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Skills in Physics and Semiconductor Devices: A Global Challenge for Digital Society

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Abstract

The number of connected objects and therefore of IoT devices that invade our daily lives is growing exponentially. These objects are based on electronics in the form of elementary components, circuits and hybrid and complex integrated systems. Electronics must therefore respond to an exponential growth in the number of circuits, components per circuit, data transmitted, stored and processed in data centers. As a corollary, the energy consumed by operators, servers and users follows the same law of growth. In the coming years, the main challenges will be to slow down these exponential growths by improving the design and architecture of components, circuits and systems for processing and transmitting information. These challenges require the acquisition of skills based on knowledge and know-how and an increase in the pool of future competent and innovative players. This approach is part of the strategy led by the national academic training network which, by pooling the skills of trainers and technological platforms at the French level, aims to meet the needs of companies within the framework of a Recovery Plan for the Electronic Sector. After a presentation of the context and the consequences on the technical challenges, and after several approaches proposed, the actions carried out by the national network of microelectronics are detailed and illustrated with several examples of realizations and results.

Keywords

Microelectronics, Devices and Systems, Digital Society Challenges, Higher Education

1. Introduction

Connected objects within the IoT (Internet of Things) are invading our daily life

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whatever the societal field of application. However, all these objects only work thanks to the electronics that compose them. These electronics are based on the technologies of elementary components and circuits that contributed to a permanent improvement of the integration [1] [2], extended to microtechnologies and microsystems [3] that allow the realization of sensors and actuators [4] [5], displays and energy harvesting, and a hybrid integration [6]. As the IoT follows an exponential growth [7] within the framework of governmental policies of digital development, it follows an equally exponential growth in the number of connected objects, in the data transmitted, stored and processed in data centers, and in the energy consumed by operators, servers and users. For the next few years, the main challenges will be to slow down this exponential growth by intervening in the various facets of the discipline, namely the design and architecture of components, circuits and systems for processing, storing and transmitting information. This processing may involve artificial intelligence (AI) if it becomes competitive in terms of circuit size, amount of data processed and associated power consumption [8].

The task ahead is considerable and the challenges are conditioned by the acquisition of skills based on knowledge and know-how, and by the increase in the pool of future players in the discipline in the broadest sense, who are competent and innovative. It is, therefore, necessary to organize training, whether initial or lifelong, in order to prepare future players to face and solve these challenges. This approach is part of the strategy developed by the national academic training structure, the National Coordination for Training in Microelectronics and Nanotechnologies, the GIP-CNFM [9] [10]. By pooling the skills of trainers and technological platforms at the French level, this network aims to meet the needs of companies within the framework of a Recovery plan applied to the electronics Sector [11]. To this, the activities are mainly dedicated to the learning of know-how which complements the knowledge provided by the theoretical teachings of the diploma courses given by the network's partners.

This document deals with the description of the announced evolutions and details the actions led by the national microelectronics community in the field of microelectronic and nano-electronic devices and circuits. Several examples of realizations and results will be presented.

2. Evolution of Connected Objects and IoT

2.1. Exponential Growth of Connected Objects

Since the early 2000s, thanks to the increasing integration and assembly of hybrid integrated circuits in the form of systems-on-chips and systems-in-package, connected objects have been applied to a wide range of societal domains such as communications, health, environment, energy, security of goods and people, and transportation, to name only the most important. This evolution was favored by the combination of technologies coming from electronic circuits on the one hand, and from other disciplines such as mechanics, optics or biology on the other hand, which allowed the creation of many families of sensors and actuators [12].

Knowing that connected objects can contain several tens of sensors, as is the case with the latest generation of cellular phones, the overall number of sensors is also growing **Figure 1** highlights this evolution, which is expected to continue. It is envisaged that in 2030, the number of sensors will reach 30,000 billion and that the number of connected objects will reach 150 billion.

2.2. Exponential Growth of IoT

In practical terms, connected objects are only a significant part of the IoT, which also includes all systems for transmitting, storing and processing information. The total number of IoTs has been estimated at 60 billion in 2020 and is expected to reach 250 billion by 2030. They are growing exponentially, like connected objects [13], corresponding to a 3-fold increase every 7 years. This last component includes artificial intelligence, AI, which processes a significant part of the data mainly within and between data centers [14] [15]. The annual amount of data transmitted is growing exponentially and reached 60 Zettabytes in 2020 as shown in **Figure 2**. It is expected to reach 180 Zettabytes in 2025 and 600 Zettabytes by 2030 [16].

In the meantime, where the majority of data is stored or even duplicated in data centers for security reasons, the total number of recorded data is expected to exceed one Yottabyte (10^{24} (ten to twenty-four)) in 2030.

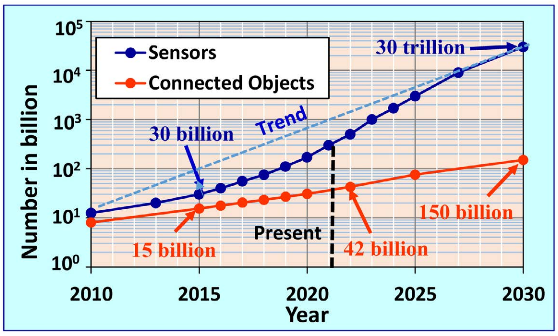

Figure 1. Past and future evolution of the number of connected objects and the number of sensors. The growths are roughly exponential.

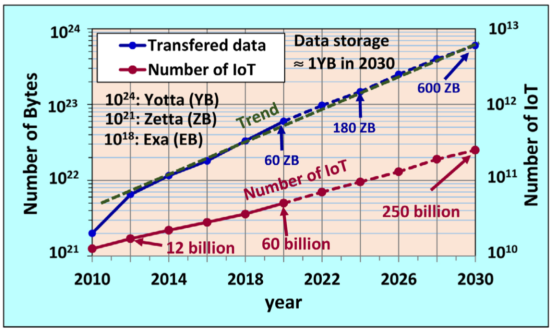

Figure 2. Past and future evolution of the number of IoT and the number of data processed each year. The growth is exponential and parallel to the connected objects. In 2030, this number should reach 250 billion. In cumulative value, the total number of data stored globally will reach the Yottabytes.

2.3. Exponential Growth of the Electrical Energy Consumption

The consequence of this growth is a considerable increase in the energy consumed by all the equipment used in digital activities. Despite improvements in component and circuit technologies over the last few years through the introduction of new generations of components, energy consumption is growing exponentially, mainly due to the exponential growth in the number of IoTs. As shown in **Figure 3**, this growth has been verified for more than 15 years and could continue over the next few years if a significant effort is not made immediately. Indeed, in 2020, the electricity consumption due to IoT, accounting the consumption of data centers, data transmission systems and equipment, local servers and users through their local devices for signal capture (lifeboxes), communication interface (PCs, tablets, cell phones, TNT), visualization (screens) and archiving (hard disks, SSD disks), represented about 15% of the global electricity consumption, with a growth of a factor of 2 every 4 years [17] [18]. Close to 50% is generated by the data centers, servers and transmission that represented more or less 2000 TWh in 2020 [18]. Moreover, almost 90% of this electricity has a carbon footprint due to the nature of its production in the world. Note that these values depend on the origin of the assessment, as several consumptions are not included in the calculation; for example, the electricity consumption of the 1.5 billion users and households. Whatever the exact values, without a special effort from the microelectronics field, this consumption will reach as early as 2030 the world electricity energy production of 2018. The slope of the energy growth in this logarithmic scale is very close to the growth of the number of connected objects in the extrapolation zone. Despite the already existing efforts to decrease the consumption of elementary components and circuits, the energy consumed does not decrease due to the growth of circuit and system complexity.

The best example is given by the increasing use of AI systems which leads to a multiplication of processing techniques and very important storage memories. In this case, the electrical power of these systems is measured in tens of kilowatt

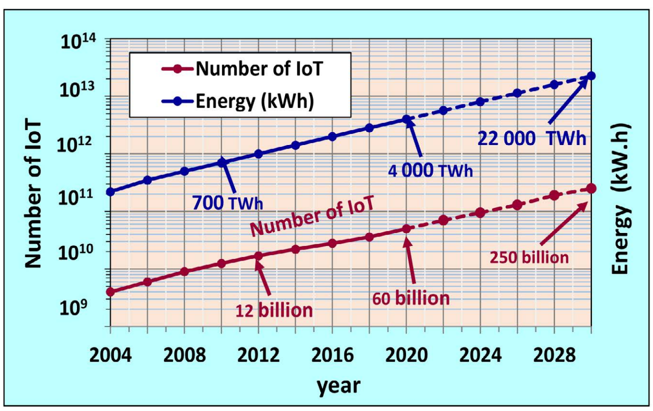

Figure 3. Past and future evolution of the number of IoT and the global electrical energy consumption related to IoT. Without modification of the energy consumption of electronics, this result is not realistic.

[19], despite all the existing improvements as shown **Figure 2**. Indeed, the increase of the number of data transfer is much faster than the IoT one. Moreover, the need for growth in data flow processing capacity implies an increase in working frequencies which are very frequently accompanied by an increase of the energy consumption due to the increase in parasitic losses.

3. Challenges on Device Technology and Circuit Architectures

The exponential growth of sensors, connected objects and power consumption is creating numerous challenges, including the use of raw materials, particularly rare elements, the energy required to transform and manufacture components and circuits, and the energy consumed in their use. To meet these needs, it will also be necessary to increase the skills of the players and therefore to make a significant effort in training, learning how to do things (know-how), and retraining.

Since every connected object is first and foremost made up of an electronic part, it is this discipline that becomes a priority in the challenges. The challenges involving innovation in electronics and microelectronics will have to:

- Reduce the power consumption of basic electronic devices, especially in the off-state in order to minimize permanent leakage currents, but also in the on-state for all digital data processing;
- Modify circuit architectures to reduce the instantaneous power consumption of billions of transistors, in particular by generalizing the use of asynchronous functions that do not consume electrical energy at each clock pulse;
- Expand the use of standby (inactivity) operations in the design of systems to minimize the power consumption related mainly to leakage currents in the off-state;
- Minimize Internet usage by promoting local communications (low-power transceiver, one of the goals of 5G).

It will also be necessary to consider the more general challenges that are essential to the field of microelectronics and components, namely quality, reliability, safety and environmental impact. For example, if in a few years, quantum electronics [20] were to develop sufficiently, we would have to take in account the cooling aspect at temperatures close to absolute zero that induces a high additional energy consumption. The future technologies will have to meet all these challenges which do not seem easy, today.

However, to this end, the challenges for education are at the present time:

- High needs of skills and know-how in all the facets of electronics and microelectronics of new graduate, engineers and PhD;
- A theoretical education and a practice training in the field of microelectronics and nanotechnologies [21];
- Basic concepts in the disciplines of the fields of application of electronics for a wide range of societal activities.

4. Challenges in Microelectronics Higher Education

4.1. Skills in the Physics and Semiconductor Devices

The evolution of electronics has been following the improvement of the technologies in order to meet the challenges previously detailed. Starting from basic devices such as pn junction diode, bipolar and field effect transistors, the content has gradually moved to the miniaturization of these basic components to the introduction of nanotechnologies [22], and to the third dimension such as:

- FD-SOI MOSFET [23] in order to minimize the leakage current due to the bulk;
- More recently FinFET [24] with a vertical channel;
- Gate-All-Around transistor (GAA MOSFET) [25];
- Nano-sheet transistor NSFET [26].

We limit this list knowing that in parallel we have attended to the birth and development of III-V compound semiconductor devices for high frequency and optoelectronics applications, but also to the power devices including GTO, IGBT, and more recently, silicon carbide (SiC) and gallium-nitride (GaN) based electronics. These last devices are at the top of the list of priorities, in terms of know-how [27] for the strategy of the French national education network which is closely interwoven with the strategy of the national electronics sector [28]. Of course, the manufacturing becomes also a need for industry. This explains the involvement of the Education network in the advanced manufacturing technologies [29], the network having several cleanrooms in interuniversity common centers that are devoted to the practice learning of technologies [10].

4.2. Skills and Know-How in the Frame of the National Network

More generally, the challenges related to IoT, connected objects and the development of the 4th industrial revolution, Industry 4.0 [30], appear at different levels:

- Continuation of the miniaturization of elementary devices oriented on the minimizing of energy consumption;
- Reduction of switching and static losses of power components;
- Introduction of the third dimension to improve circuit integration;
- New circuit architectures able to control active and stand-by zones;
- New circuit concepts allowing the generalization of asynchronous control;
- Implementation of low temperature and large area technologies;
- Development of low power sensors and actuators;
- Optimization of communication devices and protocols to limit the occupation of frequency bands and the data flow.

These concepts call for the expertise of analog electronics at the level of elementary devices as well as at the level of circuits, digital electronics for data storage and processing, high-frequency devices and circuits, discrete power devices and their drivers, optoelectronic devices and other families of devices and circuits in technologies targeting applications.

All these approaches are included in the strategy of the CNFM network which is strongly linked to the French electronics industry union, ACSIEL Alliance Electronique [31].

In what follows, we will focus on semiconductor devices, but all the compartments mentioned are important because there is a strong interdependence between them.

The acquisition of know-how has become a priority for the teachers of the network [32] involved in the training programs insofar as the development of digital tools of a pedagogical nature such as MOOCs [33] [34] significantly tends to favor virtual content and to distance trainees and students from the technical and technological reality.

However, learning know-how in the field of microelectronics and more particularly in the field of electronic devices increasingly requires an important infrastructure, expensive technological equipment in perpetual evolution, efficient characterization and modeling tools and financial and human support. This justifies the existence of the training network that allows the mutualization of these investments at the level of the 12 French inter-university microelectronics clusters, each specialized in fields related to the local research and industrial production ecosystem, knowing that the spectrum is wide. The next section will show several examples of training and realization of know-how in the world of micro- and nano-electronics components, several of them involving multidisciplinary approach [35].

5. Learning of the Know-How and Examples of Achievements

The know-how is primarily oriented towards the needs of industry, research and high-level education. The setting up of platforms on which students and users can acquire these skills is guided by the needs expressed by industry and by the results of research work; the instructors teaching on the platforms are almost unanimously teachers-researchers and researchers. The objectives and therefore the achievements are the result of research work carried out in the local ecosystem.

Figure 4 shows several examples among 120 of the realization of elementary devices and circuits realized in the different centers of the network. The steps may include design using dedicated CAD, cleanroom manufacturing, characterization and modeling. The images presented give an idea of the diversity of the themes which is justified by the industrial demand which is currently in shortage of actors in the field, at least in France. The achievements are identified on Fig. 4 by a letter of the alphabet and are described below:

a) Control of the self-organization of nanoparticles involved in the manufacture of nanometric components at the microelectronics center in Paris Ile-de-France;

b) Silicon-based nanowire involved in a sensor realized and manipulated by students of the microelectronics center of Rennes;

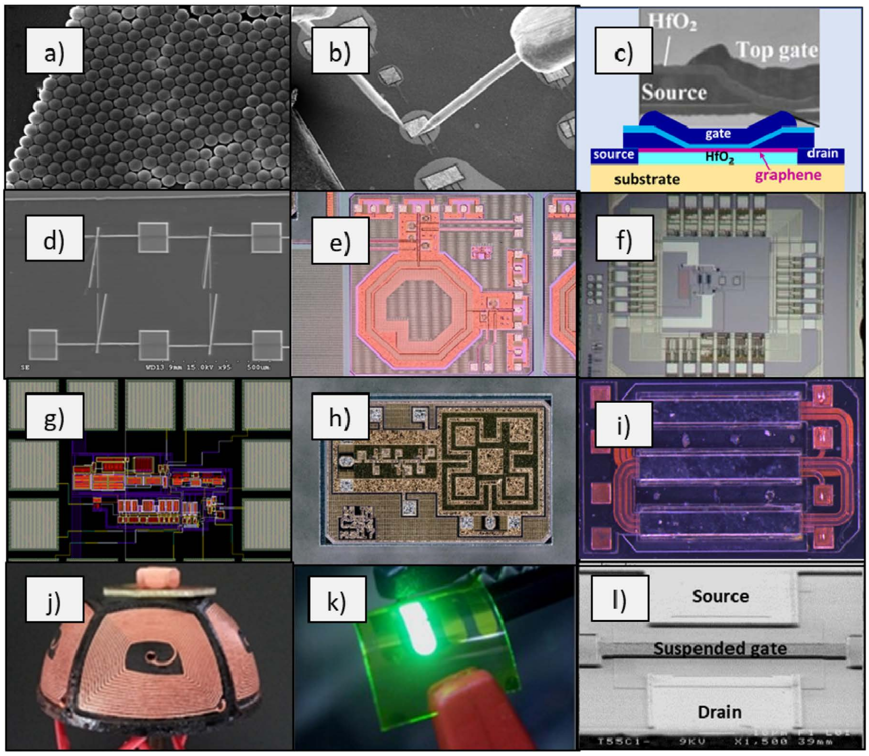

Figure 4. Twelve realizations by the students of a large panel of semiconductor devices on the technological plaforms of the twelve microelectronics centers of the French network.

c) Graphene-base transistor fabricated and characterized by students at the center of Lille;

d) Realization and characterization of mechanical stress analysis patterns in nanometer-thick layers for future devices of the Paris-Saclay microelectronics center;

e) HF integrated circuit designed and processed by students of the microelectronics center of Limoges and Toulouse;

f) Silicon-based MEMS (Micro-Electro-Mechanical-System) designed and processed by students of the microelectronic center of Grenoble;

g) Design of a low power integrated chaotic analog generator by students at microelectronics center of Marseille-Nice;

h) Radiofrequency analog integrated circuit designed and processed by students of the microelectronics centers of Limoges and Toulouse;

i) Additive manufacturing of an inductor and a power transformer, applied to a high frequency multiphase converter designed, manufactured and tested by students of the microelectronics center of Lyon;

j) Design, production and testing of plastronic devices at the microelectronics center in Lyon;

k) Design and manufacturing of organic light-emitting diodes on flexible substrate at the microelectronics center of Bordeaux;

l) Thin film transistor with suspended gate in polycrystalline silicon for chemical and biological sensors made at the Rennes microelectronics center.

Note that all designs are made by one of the software provided by the Montpellier center which manages and distributes all the CAD tools and modeling software of the national network.

6. Conclusion

Skills in physics and semiconductor components are becoming an essential requirement to face the various challenges created by the exponential growth of connected objects and internet networks. Indeed, all these objects and systems are the first users of microelectronic and nanotechnological components. In order to limit consumption of energy but also of natural resources, the global microelectronics community has an increasing need for skills and know-how that can only be acquired through high-level training that provides knowledge and know-how as well as basic knowledge in the many application areas. The French national microelectronics training network has adopted this strategy and is dedicated to meeting the challenges with the users of its inter-university platforms, whether they are students or company employees. This approach could be followed by many countries to accelerate the evolution towards a more realistic future.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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