Heading for new memories

CEA-Leti strategies, assets, and technological progress

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In search of memory

Memory has once again become a priority, for two reasons:

Data is being produced at an exponential rate. With the massive use of connected objects and smart systems, along with the increasing number of data centers, the world will most likely be generating 175 million terabytes by 2025—10 times the volume produced in 2015. Improving the performance and density of memory is crucial.

Storing and transferring data consumes up to 90% of the energy needed for computing systems. Non-volatile memories, which store information when they are not powered to reduce their energy consumption, are required. Additionally, these systems must be entirely rethought around memory as a way of limiting the transfer of data and stepping away from the Von Neumann model.

Four memory technologies

CEA-Leti is developing three emerging technologies for high-potential non-volatile memories: **phase change memories** (PCRAM or PCM), **ferroelectric memories** (FeRAM or FRAM), and **resistive memories** (ReRAM or RRAM). More recently, the institute has been studying **magnetic memories** (SOT-MRAM), known for their writing speed and record endurance.

Alongside this, CEA-Leti is focusing on the entire value chain of computing systems, such as materials, components, integrated technologies, or architecture.

These areas of research are completed through various innovative approaches:

- **near & in-memory computing**
- **in-memory energy**
- **neuromorphic circuits**

Applications: automotive, IT, telecom, industrial equipment, cybersecurity, consumer goods, high-performance computing, near sensor artificial intelligence (edge artificial intelligence), etc.

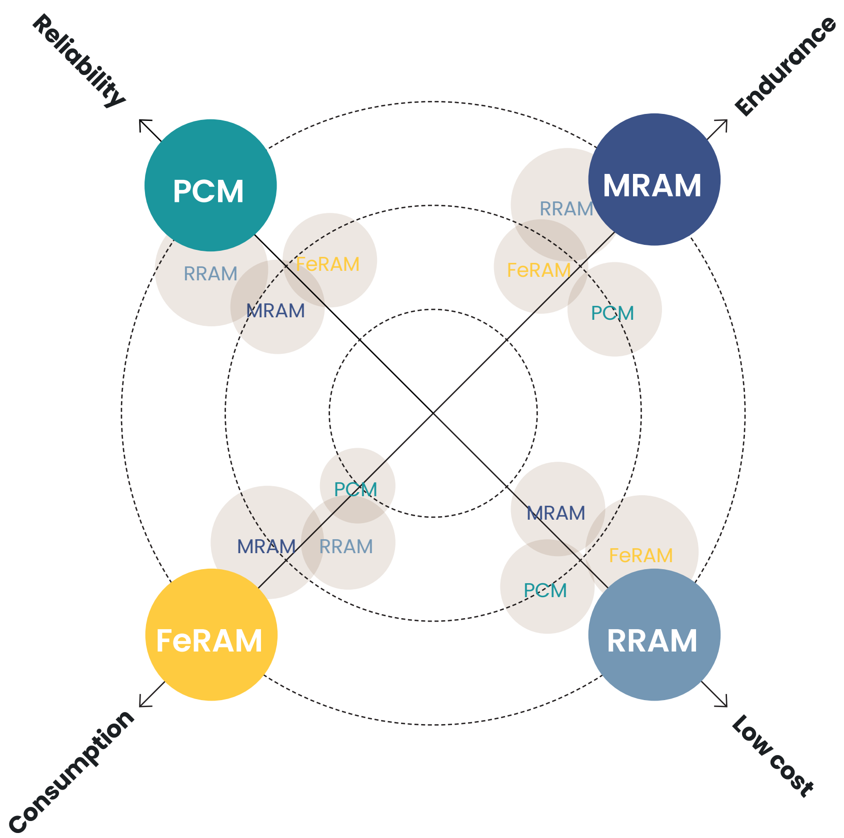
Promising memory technologies

	NOR FLASH	MRAM	PCRAM	RRAM	FeRAM (HfO_2)
Storing capacity	~200 pJ / bit	~20 pJ / bit	~300 pJ / bit	~100 pJ / bit	~10 fJ / bit
Write speed	20 µs	20 ns	10-100 ns	10-100 ns	4 ns @ 4.8 V
Endurance	10^5–10^6	10^6–10^{15}	10^8	10^5 – 10^6 on 16 Mbit	10^6–10^7 on 16 kbit
Data retention	> 125° C	85° C - 165° C	165° C	> 150° C	> 125° C
Manufacturing complexity	Complex	Medium	Medium	Simple	Simple
Multi-level cell	Yes	No	Yes	Yes	No
Industrial scale-up	Bad	Medium	High	High	High
		++ Reliability	++ Endurance	++ Low cost	++ Consumption

sept. 2022

Non-volatile memory technologies

developed at CEA-Leti



Phase-Change Memories (PCM)

How does it work?

Information is stored in the amorphous ("0" state) or crystalline state ("1" state) of a chalcogenide material, ensuring a reversible phase transition over a very high number of cycles.

Advantages?

- **Miniaturization**: the phase transition mechanism is preserved at nanoscale.
- **Cyclability**: 100 to 1,000 times higher than flash memory
- **Programming speed**: several dozen nanoseconds
- **Analog storage of information**: using intermediary states between 0 and 1 can triple or even quadruple storage density.
- **Particule manipulation** made easy

Applications

Data storage, automotive microcontrollers, edge artificial intelligence, cybersecurity

Industry

PCM memory technology has been transferred to a major player in semiconductors. Millions will be produced for mass-market applications, including for the automobile industry.

Our research areas

- **Materials**: Developing new alloys to reach specifications for targeted applications on advanced technology nodes. CEA-Leti is relying on state-of-the-art measurement and analysis techniques to explore and qualify these materials.
- **Design and integration**: Designing new PCM devices to miniaturize, reduce consumption, optimize storage density and performance.
- **Programming and tests**: For each memory that is developed, studying the most adapted protocols to improve the performance, reliability, and use of analogic behavior.
- **Co-integration**: PCM co-integration with a back-end selector so it can be implemented into 3D architectures and reach the right density for a memory ($4F^2$ surface, with F as the period between two metal lines).

3D phase change memory could become a reality for embedded computing

A phase change memory (PCM) developed for embedded computing was co-integrated with a back-end selector—a first. PCM, heralded as the replacement for today's flash memory, could also be stacked in 3D into advanced embedded applications thanks to this advance.

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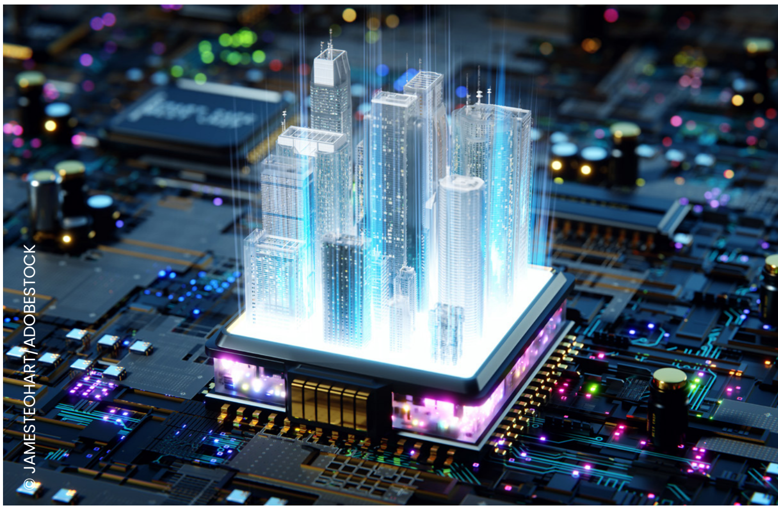

Ferroelectric memories (FeRAM ou FRAM)

How do they work?

Memory is made up of a ferroelectric insulating material separating two metallic electrodes. Following the direction of the electric polarization vector, information ("0" or "1") is physically encoded to go up or down.

Advantages?

- **Very low consumption**: at 10 fJ/bit, FeRAM consumes a lot less than any other memory
- **Cyclability**: superior to that of any other memory, up to 1015 cycles
- **Very fast writing and reading speeds**: only 4 ns at 4.8 V
- **Low manufacturing cost**

Applications

IT, telecom, microcontrollers for embedded systems, edge artificial intelligence

Industry

CEA-Leti is involved in three European programs (3eFerro, StorAIge, and BeFerroSynaptic) along with STMicroelectronics, IBM, Thales, and Ford.

Our research areas

- **Materials**: The PZT-based active material has been replaced by a lead-free material, hafnium oxide (HfO_2), which is CMOS-compatible, easily stacked in very thin layers and miniaturized.
- **Design and development**: Improvement of HfO_2-based FeRAM performance, miniaturization for integration into integrated circuits.
- **Advanced characterization and demonstrators**: Simulation, design, and creation of 200 mm and 300 mm-integrated complex demonstrators, advanced morphological and electrical characterizations.

HfO_2-Based FeRAM arrays designed & fabricated at CEA-Leti bring the technology closer to manufacturability

SAN FRANCISCO – Dec. 15, 2021

CEA-Leti has reported the world's-first demonstration of 16-kbit ferroelectric random-access memory (FeRAM) arrays at the 130 nm node that advances this energy-saving technology closer to commercialization. The breakthrough includes back-end-of-line (BEOL) integration of $TiN/HfO_2:Si/TiN$ ferroelectric capacitors as small as 0.16 µm², and solder reflow compatibility for the first time for this type of memory.

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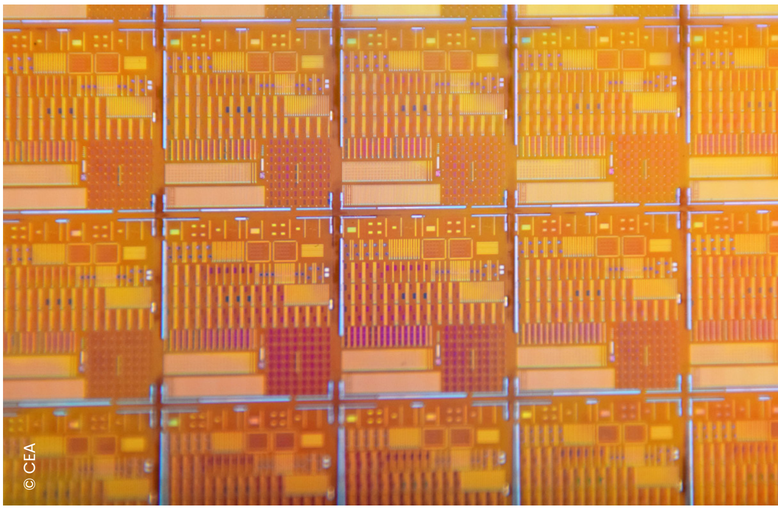

Resistive memories (RERAM or RRAM)

How do they work?
Under the effect of an electrical field, a conduction channel forms and ruptures reversibly, inside an insulating material that is sandwiched between two metallic electrodes.

Good to know: RRAMs are split into several categories: CBRAM and OxRAM. CEA-Leti conducted research on CBRAMs in the 2010s and is now focusing more specifically on OxRAM based on HfO_2 materials, which offer better performance in terms of speed and integration reliability.

Industry
Since 2020, CEA-Leti has been transferring these technologies to industrial partners worldwide.

Advantages?
- **Speed**: 100 ns programming time, or less
- **Very low cost**
- **Low consumption**: approximately 100 pJ/bit

Applications
Internet of things, edge artificial intelligence, neuromorphic computation, cybersecurity

Our research areas
- **Industrialization**: Rise in maturity of RRAM technology for industrialization purposes—new materials, new layers and stacks, electrical characterization, programming and addressing protocols, modeling and simulation, integration into logic circuits, and tests.
- **Co-integration**: RRAM co-integration with a back-end selector so it can be implemented into 3D architectures and increase density.
- **New applications**: Developing RRAM for new cybersecurity applications, neuromorphic circuits, edge artificial intelligence, etc.

Tenfold reduction in ReRAM cell variability
A solution to the problem of excessive variability in ReRAM (resistive memory) could be found in Mott insulators, metals that conduct electricity in theory, but that turn out to be insulators.

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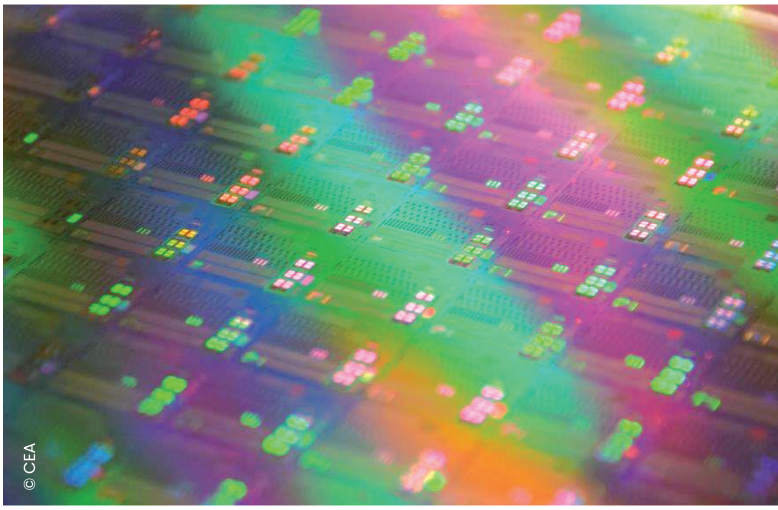
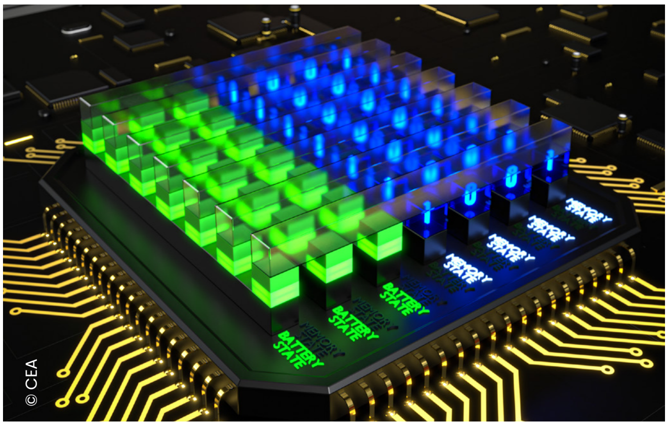


New strategies:

Computing, energy, and neuromorphic



In-memory computing

Co-integrating RRAM memories and logical devices makes some computation tasks more energy-effective and speedier, for example in neuromorphic computing or edge artificial intelligence. CEA-Leti is developing an architecture that enables both large-scale computing memory and very high density integration, leveraging vertical cell stacking.

As part of a €2.75M ERC project, CEA-Leti is developing a circuit accelerator that is 20 times less energy consuming than a traditional circuit, using state-of-the-art Von Neumann architecture.

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In-memory energy

CEA-Leti is studying a disruptive solution, which involves diverting RRAM memories from their main function, using them as a way of storing energy and information. Their energy and power density are comparable to that of supercapacitators.

These extremely compact memories can be placed as close as possible to processors, which would simplify the circuit's distribution system and improve its efficiency. Applications under consideration are the internet of things and portable objects.

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Towards neuromorphic circuits

Time and energy costs arising from the transfer of data between a memory and computing have become the main challenge of IT systems, including in applications in which data is essential, such as natural language voice recognition. Researchers draw on inspiration from the living, including from the brain, to maximize system efficiency, both in terms of performance and energy budget.

Neuromorphic circuits differ from traditional Von Neumann architectures in terms of how elements are organized, including memory and computing: much like brain synapses and neurons, neural networks and computing centers are positioned nearby, in a single circuit. Hence, it no longer makes sense to think in terms of isolated memory components, and researchers are focusing on a more global computing approach.

To develop neuromorphic circuits that can meet edge artificial intelligence constraints, including available energy and memory, CEA-Leti is relying on several approaches:

Biomimicry

On-chip neural networks

CEA-Leti is finding inspiration in the human brain, developing spiking neural networks. In 2019, the institute unveiled the first entirely integrated on-chip neural network with a RRAM memory, for massively parallel, low consumption, and low latency computation.

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Local neural networks

CEA-Leti is finding inspiration in the nervous systems of animals, in which computing and memory elements are spread out and placed nearby. Backed by an ERC, the project will leverage nanoscale silicon-based memory devices inspired by the nervous systems of insects to create the first smart chip associated with a local neural module that can process sensory data in real time.

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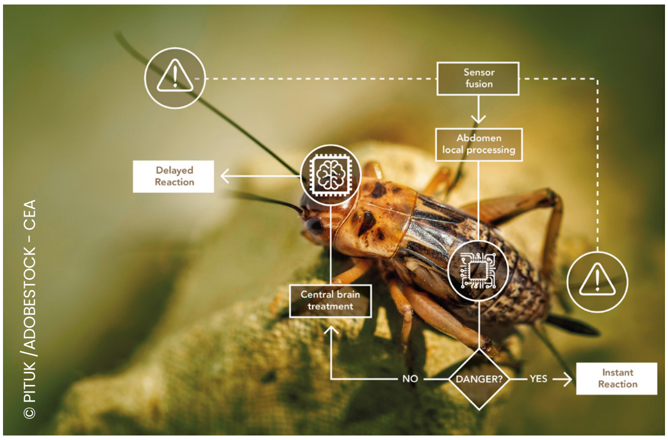

Advanced R&D on memories:

Why you should work with CEA-Leti

Expertise

20 years of R&D on memories, more than 60 patents, and complete expertise: choosing and optimizing materials, designing and developing devices, manufacturing processes, technological integration, programing protocols, tests, etc.

Synergies

An ability to orchestrate and create synergy between these skills to optimize the performance, size, cost, and consumption of each memory for each application.

Equipment

State-of-the-art 300 mm cleanroom facilities to validate processes under real conditions and easily transfer them to founderies.

CEA-Leti's capacity to develop ready for production memory technologies depending on our partner's application targeted, positions the institute as a leading world R&D player. CEA-Leti is already collaborating with a dozen worldwide industrial partners.

Glossary

PCM /PCRAM: phase change memories

FeRAM /FRAM: ferroelectric memories

RRAM/ReRAM: resistive memories

Acknowledgments

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About CEA-Leti (France)

CEA-Leti, a technology research institute at CEA, is a global leader in miniaturization technologies enabling smart, energy-efficient and secure solutions for industry. Founded in 1967, CEA-Leti pioneers micro-& nanotechnologies, tailoring differentiating applicative solutions for global companies, SMEs and startups. CEA-Leti tackles critical challenges in healthcare, energy and digital migration. From sensors to data processing and computing solutions, CEA-Leti's multidisciplinary teams deliver solid expertise, leveraging world-class pre-industrialization facilities. With a staff of more than 1,900, a portfolio of 3,100 patents, 11,000 sq. meters of cleanroom space and a clear IP policy, the institute is based in Grenoble, France, and has offices in Silicon Valley and Tokyo. CEA-Leti has launched 70 startups and is a member of the Carnot Institutes network. Follow us on cea-leti.com and @CEA_Leti.

Technological expertise

CEA has a key role in transferring scientific knowledge and innovation from research to industry. This high-level technological research is carried out in particular in electronic and integrated systems, from microscale to nanoscale. It has a wide range of industrial applications in the fields of transport, health, safety and telecommunications, contributing to the creation of high-quality and competitive products.

For more information: cea.fr/english

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Research for industrial innovation