

Evolution of the next generation of sensors in the connected world: technical and human challenges

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Abstract

Since the early 2000s, the number of connected objects including sensors has grown exponentially, resulting in an exponential increase in the amount of treated data as well as in electrical energy consumption. If this trend does not slow down, by 2030, all of the world's electrical energy production will be devoted to digital activities. All storage, transmission and processing hardware involved in connected sensors is based on microelectronic technologies. The current challenge is thus to divide the consumption of these objects by a factor 10, at least, by implementing the recent research results in the field. The implementation of new architectures, new technologies, involving analog and asynchronous functions should optimize the size of the connected and smart sensors, minimizing their electrical consumption. In addition, these approaches require new skills directly related to the needs of microelectronic companies that have been experiencing a job shortage for more than five years. After a presentation of the context, the paper details potential solutions for improving techniques to meet the challenges, paying attention to technical improvements and expected skills. The final goal is to highlight the priority capabilities expected from future graduates to develop adequate sensors in a global IoT (Internet of Things) approach respecting the energy and environmental constraints.

Keywords: Electrical engineering, microelectronics, connected sensors, energy consumption, skills and know-how.

1. Introduction

Since the early 2000s, the number of connected objects, part of Internet of Things (IoT) involving sensors and smart sensors has grown exponentially [1], resulting in an exponential increase in the amount of data [2] as well as the amount of electrical energy consumed [3–5]. The number of sensors has experienced a huge increase, and it is expected to reach several tenth sensors per connected object, such as iPhone [6], which has led to an increase in the amount of data to be processed within and between each hardware object [7]. The total number of sensors whatever the applications is expected to reach 30 trillion by 2030 [8] as shown on Fig. 1. More and more of them are involved in connected objects and in autonomous equipment such as robots, creating a family of smart sensors.

This figure is issue from reference [1] and is completed with the exponential evolution of smart sensors that are about 80 billion today. The digitization of many of the world's administrations and education systems, and the development of new applications via the IoT in all areas of society, will maintain the pace of data growth. What's more, the new generations of wireless communications and artificial intelligence are set to generate a further acceleration in the amount of data processed and the associated energy consumption, which are not yet taken seriously despite early publication on the subject in 1999 [9]. All of the world's electrical energy production will be devoted to connected activities (IoE), by 2032, already [8], if we suppose that the field of electrical car remains negligible.

The entire equipment chain (generation, storage, transmission and processing) is based on microelectronic components, circuits and systems [10], both analog and digital at hardware level. The current challenge is to divide the consumption of this whole electronics by a factor of between 10 and 100, by

implementing the results of recent and realistic research in the field of microelectronics and nanotechnologies [11]. The new processes should make it possible to achieve an integration level equivalent to that of the 3nm node and thus increase the performance of data processing but also relatively reduce energy consumption. In fact, the implementation of new architectures, new materials and new technologies applied to embedded electronics should optimize the size of the circuits with the application, minimizing the consumption of connected objects or connected sensors [12]. The generalization of analog and asynchronous functions is also a way to reduce the power dissipation of large electronic systems.

In addition, the implementation of these approaches requires new skills directly related to the needs of microelectronic companies that have been experiencing a job shortage for more than five years [13] that have led to Chips Acts strategy, in Europe [14], in USA [15] with equivalent strategy in the Far-East. These skills will automatically be linked to the nature of the work. This will be associated with a growth in the pool of people trained at all levels of study, from technician to doctor, on subjects covering the spectrum of the field, from very low to very high power, from ultra large integration to large area technologies, from analog to digital.

After a presentation of the context, the paper will detail potential solutions for improving techniques to meet the challenges. Particular attention will be paid to technical improvements and expected skills. The paper will conclude with a presentation of the priority capabilities expected from future graduates to develop adequate smart sensors in a global IoT approach respecting the energy and environmental constraints

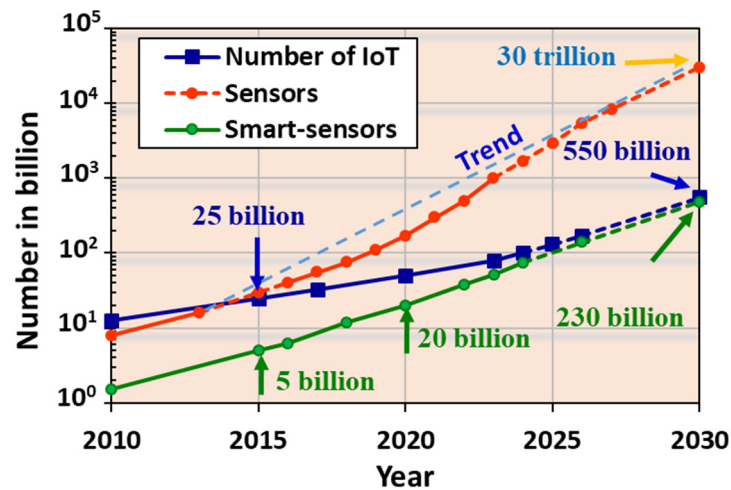


Fig. 1. Expected evolution of number of sensors in the world whatever the IoT applications (Internet of Things). By 2030, more than 230 billion is planned.

2. Electronics role

The evolution of microelectronic integration has enabled a billion-fold increase in the number of elementary components on a single integrated circuit since 1963 [16], thanks to the reduction of lateral dimensions and thus of minimum pattern size. Since the early 2000s, this approach has been complemented by the use of the third dimension, which enables the stacking of circuits and patterns from different technologies [17].

This evolution has been accompanied by the possibility of creating complex, fully integrated systems and more specifically connected objects that may contain analog sensors or actuators, DACs and ADCs, digital signal processing functions, memories, but also security, alarm and monitoring circuits, as well as transceivers [18]. This approach has enabled the development of smart sensors, the number of which has multiplied prodigiously: by 2030, the number of sensors worldwide is expected to reach 30 trillion, the vast majority of which will be connected and thus involved in connected objects [6]. This has also widened the spectrum of applications covering the main societal needs, from communications, health, security, environment, energy, mobilities [8]. Let us notice that a lot of sensors based on electrostatic phenomenon were developed during the last 30 years and cover a lot of the applications mentioned above [19].

While integration technologies have made it possible to reduce the energy required to process an elementary digital signal, the simultaneous reduction of dimensions to the nanometric scale has led to a very

significant relative increase in leakage currents in elementary devices. At dimensions of just a few nanometers, the power consumption of a highly complex circuit at rest becomes greater than that devoted to data processing, particularly in synchronous digital technologies. This phenomenon is known as "power tyranny" expression given by the authors [20]. It leads to the design of integrated circuits in which the surface area of the clock (which constantly powers all the elementary components, up to several billion of them) occupies a third of the surface area in planar technology [21]. The obvious consequence is a significant increase in the energy consumed by each circuit and more especially by smart sensors.

As already mentioned, the exponential growth in the number of connected objects *de facto* leads to an increase in the energy consumption of the entire digital domain, despite ongoing improvements in technologies and circuits. Indeed, a projection over the next ten years shows a 5-fold increase in the number of bytes transferred every 5 years, and a 2-fold increase in electrical energy consumption every 3.3 years. In 2019 at the World Economic Forum [22], it was estimated that each day:

- 500 million tweets were sent,
- 294 billion emails were sent,
- 4 petabytes of data were created on Facebook,
- 4 terabytes of data were created from each connected car,
- 65 billion messages were sent on WhatsApp,
- 5 billion searches were made.

On this basis, if we add all the other data exchanges via streaming, and the uploading of photos and videos to the cloud, an extrapolation has been built with exponential growth similar to the previous one [8]. Fig. 2 and Fig. 3, after reference [8] give a good overview of this prospective evolution. Fig. 3 is modified after several adjustments to prospective values since it was written. The number of processed or transferred data (data storage) should reach the yottabytes (10^{24}) by 2030, and the total electrical energy consumption 23,000 TWh, that correspond to the global electrical energy production of 2018 [1–2]. For a simple comparison, the energy spent by the global air traffic should be five times lower using the equivalence between one million tons of petrol and 11.63 TWh of electrical energy. In other words, if we expect a negligible increase of the energy consumption of the other sectors, and if nothing is done to slow down this trend for IoT consumption, by 2032 all the electrical power currently produced worldwide will be consumed by digital systems, which will become completely unacceptable. There is therefore an urgent need to fundamentally revisit the evolution of the IoT domain, both on the user side, to minimize the growth in the amount of data to be processed and transferred, and on the hardware side, to implement new technologies and new architectures that minimize energy consumption of circuits and systems.

In the following, we will focus on electronics applied primarily to IoT or IoE (Internet of Everything) applications, although the spectrum is constantly expanding. In fact, power consumption is becoming so high that high-power electronics are becoming an issue, in particular to improve the performance of data center power supplies, which can consume up to 2GW [23–24]. The efficiency of voltage conversion and power delivery is only 37% on average [25], with Joule effect losses generated between production power plant accounting for the essential [21], other losses existing at the level of the connected objects. In 2020, in USA, this percentage was estimated to 40% [26]. It should be noted that the 2022 worldwide efficiency of electricity generation from natural resources (gas, oil, nuclear, etc.) was only around 27%, due to electricity production and converter efficiency and thus much lower in many developing countries [21]. However, by implementing new microelectronic power components based on wide bandgap materials such as SiC and GaN [27], an improvement of even 3% on the global yield would be significant. The future of connected sensors must therefore respond to the primary need, namely to reduce by a factor of at least 10 the energy consumption of all circuits and systems involved in the Internet of Things or Internet of Everything (IoE), and more particularly of connected objects. The challenges are considerable, since we need to tackle the factors that control energy consumption, knowing that the aim is not to reduce the amount of data produced, transferred and processed, but rather the consumption of physical electronic hardware. By way of example, Industry 4.0 is currently making lightning progress, involving huge numbers of robots that rely on smart sensors, and associated energy consumption that will also need to be reduced [28].

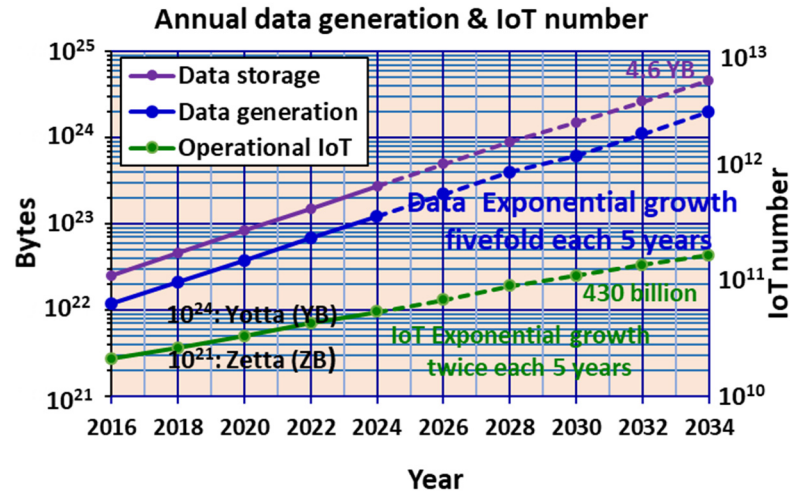


Fig. 2. Expected growth in the number of connected objects and data. By 2030, the amount of data stored will reach the yottabyte mark.

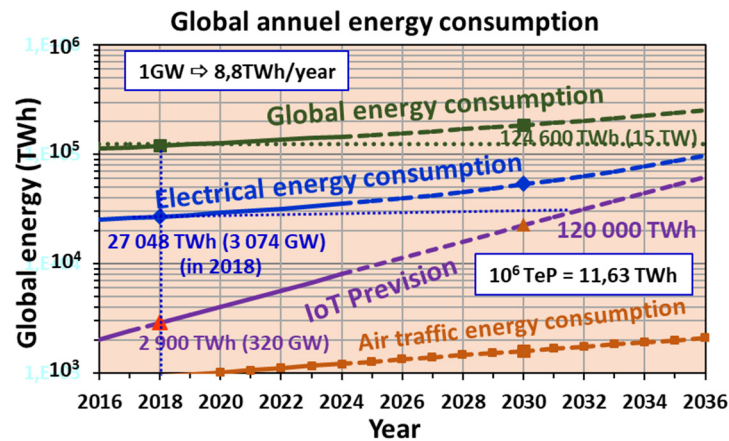


Fig. 3. Expected energy consumptions in the world. By 2032, the worldwide electrical energy consumption of 2018 should be fully devoted to digital world.

3. Challenges in microelectronics

Challenges must therefore focus on the various elements that influence the electrical properties of circuits and systems that govern the connected sensors. These cover the overall architecture of circuits that assemble numerous concepts and functions, their operating principles, the technologies that depend on the evolutionary nodes of integration, but also the implementation of technological processes and the materials used.

The biggest problem today is the huge international competition to meet market needs as quickly as possible. New tools for designing complex circuits call on databases such as IPs (Intellectual Properties), which enable a company to copy functions widely used in connected sensors.

The underlying problem is that circuit sizing is inadequate, and the designs selected are systematically over-dimensioned in terms of memory capacity, number of bits in microprocessors or microcontrollers, or in FPGAs, and even in the frequency domain if the analog signal detected has low kinetics. They are also not optimized for standby control, and are mostly chosen for mature silicon technologies, with high leakage currents in ULSI circuits, unfortunately.

New products are beginning to appear, including circuits based on composite materials IGZO (Indium Gallium Zinc Oxide) deposited in thin layers on flexible film [29]. For example, an INTEL 4004-type processor has recently been produced, with the advantage of an I_{on}/I_{off} current ratio of 10^9 for the elementary transistors [30]. What's more, the use of thin films limits the use of resources such as gallium and indium,

which are becoming increasingly rare on the planet and therefore also very expensive. This will require innovation in the following design and architecture activities or specialties:

- Adapting circuit architectures that can monitor the idle of areas [12]; new microcontrollers apply this approach and a decreasing of 30% of the consumption is reached,
- Combining asynchronous and synchronous electrical IP (Intellectual properties). This approach is currently developed by specialists of asynchronous electronic that can involve neuromorphic functions in order to minimize the size of the circuits,
- Combining digital and analog electronics modules; the analog part allows minimizing the consumption of the clock,
- Developing systems for "edge-computing" which enable local processing [31]; for smart sensors, this is a way to minimize the transmission of data and the related electrical consumption,
- Opening up the spectrum of electronics applications by 3D integration (new software for design and routing hybrid assembling). This new packaging can involve chiplets that are assembled on the same chip, minimizing resistive and capacitive losses [11],
- Focusing the electronic innovation on sustainability. The adoption of new materials can minimize the energy of extraction and purification for microelectronics applications.

As far as technological processes are concerned, the most important points to work on and innovate will be the following:

- Creating active and passive new nanometric components with infinitesimal electrical consumption and new materials such as wide bandgap oxides or organic semiconductors [32],
- Increasing the electronic operating frequencies in order to increase data flow, this approach is however complex due to the possibility of increasing losses with higher frequencies
- Improving the efficiency of power electronics: components and circuits thanks to new materials, new architectures, new converters [27]; a way to decrease the ON resistance as well as the OFF current,
- Developing energy harvesting systems, integration in 3D architectures, hybrid technologies, new stacking, new packaging [33–34]. These functions and capabilities are major in the innovation of sensors that are almost all connected in the more recent generations.

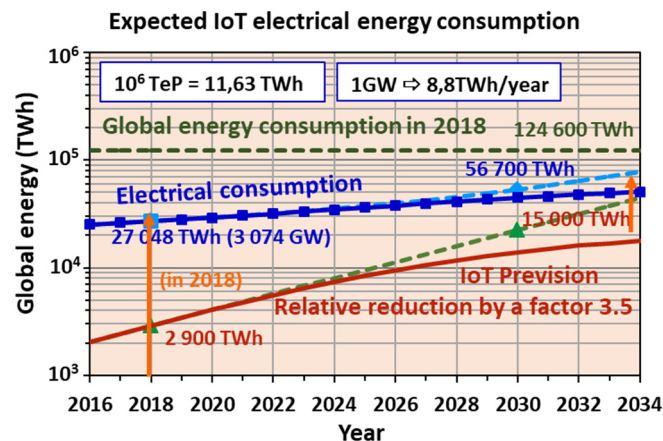


Fig. 4. Simulation of projected IoT electrical energy consumption in the 1930s, assuming that electronics energy consumption will be progressively divided by 10 by 2034 (after revision of data of reference [1]).

If the objectives of improving electronics towards low power consumption and optimizing devices, by estimating a progressive division by 10 of global power consumption over the next 15 years, power consumption could follow the trend shown in Fig. 4. This figure is an extension of Fig. 3 and is deduced from an annual reduction model based on a factor of 10 over the 12 years (2022–2034) for electronics consumption. This forecast seems realistic, as the years 2022–2024 have seen the start of application of this strategy by several of the world's leading microelectronics companies. The increase would lead to a maximum global digital power consumption 2 times lower than the total energy consumed in 2018.

Sensors and actuators are increasingly connected and make use of the numerous development facilities provided by design tools such as FPGAs. These tools have the great advantage of implementing IPs (Intellectual Properties), which enable accelerated design and rapid market introduction of new products in a wide range of applications. However, these solutions, which are commercially advantageous in the very short term, because they are not optimized and therefore consume energy, will rapidly reach an insurmountable limit in terms of global electricity consumption. Therefore, the strategy must change, considering that the best solution is to drastically reduce the consumption of all the physical supports of these connected objects and connected sensors, i.e. electronic circuits and systems. Clearly, meeting these challenges requires the skills and know-how in the field that are essential to an innovative approach.

4. Skills and know-how

The skills mentioned cover the entire technical and technological spectrum of the microelectronics field. To ensure that training at all levels continues to evolve, a survey of industry needs recently was carried out at French level by a national working group [13], but the result can be applied in a similar way at least at other European countries [14–15]. Manufacturers refer to these needs as "jobs in shortage" resulting of a survey on the last 4 years. Fig. 5 shows the percentage of unfulfilled job offers for the five different microelectronics specialties that have been prioritized in 2022 [35–36]. The red bars indicate the level of recruitment failure. For example, specialists in embedded electronics, who implement circuits such as FPGAs, are the most concerned by the shortage: 64% of recruitment failure. This weakness can be connected to the incredible development of connected objects and connected sensors in many societal domains.

In engineering science, training must include not only basic knowledge, but also a significant amount of know-how [37]. As already mentioned in previous papers [1], a national organization, the GIP-CNFM [38] has proved very useful, at French level, to ensure practical training at a cost accessible to academic institutions. With 64% of non-satisfied employment, embedded electronics is the worst case.

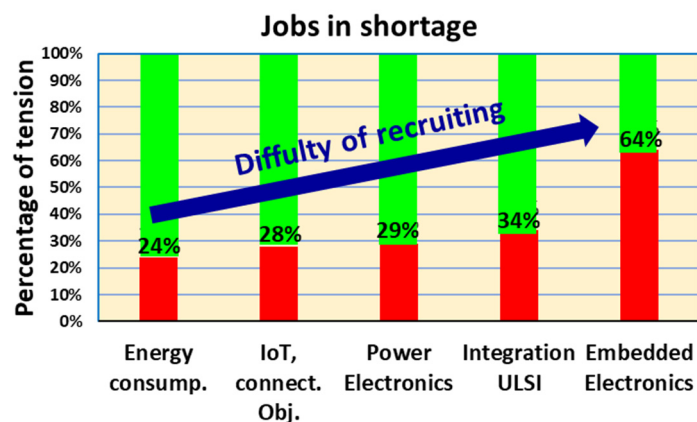


Fig. 5. Percentage of jobs in shortage edited by the French national industry sector in 2022.

The national network is made up of 12 inter-university centers, providing the national microelectronics community with around 100 platforms, including 7 technology clean rooms. Throughout France, these platforms cover all the key areas of microelectronics for training, research and industry. The main missions of the GIP-CNFM network are shown in Fig. 6. The aim is to train the industry's future players to meet new challenges. The network welcomed around 20,000 students on its platforms each year, representing some 900,000 hours of training for students at all levels, from technician's certificates and bachelor's degrees to doctorates, master's degrees and engineers [39]. Part of the activities is also devoted to raising awareness among schoolchildren, so that they are more attracted to this field of science [40]. Several of these platforms are dedicated to sensors and actuators, connected objects and smart sensors. A multichip project prototyping is now available at the level of the network [41]. This possibility opens a way to develop new products created by start-up or companies in connection with academic laboratories. The medium-term objective is to train these technicians, masters, engineers and PhDs so that they have the background of knowledge and

know-how to meet these challenges in their future careers. It should be noted that these platforms are open to lifelong learning, thus enhancing the performance of industry players.

It can be mentioned that the national network offers to the academic institutions and to companies practical training on the technical platforms. The curricula are defined by the academic institutions that decide or not to form their students on the microelectronics platforms. The strategy of the GIP-CNFM is to propose practical activities in line with the industry and research needs. Unfortunately, the policy of the academic institutions is more governed by attracting students in cheaper study domains than sciences and engineering. Since 2010, the number of students has been decreasing in these fields, and despite attractiveness developed by the microelectronics community (teachers, researchers and industrialists), these fields were progressively left by the students. To counter this trend, the national network organizes a number of events each year, including platform open days, regional science fairs, educational conferences on microelectronics for teachers and industrialists, and thematic days with the Union of Electronic Industries. However, the effect is not immediate, and was temporarily blocked during Covid pandemic. We have maintained the activity and the training at the level of the network, but not enough to face the new needs.

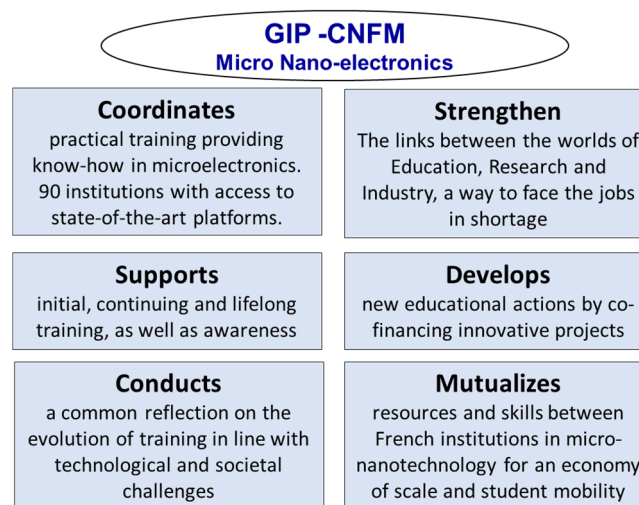


Fig. 6. Main missions of the French national training network, GIP-CNFM. The target is to provide skills and know-how to the future graduates enrolled in academic institutions as well in companies, in line with the needs of industry and research activities.

5. Electronics solutions and training

On a more technical level, various approaches to improving performance are proposed for both initial and ongoing user training. The priority themes relating to "connected sensors" and other connected objects are as follows:

- Analog, digital and hybrid circuits including testing, quality, reliability, CEM electronics, cyber security,
- Communication/RF, HF, VHF and microwave circuits; this topic is mandatory for connected objects and smart sensors,
- Nanoelectronics including new processes and new materials (compound semiconductors, organic semiconductors, insulator and flexible substrates),
- Electronic Design Automation, new architectures compatible with new hybrid packaging,
- VLSI and FPGA systems and applications (embedded electronics and new boards including flexible electronics),
- Power electronics, devices and systems including new wide bandgap semiconductors, new insulators and new packaging.

Among these topics, several examples are given in the following. All these training works shown on Fig. 7 are made by students on different platforms attached to different microelectronics interuniversity centers.

Several projects were carried out on two or more platforms at two or more centers. Indeed, in line with local research and industrial activities, each center has preferred specialties with a certain level of excellence and common with research laboratories. A strategic committee established by the network and containing teachers and industrialists allows application of the national policy. Dozens of other realizations are made each year in the same context [38–39].

The most complex practical training courses, which aim to present a functional object at the end, for example a surface acoustic wave sensor, are carried out within the framework of projects by a student team of 2 to 6 members. Their missions are shared so as to cover the different technical aspects, technological manufacturing on one side", and data communication on the other, for example.

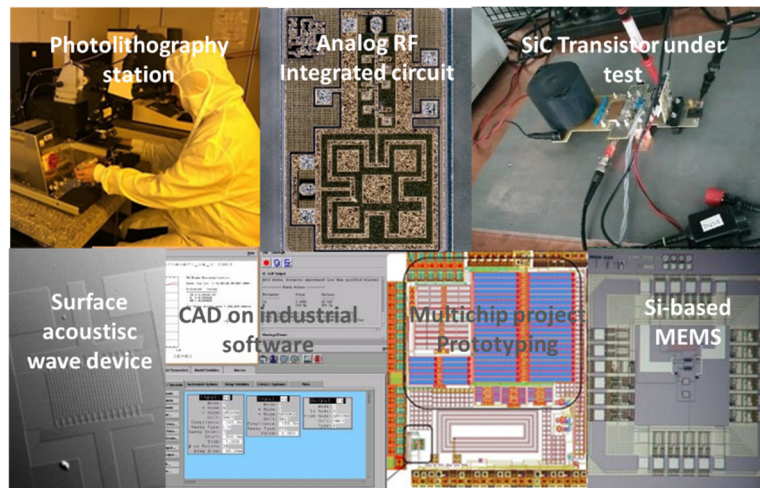


Fig. 7. Examples of training works made by the students included in the smart sensor development strategy: technology, design, test and sensors are introduced in the training.

In the network more than one hundred platforms are shared by the twelve centers. They cover all the specialties of the domain. The strategy of the network and of the direction consists in finding common projects and programs that can financially support the academic partners in order to push the innovation in line with industry and employments.

This behavior has started more than ten years ago, and the effects became visible in 2020. Unfortunately, the dynamic was stopped during Covid-19 confinement. In 2023, a new national program to develop microelectronics was launched and the network was selected to apply the proposed strategy [42]. Thanks to this new project, we hope to recover the trend of improvement in the coming years.

6. Conclusion

In the context of the incredible development linked to the enormous expansion of the IoT, the next generation of connected sensors will depend heavily on the associated electronics and the corresponding consumption of electrical energy. We have outlined a number of innovative technical solutions for the medium and long term, which should require new product designers and production players to adapt. This calls for a change of strategy in the training of future players, in particular innovative practical training in line with the needs of industry and research, which must keep pace with constant change.

At the level of the French national microelectronics network, we are applying this new strategy thanks to a recent national project [42]. We intend to follow the international evolution of the leaders in the field who design and manufacture these products, knowing that they have already started the race to reduce energy consumption. If they succeed, it will be compulsory to avoid falling into Jevons' paradox [42], i.e. that as the consumption of IoT and smart sensors decreases, the consumer goods companies could increase their number in contradiction with the objectives.

In parallel, new know-how will enable to form new players covering different registers of microelectronics in order to improve connected sensors in a growing spectrum of societal applications. This is a real challenge on a global scale.

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