New Approach for Sensors and Connecting Objects Involving Microelectronic Multidisciplinarity for a Wide Spectrum of Applications

O. Bonnaud\textsuperscript{1,2}
\textsuperscript{1}Department Microelectronics and Sensors, University of Rennes 1, France
\textsuperscript{2}GIP-CNFM, Minatec, France

Abstract—The fabulous evolution of the field of microelectronics and nanotechnologies was mainly governed by the reduction of dimensions during the last fifty years. This increasing of the circuit integration that is observed in a large spectrum of applications represents today the key factor of the evolution of the next ten years. In parallel, since the beginning of the 2000’s, the evolution becomes different by involving not only the reduction of dimensions of the elementary devices, but also the integration of systems involving these circuits. This means an opening of the spectrum towards a multidisciplinary aspect in order to combine an electronic circuit with physical, biological, or chemical sensors, which can include signal treatments and communication modules, as well as actuators. These functions appear fundamental for the control and the improvement of the environment. After a presentation of the present situation and the possibility of developing connecting objects, a special attention is paid to the development of sensors and actuators based on thin film technologies and large area electronics. They are well adapted to create heterogeneous architectures leading to new sensors able to analyze chemical or biological species, and particularly suitable for the analysis and the monitoring of the environment. In addition, these new objects need new skills and new know-how. The formation of engineers and doctors must be adapted and include practice in dedicated environment. This point is approached in the last part of the paper.

Keywords—Microelectronics, microsensors, connecting objects for environment control, multidisciplinary approach, practice-oriented pedagogical approach

I. INTRODUCTION

The field of microelectronics and nanotechnologies is permanently evolving with a very fast rate and allows the development of sensors and actuators that are compatible with the technologies. The new technologies, more especially those involving thin film technologies and large area electronics, allow developing of new sensors able to analyze chemical or biological species. These sensors are particularly suitable for the analysis and the monitoring of the environment. After a presentation of the context of the field and of the new trend of the systems involving microelectronics devices, the paper gives some details on the technologies recently developed to create new architectures and new devices that can be included in a heterogeneous approach. Several examples of the new devices are given and show their capability to design and fabricate sensors as well the adaptation to the integration.

All these technologies involve complex processes and designs that need new competences, skills and know-how. To answer to this needs, that paper makes some considerations on the effort that should be provided in the formation of engineers and doctors to insure this evolution. This approach is particularly developed in France in the frame of a national network that contains twelve centers that include many platforms devoted to the computer-aided design, the technological fabrication in cleanrooms, the analysis, the test and the characterization of the circuits and systems.

II. FAST EVOLUTION OF THE TECHNOLOGIES

The field of microelectronics and nanotechnologies is permanently evolving with a very fast rate. The integration of electronic circuits as G. E. Moore has predicted in 1965, varies exponentially; this heuristics law was verified during more than forty years [1]. This increasing of the integration that is observed in a large spectrum of applications represents today the key factor of the evolution of the next ten years. In parallel, since the beginning of the 2000’s, the evolution becomes different by involving not only the increasing of the electronic circuit integration by the decreasing of the minimum size of the elementary devices, but also by implementing the heterogeneous integration of systems involving these circuits. The technologies have thus shifted from pure microelectronics devices to hybrid systems that involve new technological approaches combining, very high integration, thin film devices, packaging and also new functions and components such as optical devices, batteries, energy harvesting, transmission systems and signal processing [2], as shown Fig. 1.

In parallel of the Moore’s Law evolution, the Fig. 1 highlights the new technologies from silicon in package (SIP), system on chip (SOC), systems on package, to organic electronics, large area electronics that can include displays. They take part on what is called “More than Moore’s” evolution.

This corresponds today to an increase of the complexity by combining several technologies, by playing with the packaging, by designing the elementary devices and the integrated circuits in 3D (or three dimensions), knowing that

Corresponding author: Olivier Bonnaud

e-mail address: olivier.bonnaud@univ-rennes1.fr

Presented at the 3rd ISNPEDADM 2015 (New electrical technologies for environment), in October 2015
most of the integrated circuits are always planar. It is also possible to apply the microelectronics technological processes to the micromechanical structures allowing the development of all the family of MEMS (Micro Electrico-Mechanical Systems) including BIOMEMS, OMEMS. The combination of the new microelectronics technologies with these functions induces new generic technology families such as mechatronics, optoelectronics, bioelectronics, systems-on-chips, embedded electronics, electronic sensor nodes, organic electronics, large area electronics, etc. that combine skills in several fields and that are intrinsically multidisciplinary.

In practice, this means an opening of the spectrum towards a multidisciplinary aspect in order to combine an electronic circuit with physical, biological or chemical sensors that can include signal treatments and communication modules, as well as actuators. Of course, these new functions appear fundamental for the control and the improvement of the environment.

III. CONNECTING OBJECTS

Through the evolution of the technologies, it is now possible to fabricate a full system that can be composed by sensors, actuators, and signal processing circuits. In addition, the full system may contain displays, alarms or control panels. Associated to the new connection environment, that includes the GSM, Bluetooth, Zibbee, WiFi, 3G-4G, internet, etc., and consequently to the communication protocol the more suitable to the environment, the sensors and actuators are becoming connected. They constitute the new families of devices, namely the connecting objects. Fig. 2 shows the constitution principle of these objects [3].

They are supposed to contain two separated parts, the first on the site of the detection or of the actuation, and the second in a remote place. They are also supposed to contribute to the most important development in the next ten years following the prediction of the industrial bodies [4] of the domain. Indeed, the fields of applications appear very numerous. Fig. 3 shows the main domains that are the most concerned today: health, environment, energy, security, transport and communication [5].

The microelectronics industry that includes integrated circuits but also large area electronics and systems, is expected to experience a huge development. It could govern a worldwide annual activity higher than seven to ten thousands billions of US Dollars in the near future [4].

But as already mentioned, the spectrum of application is becoming very wide and the multidisciplinary knowledge becomes more and more required in order to create innovative objects.

In practice the multidisciplinary approach appears under two different forms.

The first form is directly linked to the microelectronics technologies. Indeed, the increasing complexity of the fabrication process requires to combine many aspects. For example, the photolithography step that is involved several tens of times during the fabrication of an integrated circuit of the last generations, needs a high mastering of the process, associated to a solid knowledge mainly in electronics, physics of semiconductors, crystallography, physics of solid, the mechanics, the thermodynamics, chemistry, statistics, optics, quantum physics, the computer automation, and in the computer-aided design.

The second form is linked to the application domains that may include the mechanics, the biology, the chemistry, the communications and transmissions, energy conversion, energy storage, the energy harvesting, optics, by mentioning the more concerned, today.

This multidisciplinary knowledge is not mastered by only one engineer. It corresponds to the cumulated knowledge of a large team composed of many scientists, engineers and specialists in each field. That is the challenge of the near future.

IV. COMBINATION OF TECHNOLOGIES FOR SENSORS

The new technologies of packaging and the new possibilities of the 3D devices and systems open a wide spectrum for the microelectronics systems. Fig. 4 shows the principle of a smart sensor that can contain, a sensing area adapted to the application, and an electronic circuit for the signal treatment. To simplify, four approaches can be involved:

- a system on chip that consists to fabricate in the integrated circuit two zones, the first with the sensing area, the second with the signal treatment electronics,
- a system-on-chip for which the sensing area is deposited after the fabrication of the electronics for the signal treatment. It corresponds to a three dimension approach,
- a system in package that involves the two zones fabricated independently and finally packaged. In the new technologies, the two zones can be fabricated in thin film technology with adapted depositions. The substrate can be glass or flexible polymer, for example.
- a sensing area, and an integrated circuit, both thin film based, that are fabricated on the same substrate.

In a previous paper [6], examples were given on the possibility of fabricating magnetic field detectors [7] or biological sensors in the thin film technologies involving, on the one hand, thin film transistors deposited on low temperature substrates,
Fig. 2. Principle of a connecting object: sensors and actuators can be monitored by a remote device. On site the system may be fully integrated in a system in package (SIP) [4].

Fig. 3. Application domains of the connecting objects. The most important fields concern health and environment [5].

Fig. 4. The CMOS-like polycrystalline silicon TFT allows the fabrication on the same substrate, for which the area can be very large, of a sensing area and of the related signal processing circuit [6].

and on the other hand, specific architectures well adapted to the application [8], [9]. This sensor is based on an airgap transistor, a device including a suspended gate and allowing a very high sensitivity to detect chemicals or biological cells.

V. BASIC DEVICES IN THIN FILM TECHNOLOGY

When possible, of course, the technology is much better adapted if the sensor area and the associated electronics are manufactured with the same technological process. That is the reason to develop sensors involving the TFT technology.

In the following, we will present several types of sensors basically developed with this thin film technology. The first basic device is a CMOS-like thin film transistor circuit. Fig. 5 shows a schematic cross-section of such a device fabricated, either on silicon substrate, or on glass substrate or on organic flexible substrate [10].

This circuit is composed of two thin film transistors, n-type and p-type. The films are deposited by low temperature technique that can be mainly LPCVD (low pressure chemical vapor deposition), or PECVD (plasma enhanced chemical vapor deposition). From this process, it is possible to design all the classical electrical functions of electronics that can be involved in digital or analog circuits [11].

In order to improve the electronic circuits, new devices in the same thin film technology but with a vertical channel are in development. For the same supericies than a lateral TFT transistor (planar architecture), a vertical channel TFT may have a drain-source current more or less 50 times higher [12], in comparison with its counterpart in planar technology. Fig. 6 shows a cross-section of such a device. In this case, two parallel channels are fabricated on both sides of the tooth (or finger). The source of the transistor can be in the upper part of the stacking and the drain in the bottom. The architecture may involve a lot of parallel fingers which allows a large increase of the total current driven by the transistor, for the same supericies of the circuit. The channel length is controlled by the thickness of the polysilicon thin film located in between the stacked source and drain regions. In order to minimize the potential leakage current through this undoped film, an electrical barrier is introduced, and consequently, a
thin undoped polysilicon film is laterally deposited to create the two quasi-vertical channel regions. In terms of integration and in terms of amplification properties, these structures are very promising.

Another important structure in this technology is a thin film transistor involving a suspended gate creating an airgap, or SGFET (Suspended gate field effect transistor), as shown Fig. 7.

This structure can be functionalized by specific film deposited at the surface of the channel. The airgap thickness is submicronic. Due to the very small dimensions, the electrostatic effects can be very high. The drain-source current of the transistor being strongly dependent of the electric field in the channel region, a very high sensitivity to the distribution of charges located in this zone is obtained [9].

This generic structure has opened a large field of applications. Indeed, each time the charge distribution can be modified, a detection with a high sensitivity becomes possible.

Let us notice that this generic architecture can be fabricated as well in an integrated circuit as in thin film technologies. The potential applications are mainly the chemical sensors and the biosensors [13].

As above mentioned, the multidisciplinary approach becomes a key factor for the future of electrical engineering and microelectronics. The problem is that the engineers cannot be specialist of all the fields of applications. However, to be efficient, they need to be sensibilized to these application domains. This objective is a major component of the strategy of the French academic national network, entitled “CNFM” for National Coordination for Education in Microelectronics and nanotechnologies [14], [15]. This network coordinates twelve common microelectronics centers that are spread over the national territory and that manage microelectronic platforms devoted mainly for higher education. These platforms allow practice in technology through the seven common cleanrooms, as well as in the computer-aided design, the characterizations and the test. The most important point is that the practice that is considered fundamental for a good learning of the discipline, is accessible to 88 institutions (universities, institutes, “Grandes écoles”) and to 60 research laboratories. These Institutions or these laboratories can send their students or researchers towards the common centers [14], for a specialized training in the domain. These activities of the network are financially supported by the French Ministry of Higher Education and by a program IDEFI-FINMINA in the frame of Excellence Initiative [16], [17]. In the following, several examples of practice are given; they are oriented towards the multidisciplinary aspect.

The first example concerns the common studies with mechanics. Fig. 8 shows several devices designed and fabricated by the students in the centers of Grenoble and Rennes. They are gathered in the MEMS family (Micro-Electro-Mechanical Systems) by combining electrical and mechanical properties. These devices are fabricated in a fabrication process compatible with the classical microelectronics silicon technologies.

Membranes or cantilevers are used in order to create mechanical movements from an electrical activation, or to create electrical signals from mechanical activation. The fields of application are wide. In the first case, the bending of the membrane induces a modification of the conductivity in the doped thin zones.

In the second case, the cantilever may bend by thermal effect. By giving a specific shape to the cantilever, two parallel branches in series, this cantilever may also move laterally thanks to a relative variation of the linear expansion linked to the difference of heating associated to the difference of resistance in the two branches. This structure becomes an actuator.

Fig. 9 shows a biological detector designed from the generic architecture presented above. This sensor is functionalized through a chemical or biological treatment. It allows the fabrication of a biological lab-on-chip as shown on the right-hand side of the figure.

This practice is managed by teachers having both competencies, in microelectronics and in biology, more especially in the center of Rennes [18].

Fig. 10 shows devices combining optical and electrical
properties, in the chosen cases, a generator of light (light emitting diodes) and an energy converter (photovoltaic solar cells).

These devices are fabricated by the students, in the centers of Bordeaux and Rennes. In these two examples, the devices are fabricated on flexible substrates, that means a technological process at low temperature.

This approach corresponds to the expected evolution of the techniques.

Fig. 11 shows a connecting object designed and fabricated by the students in the frame of a laboratory project [5] within the center of Grenoble.

It combines communication, transmission, mechanical, electrical and microelectronics properties. The fabrication of this miniaturized drone needs multidisciplinary competencies. This work is adapted to the students at the master level in electrical and information engineering.

Other examples of multidisciplinary practice on the platforms of the other centers could be added. To give an idea of the whole activity of the network in this multidisciplinary strategy, more than 3,000 students among the 13,000 are made aware each year [19].

VII. DISCUSSION AND CONCLUSION

The multidisciplinary approach constitutes a key point for the development of the future innovative systems. The multidisciplinary aspect occurs at two levels: the first in the field of microelectronics by involving several types of technological processes, and the second in the field of applications that may concern a wide spectrum from communications, energy to biology and environment. These applications may have an economical and societal importance in the next ten years. This trend is confirmed by many expert committees around the world and more especially at the European level in the frame of H2020 program [20], [21]. To achieve these objectives, a special effort must be done in the higher education. The students and engineers who are engaged in the field of microelectronics and who are trained in this strategy, today, should be the main innovative actors in the near future. They
should answer to the challenges of the energy, the health and the environment.

ACKNOWLEDGMENT

The author would like to thank all his colleagues managing or working in the 12 microelectronics centers and to his collaborators within “Microelectronics Group” research laboratory that he has managed during more than 25 years. Special thanks to Lorraine Chagoya-Garzon who has contributed to the redaction of this paper. A part of the presented work is financially supported by the IDEFI-FINMINA project in the frame of the French Future Invest Initiative program and that is coordinated by the GIP-CNFM.

REFERENCES

[14] “Coordination nationale pour la formation en microélectronique et nanotechnologie,” CNFM, (also website of GIP-CNFM).
[17] FINMINA project, website of CNFM.