisor Olivier Thomas de Leff, co-supervisors Prof. Boris-Je Nikolic of the Berkeley Wireless Research Center, and thesis director Prof. Linda Nuismer, Telecom ParisTech. Natalija received her PhD in March 2016.

WHERE ROBOTICS MEETS HUMANS
Andres Ospina, a PhD student in robotics, won the 2015 Mechatronics Award at the European Mechatronics Meeting (EMM), for his research on a tactile sensing system ready for integration in small robotics fingers or human-machine tactile interaction.

Based on 3-axes MEMs force sensors, the innovative system provides a sensitive surface capable of measuring the contact position, the force components and the torque components.

BEST PAPER AWARD FOR WORK ON ULTRA-LOW POWER ICs
Research on innovative power reduction techniques for ultra-low-power non-volatile integrated circuits won the Best Paper Award at ASYNSync Conference 2015. The paper was co-authored by Edith Benegf, a senior scientist at Leti, and two partners, Elsar Zanettol of CEAS/SPINEC, and Gregory Di Pendias of CNRS/SPINEC. Their project was a first demonstration of the implementation of the non-volatile C element and half-cell, based on a hybrid technology that incorporates both CMOS FDSOI and 40nm DTMFAM magnetic technologies.

In their project, the team implemented non-volatile asynchronous circuits that have a quasi-zero leakage consumption, almost instant back-up and wake-up time and are robust even in unstable power-supply environments.

ROBERT ESTIVILL STRoud HONORED FOR ATOMIC-PROBE TOMOGRAPHY RESEARCH
Robert Estivill Stroud won a Presidential Scholar Award from the Microscopy Society of America for his research that showed how atomic probe tomography can be used to characterize the chemical composition of 14nm-node devices in three dimensions with a sub-angstrom scale.

This breakthrough provides fundamental knowledge of local dopant distributions in devices, primarily born that cannot be obtained in three dimensions by other characterization techniques. This method will be used in other research programs involving atomic-probe tomography.

ROBERT ESTIVILL STRoud HONORED FOR ATOMIC-PROBE TOMOGRAPHY RESEARCH

LETI PAPER HONORED BY IEEE ELECTRON DEVICES SOCIETY

Team members were Sylvain Barnaud, Jean-Michel Hartmann, Virginie Maufouru-Audouin, Lucile Testi, Vincent Delaey and Dominique Latond.

RECONFIGURABLE TRANSMIT-ARRAY ANTENNAS PROJECT EARNS BEST PAPER AWARD
PhD student Luca Di Palma won the Best Paper Award at the Journées Nationales Microondes conference in Bordeaux for his research that showed how a new architecture of reconfigurable transmit-arrays antennas enables a thickness reduction of 45 percent compared to standard ones.

The innovation resulted from using four local sources instead of one, and investigating the impact of this architecture change in the radiation performance. The Leti lab was the first to demonstrate this architecture, establishing it as a leader in reconfigurable transmit-array antennas.

Several prototypes have exhibited innovative technical solutions and superior state-of-the-art performance.

THE BOOK OF NEMS
Highlighting International achievements in NEMS research and development over the years, Laurent Dufour and Julien Arcamone wrote a book, “Nanoelectromechanical Systems”, which has been published in French and English. It is a comprehensive and didactical review of this field. It will help students and researchers discovering and understanding NEMS.

The book presents Leti and other organizations’ successes, and knowledge in NEMS to the scientific community, which may encourage students to come to work at Leti, and open pathways for Leti to join national and international consortia for academic collaborative projects.

SIMON DELEONIBUS: A PIONEERING CAREER IN NANOTECHNOLOGY
Simon Deleonibus, former director of Leti’s Components and Technology Division, was selected Fellow of The Electrochemical Society (ECS) in 2015. The award recognizes the scientific breakthroughs and achievements that distinguished his long career.

Early in his career, he co-invented a contact-free technology principle, which, in its longest version, improved the speed and reduced the costs of microprocessors. This technology is used today as a standard process by the microelectronics industry.

In 1999, together with his team at Leti’s Electronic Nanodevices Laboratory, he realized the world record for the smallest transistor and his lab pioneered numerous process modules enabling and anticipating the future miniaturization of integrated circuits.

He received the 2005 French Technologies Academy Grand Prix, an annual award given to an engineer for his “innovation, development and proof of usability by the industry.”

In 2006, Deleonibus was named Fellow by the IEEE for his contributions to nanoscale CMOS device technology.

LETI AND INTERNATIONAL PARTNERS WIN BEST PAPER AWARD AT ECOG 2015
Marc Arqua  
International Expert  
Analog electronics, X-ray image sensors

Marc Belleville  
Research Director  
IC design and microsystems

Barbara Di Salvo  
Research Director  
Memory technologies, neuromorphic devices

Lea Di Ciecchio  
Research Director  
Bonding techniques, hetero-integration and power devices

Laurent Dueso  
Research Director  
Millimeter-wave wireless communication systems, millimeter-wave circuits, antennas and technologies

Thomas Ernst  
Research Director  
Logic devices and sensors

Olivier Faynet  
International Expert  
Process integration and devices physics of SOI technologies

Jean-Marc Fedeli  
International Expert  
Silicon Photonics and optical sensors

Guy Foullet  
International Expert  
Optoelectronics devices, characterization and physics

Yves Foullet  
International Expert  
Microfluidics, Lab-on-a-chip

Franck Feurmel  
International Expert  
Direct bonding techniques and hetero-structures

Patrice Gergaud  
International Expert  
X-ray characterization in micro and nanotechnologies

Pierre Grangot  
Research Director  
Data processing for biomedical devices

Jean-Michel Hartmann  
Research Director  
Epilayer, hetero-structures for microelectronics and optics

Laurent Herault  
International Expert  
Communication systems, radiofrequency networks and architectures

Suzanne Leaceq  
Research Director  
Control theory applied to SoC and power electronics, data fusion

Pascal Malley  
Research Director  
Biosensors, bio-electrochemistry

Francois Martin  
International Expert  
Microelectronic Materials and Processes

Sylvie Mayargues  
International Expert  
Wireless communications, digital communications, signal processing, propagation

Catherine Mestais  
International Expert  
Microtechnologies for health, medical imaging

Dominique Morchon  
Research Director  
Circuits and Systems Design for Telecommunication Applications

Hubert Monnet  
International Expert  
Molecular adhesion, direct bonding, thin film transfer

Laurent Pain  
International Expert  
Lithography - optical, Electron beam, Imprint

Gilles Poupin  
International Expert  
Advanced Packaging and 3D Integration

Christine Raymond  
International Expert  
RF Technologies and Components

Gilles Reimbold  
International Expert  
Electrical characterization of nanoelectronic devices, physical modelling and reliability

Alexei Tchelikovsky  
Research Director  
Optoelectronic devices, photonics

Francoise Tempier  
Research Director  
Display technologies and systems
COLLABORATIONS

A DYNAMIC LOCAL ENVIRONMENT

LETI, A CARNOT RESEARCH INSTITUTE

SCIENTIFIC COLLABORATIONS
A THRIVING ENVIRONMENT FOR RESEARCH

Leti, a technology research institute at CEA Tech, is located in the French Alps, in the heart of the dynamic city of Grenoble. Grenoble, also called the French Silicon Valley, has the highest concentration of R&D jobs in all of France. 25,000 professionals work in world renowned European research facilities, national and university research labs and industrial R&D centers. Its unique collaborative ecosystem has earned Grenoble worldwide recognition as a model for innovation. Grenoble is also home to a large international academic community with over 62,000 students of 160 different nationalities.

GIANT, Grenoble’s Innovation campus for Advanced New Technologies, has become a center of globally relevant resources and assets that enable the scientific community to thrive. Offering competence, connections and capabilities in education, research and innovation, the GIANT campus fosters collaboration and creative interaction among researchers and students from universities, research labs and Industry. Acting as a catalyst for much of the cooperation, CEA joined with seven other major players to launch the GIANT campus, including the University of Grenoble Alpes (UGA), the National Scientific Research Center (CNRS), Grenoble Institute of Technology (INPG), Grenoble School of Management (GEM), the Institut Laue-Langevin (ILL), which provides one of the most intense neutron sources in the world, Europe’s largest synchrotron X-ray source (ESRF) and the European Molecular Biology Laboratory (EMBL). Today, groundbreaking fundamental and applied research is being carried out at GIANT in the areas of information and communication technologies, alternative energies and micro and nanotechnologies for biology and healthcare.

Within GIANT, Minitec is an international hub for micro and nanotechnology that brings together world-class capabilities and infrastructure for researchers, students, entrepreneurs and start-up creators. The Minitec campus is a multicultural melting pot of ambitious projects and advanced learning where exchanges and cooperation of all kinds take place. Leti is the main technological research laboratory of Minitec, interfacing both with academia and industry, bridging the path between science and innovation.

SUSANA BONNETIER
Leti International Academic Collaborations Coordinator

LETI IS A CARNOT RESEARCH INSTITUTE

The Carnot Label is granted to French public research structures dedicated to fostering innovation with industrial partners.

Marie Semeria during a Carnot Institute meeting

Founded in 2006, the Carnot program was designed to recognize and support research institutes with high scientific standards, professionalism and a commitment to develop high quality research partnerships with industry, from SMEs to large companies.

Carnot institutes conduct upstream research, are capable of conceiving applications and operational research and engage in partnerships and collaborative research that help improve the competitiveness and growth of their business partners. A total of 60 M€ of French state funding is allocated each year to help the institutes invest in research projects that anticipate future scientific and technological needs. These projects are carried out with top-notch academic partners and industrial world-wide such as the Fraunhofer Institute, VTT, CSEM, TNO, EPFL, ETH, Stanford, UC Berkeley, Caltech, MIT, AIST, and INIST to name a few.

The 33 Carnot institutes cover a very wide range of fields, serving all major business sectors. They represent 15% of France’s public research workforce and carry out 55% of all public R&D contracts financed by corporations in France. The resulting patented inventions become novel technological solutions through co-development with industrial partners.

The Carnot institutes share a common charter of professional standards and are capable of championing them individually and collectively. The Association of Carnot institutes, or AICarnot, acts as coordinator of the Carnot network. Leti’s CEO, Marie Semeria, has been president of AICarnot since the fall of 2014.

To find out more about the Carnot Institutes:
www.instituts-carnot.eu
‘LETI IS THE BEST CHOICE’
FOR VISITING RESEARCHERS

Stanford University Prof. Yoshio Nishi came to Grenoble to head the Chair of Excellence Project funded by the Grenoble Nanosciences Foundation, and to work on the OxRAM project with Leti and IMEP-LaHC. The four-year project focused on developing a new memory technology: oxide-based resistive memories, in particular HfO2-based.

Among its achievements, the team studied the impact of alloying/doping HfO2 with other materials for improved RRAM performances. Using ab-initio calculations, they pointed out that incorporating aluminium in HfO2 results in better thermal stability of devices, due to shorter bond lengths associated with their higher atomic concentration. This has been confirmed by experiments.

Prof. Nishi, a professor of electrical engineering, spent several months in Leti’s memory lab, and co-tutored a PhD student and a post-doc. The team also published eight papers.

His relationship with Leti began about 30 years ago, when he was director of R&D at Toshiba and he met Leti scientists at conferences. “I have known Leti for a very long time,” he said. “The culture is very welcoming and there is a very strong work ethic. When I left the office at 7:30 p.m., sometimes people were still working, which is very different than in the U.S. and Japan. But I also was impressed at how the French people spent their weekends focused on their families.”

He found that Leti’s openness and commitment to innovation provide an encouraging setting for serious researchers.

“After lunch in the cafeteria, people gathered in a space for coffee, with a wonderful view of the snow-covered mountains,” Prof. Nishi recalled. “It was very nice to speak with Leti people in that setting and, in fact, some very interesting ideas came from those discussions. I tell my colleagues that if they have the chance to work in a foreign country, Leti in Grenoble is the best choice.”

PROTECTING BRAIN CELLS
FROM PARKINSON’S DISEASE
WITH NEAR-INFRARED LIGHT

Prof. John Mitrofanis clearly remembers the day in 2015 in Clinatec’s operating room when the multidisciplinary team in a pre-clinical trial proved their near-infrared light (NIR) treatment had stopped the progression of Parkinson’s disease in monkey brains.

“It was a ‘eureka’ moment!” he said. “Light bulbs went off in our minds. We hugged each other!”

Prof. Mitrofanis, a professor of anatomy at Sydney University in Australia and a specialist in brain-tissue examination, had special reason to be thrilled. The Clinatec team was working on the NIR treatment they had discovered as a neuron-protecting agent. Applied externally, the technique worked on mice, but the thickness of the skull and the size of the brain in larger animals blocked that treatment.

Leti developed an implantable optical-fiber delivery system to apply the light intracortically directly on the affected monkey brain cells. Prof. Mitrofanis and Clinatec scientists confirmed that the NIR stopped PD brain-cell destruction. Preparations for a clinical trial are underway.

Prof. Mitrofanis’s collaboration on PD research with Clinatec co-founder Alain-Louis Benabid goes back 15 years.

“There is no other place like Leti and Clinatec – that combines the expertise of medical and biology specialists with engineers – and brings people together for the good of a project,” he said.
FRAUNHOFER INSTITUTE FOR TELECOMMUNICATIONS/HEINRICH HERTZ INSTITUTE

LETI’S INTERNATIONAL ECOSYSTEM POWERS GLOBAL ADOPTION OF WIRELESS ADVANCES

Technology development was only part of the agenda when Berlin’s Fraunhofer Institute for Telecommunications began working with Leti on millimeter-wave radio for cellular wireless networks. “To succeed, research advances had to be easily adoptable by network companies worldwide and the Leti-Fraunhofer partnership provided the ideal means of ensuring this,” explained Thomas Haustein, head of Fraunhofer’s Wireless Communications and Networks Department. “Leti has an international ecosystem and is well connected outside Europe. That’s essential for technology dissemination, and we’ve seen it in other joint 5G-related projects.”

The millimeter-wave project received substantial standardization contributions from Intel and Orange in Europe, and KDDI and Panasonic in Japan. “That created momentum, and paved the way for integration after the research was completed,” he noted.

To be sure, the project partners’ complementary technical expertise was critical – Fraunhofer’s deep knowledge of lower layers in the communications stack and antenna propagation fit perfectly with Leti’s expertise in radio resource sharing, modeling and measurement.

“Working with Leti has a special momentum, because of its broad cultural background,” Haustein said. “Going to the next level of forming a European-Asian consortium requires embracing cultural diversity and understanding of how to make things work, and Leti is a great partner for this.”

MIT – INTERNATIONAL SCIENCE AND TECHNOLOGY INITIATIVES

MIT STUDENTS FIND CHALLENGING REAL-LIFE PROJECTS AND A WORK-LIFE BALANCE AT LETI

Students from MISTI – a MIT’s flagship education program – hadn’t realized how much they like doing research at the nanoscale until they went to Leti. According to Molly Schneider, MIT-France Program manager, the custom-tailored internship experience at Leti helped her students expand their academic focus and envision research as a career.

Working on projects at Leti has made MIT students appreciate their potential. “They want to solve challenges and feel that they are contributing”, notes Molly, “and being part of a research team is a powerful experience. Projects at Leti are international and multidisciplinary, which is not the case everywhere.”

At Leti, students are in the academic, industrial and large research infrastructure environment of Grenoble. As part of GIANT’s internship program, they are exposed to research taking place in other laboratories and get involved in social and cultural events. “There is a real commitment to give the students an immersive experience”, says Molly, “and the support offered by GIANT is unique in Europe.” Students also appreciate France’s work-life balance. “They see that people work hard to move their projects forward and are still able to share lunch with friends and go on vacation.”

Leti has been hosting MIT students since 2008. These have developed a long-lasting relationship with their supervisor, a real mentor in most cases. “Access to the nanotech equipment at Leti is another plus”, adds Molly. “One student found herself working in seven different lab spaces including clean rooms, biogas and chemistry labs and machine shops!” During one of Molly’s visits to Leti, a student shared his enjoyment with what he was doing. “His excitement was palpable and that is what I feel most when I come to Grenoble.”
THINKING BIG AT LETI: SUCCESSFUL COLLABORATION IN OPTICAL TOMOGRAPHY

The Department of Physics at Politecnico di Milano (PolMI) and Leti are developing new optical imaging approaches combining innovative detectors developed at the university, and Leti’s new time-resolved diffuse optics approaches.

“The key technological advance involves applying time-domain detection as a way to go deeper into tissue and get images with functional and chemical information for clinical diagnostics,” said Prof. Antonio Pifferi at PolMI, who leads the Department of Physics’ collaboration with Leti. “We want to extract information coming from deeper regions in the brain, for instance, or from suspect lesions in the breast.”

Prof. Pifferi said that scientists at Leti have “an extremely high level of expertise and professionalism, adding that Leti’s culture encourages people to think beyond the immediate projects, with a strong focus on industrial and clinical translation.

“Our collaboration actually goes beyond the professional aspect. When I come to Leti in Grenoble, I always feel like a family atmosphere, interactions are friendly and easy-going,” he said. “In addition to the ongoing work, we discuss new project ideas and engage with new fascinating concepts — and this is what eventually makes research enjoyable and fruitful.”

FROM BASIC RESEARCH TO THE IOT: ‘REALLY GOOD WORK AND FIRST APPLICATION OF THE THEORY’

Prof. Claude Berrou from the Graduate School Telecom Bretagne teamed up with Leti researchers on a PhD project that built on the school’s work in artificial neural networks. Their innovation, which enables power efficiency on a small silicon footprint suitable for Internet of Things applications, demonstrated that features of neural clique networks can provide quick, optimal power management in electronic devices.

Prof. Berrou, who previously developed a new family of quasi-optimal error-corrector codes called turbo codes, said Leti’s expertise and its emphasis on applications make it a top institute for visiting researchers.

“I am deeply interested in applications for research,” he explained. “Previously in France, technology was not considered important for academic researchers. But this has changed now, and academics are increasingly looking at applied science and technological applications.”

Leti shares this vision and opens its doors to scholars interested in putting basic research to work to improve people’s lives.

“I’m very pleased with the experience of this project at the scientific level. It was really good work and the first application of the theory,” Prof. Berrou said. “We had several publications, and thanks to these, we proved the importance and the success of our theories.”
FORSCHUNGSZENTRUM JÜLICH (FZJ)

POLITECNICO DI TORINO

LETI STAYS PLUGGED IN TO BASIC RESEARCH IN THE GRENOBLE ECOSYSTEM

For Dan Buca, a group leader and senior scientist at FZJ, R&D that has an impact takes more than scientific knowhow. It must also be based on a foundation of strong relationships among researchers. Such partnerships are at the heart of Leti’s culture.

“The personal relationships and the ease of collaborating with Leti brings success to our projects,” he said. “They listen. They don’t start sentences with ‘no, this is complicated’ or ‘we first need to get a project number,’ and so on. They first try to see if the problem can be solved and then they look for ways to do just that.”

CEA and FZJ, a member of the Helmholtz Association of Institutes, have had cooperation agreements since 2008 to explore common areas of interests such as high-performance computing, new energy technologies and nanotech materials science.

Dr. Buca praised Leti’s anicuity and said that it is “the only research institute in Europe that combines a strong focus on basic research, whose payoff may or may not come for many years, with a commitment to bring new technologies to market in the near term.”

He added that “what Leti still has, and other major research groups in Europe seem to have lost, is the freedom of playing in both the fundamental research and applied research arenas.”

Dr Buca gives the Grenoble Research ecosystem some of the credit for that.

“Basic research in Grenoble’s ecosystem keeps Leti active in prospective developments that could have a strong impact in 15 years. Working with other research institutes is the best way to stay informed about on-going basic research and its technological potential,” Dr. Buca said.

‘CROSS-FERTILIZATION’ PREPARES GRADUATE STUDENTS FOR RANGE OF PROJECTS

Politecnico di Torino, one of Italy’s top engineering and IT universities, takes pride in its educational programs, international appeal (its students represent over 100 countries) and extensive research connections with technology-driven companies. Those qualities are all reflected in its collaboration with Leti, now in its fourth year, which enables master’s and PhD students to spend six months working with research teams in Grenoble.

“It gives us excellent access to technologies, and helps calibrate what we do in our own programs,” said Professor of Computing Engineering Massimo Poncino, who has placed a number of students in the program. “Leti is tightly connected with its local industrial partners, who work on the very latest advances, and it’s important for our students to see their priorities in circuit logic, digital systems and other areas.”

The program has become a source of cross-fertilization, with students bringing back perspectives and knowledge that have been immediately helpful on other projects, Poncino said. Several participants have coauthored conference and journal publications, and one participated in a patent filing for a circuit that can reduce power consumption by relaxing its precision depending on working conditions.

A big plus: most Politecnico students work in Leti’s small laboratory research teams of two or three scientists who are permanent staff, so they get immediate responsibility for achieving research goals.

“Sometimes with other labs, people might only get an hour a week with colleagues. At Leti, you get feedback and interactions every day — it’s more like working in an experimental office,” Poncino explained. “Leti and Politecnico believe strongly in this very successful program.”