Integrated sensors: expanding the boundaries of microsystem design for multidisciplinary customers

F. J. Ramirez-Fernandez[1], J. F. Justo[1], E. Galeazzo[1], M. Dantas[1], J. Corso[3], H.E.M. Peres[1], W. J. Salcedo [1], N. Peixoto[2]
[1] Microelectronics Laboratory, Escola Politécnica, Universidade de São Paulo, CP 66318, CEP 053015-970 São Paulo, Brazil
[2] The Krasnow Institute for Advanced Study, George Mason University, Fairfax, VA 22030, USA
[3] Freescale –Brazil
jramirez@lme.usp.br , jjusto@lme.usp.br, bete@lme.usp.br, hperes@lme.usp.br, walter@lme.usp.br, npeixoto@gmu.edu

Abstract - **One of the main challenges in technology education is how to keep up with the ever changing tools, processes, and standards dictated by newly developed tools not available at the university. Silicon foundries currently offer custom processes that can be adapted to develop sensors, optoelectronic devices and microelectromechanisms with a small budget. As a result, students from different scientific areas, in electronics and electrical engineering, profit from the same idea. Another advantage of this *outsourcing* is the possibility of sharing circuits, laboratory experiments, and courseware among universities and among disciplines, democratizing the educational experience and, thus, improving the formation of qualified human resources. With the knowledge of the design rules any person can submit his/her project as any of their counterparts in another country. During the post-processing steps, the sensing element can be tailored toward the specific application they are designed for. Students from several backgrounds are involved in the early and later stages of the process, and help with debugging, as well as with field testing. Examples of interdisciplinary projects realized under this paradigm include: electrophysiological signal microelectromechanical systems, signal acquisition, electronic nose, telematic system for several applications such as sensors network, cells culture, and field emission devices.**

Index Terms – Smart sensors, integrated sensors, signal processing, microelectromechanical systems, electronic nose, sensing network.

INTRODUCTION

Engineering education has experimented great evolution with the development of microelectronics, when using systematically organized and didactic resources. With the emergence of foundry outsourcing and of post-processing services, engineering education begins a modern generation [1]

This paper discusses our experience for continuing engineering education program for teaching microelectronics using the available resources local facilities to build sensors. The aim of this program is to provide the necessary conditions for developing integrable solid state sensors, optoelectronic devices, microelectromechanisms, and encouraging the design of integrated circuits. In order to guarantee viability of this proposal, it is structured with a small budget. The integration of researchers (students) from several institutions is sought in interdisciplinary projects in fields such as biomedical engineering, materials science, electronics engineering, instrumentation, and computer science.

The South-American experience, to industrially incorporate Microelectronics (ME) in their economies, contributed to the formation of human resources in areas related to semiconductor technology. Engineers were formed in processes of fabrication, electrical characterization and circuit design by using conventional silicon technologies. In those countries, conditions to advance technology were only favorable until the beginning of the 80s. Since then, there has been a growing technological gap compared to developed countries. With the standardization of fabrication and integrated circuit design, it is again possible to involve the participation of professionals in specific fields. The new concept of design and integrated circuits fabrication, offered by silicon foundries, represents the most concrete option to offer technical advances to regions with low investment in emerging technologies [2].

Standard foundries also make silicon micromachining possible for universities that do not have an in-house custom integrated circuit fabrication facility. The possibility to make a post-processing step on the final chip, or to develop the sensor apart, allows reconciling the fabrication of sensor element with electronics circuits to create smart sensors. Most smart sensors consist of substrate electronics that implement the drive and control functions with one or more additional specialized layers of polysilicon, piezoelectric, or pyroelectric material to yield the transducer function [3].

The development of sensors system is an interdisciplinary task that requires the detailed knowledge of experts from completely different fields. In general, computer scientists, electrical and electronic engineers, physicists, biochemists, biologists, or medical engineers can be involved. This initiative supplements other programs in course to develop solid-state sensors to monitor environmental factors [4].

In this area, an important institution in Brazil is the Laboratório de Microeletrônica at the Escola Politécnica of the Universidade de São Paulo (LME-EP-USP). Most specialists in semiconductor technologies have graduated at LME, including not only Brazilians but also people from other South-American countries. LME has a tradition heading a Continuous Engineering Education program on Microelectronic and also forming human resources for the industry. Since early 70s, LME has granted degrees to more than 500 technicians and microelectronics engineers, 180 M.S. and 60 Ph.D. in fields such as technological processes, semiconductor devices, and integrated circuit design.

From the beginning, considerable attention has been given to Brazilian industrial issues. The country had tried manufacturing high quality products to compete in the commercial marketplace. Nowadays, the challenges are completely different; the number of semiconductor companies has reduced drastically, with little opportunities to rise again. Nowadays, the interest is focused on integration between electronic systems with other fields, such as biomedical, neuroscience, mechatronics, automotive, and environmental ones [4].

Therefore, there is also an increasing demand for environmental monitoring by means of selective, fast, compact, easy to operate and low cost embedded systems. In this context, nanomaterials fabricated for sensing application that are compatible with integrated circuits technology can be a solution. Nanomaterials, such as porous silicon (PS), have attractive properties, such as high specific area and high chemical surface activity, but presents high sensitivity. Additionally, several properties, such as selectivity and stability, need to be improved. In this context, this article, presents several results obtained by the Integrated Sensors and Microsystems Group (SIM) from LME-EP-USP as our educational experience to train specialists to work in interdisciplinary areas alike: monitoring and controlling of environmental conditions, such as air pollution levels and hazardous gases; measuring and signal processing of biomedical and chemical quantities, certification of fuel quality; MEMS; electro-optical transducers; virtual instrumentation, and remote monitoring and remote control of experiments, optionally by internet.

MICROELECTRODE ARRAYS

Microelectrode arrays (MEAs) have been used over the last three decades in cellular biology as a tool for probing electrophysiologic activity either *in vitro* or *in vivo*. The availability and development of microelectromechanical systems (MEMS) has enabled the fabrication of three-dimensional structures that add spatial resolution and cell development control [5-6]. Moreover, the miniaturization of sensors that can be implemented with the electrodes, such as temperature and pH sensors, enables the production of microsystems which will eventually bypass biomedical equipment and provide enough data to define neuronal activity and system status.

Although a high control of neuronal systems could be desirable, a high connectivity and, therefore, complexity of neuronal networks makes it very difficulty to analyse the amount of data available from such systems. Simplification of neuronal networks that can be isolated, maintained or even formed *in vitro* with a limited number of neurons has proven useful for understanding transfer functions and describing the basic characteristics of circuits, such as pattern generators or rhythmic activity [7]. Such neuronal networks can also be used as sensors for environmental conditions or drug influence on the whole organism. The first step toward such systems is the analysis of cellular adhesion and growth over micromachined substrates, which can then be further developed with onboard circuitry and electrodes. This paper presents results on the electrical stimulation of *Helix aspersa* neurons in culture on microelectrode arrays.

MICROELECTRODE ARRAY FABRICATION

Planar microelectrode arrays containing 100 electrodes were fabricated on a glass substrate; passivation is either a duplex layer of ECR silicon nitride followed by PECVD thick oxide or polyimide (PI 2525, HD Microsystems). Individual electrodeposition of platinum black on electrodes is performed in order to obtain ohmic impedance below 50 kΩ (at 1 kHz, sinusoidal excitation wave). Alternatively electrodes are coated with a conductive polymer (polyaniline or polypyrrole) in order to ensure stability during experimental conditions. Medium and long-term (from 10 hours to 10 days) characterization is performed in order to probe electrode stability. The electrode-electrolyte interface has not been modified either by means of mechanical movement or variation of the chemical composition of the electrolyte.

SIGNAL RECORDING AND STIMULATION

Computer controlled acquisition and stimulation is performed by means of virtual instrumentation developed with LabVIEW®. Signal acquisition can be performed at 32 channels differentially and input levels are set according to signal variation observed during the experiment. Upon identification of active electrodes, a maximum of four sites are chosen and saved for subsequent analysis. Cells placed over the electrodes can be visually identified and respectively accessed by means of differentially recording from neighbouring electrodes. Stimulation threshold for isolated cells is then probed by applying charge balanced square pulses in trains between electrodes, which are disposed across the cell body. Threshold is defined as the electrical stimulus that repeatedly elicits extracellular action potentials to each of the applied pulses. The current profile depends on the electrode impedance and seal to the cell. Charge injection threshold is found to be 0.08 $\mu C/cm^2$. Depending on time in culture, threshold can vary by one order of magnitude. Nevertheless, this value is much lower than the threshold usually found for neural implants, such as the retinal due to controlled environment. Then, the determination of lower baseline for neural prosthesis can start by looking at some cultured cell thresholds. This work also allowed inhibiting neuronal activity by means of electrical stimulation (unidentified neurons from the parietal ganglion). In this case, the spontaneous activity is in the range of 4 to 12 spikes/s. As soon as the stimulus sequence begins, the activity is completely depressed, showing the inhibitory effect observed in roughly 20% of the unidentified neurons maintained in culture for more than 10 days.

Threshold is considered to be the electrical stimulus that repeatedly elicits extra cellular action potentials to each of the applied pulses. Figure 1 shows an example of stimulation by a square pulse. The current profile depends on the electrode impedance and seal to the cell. Charge density can be evaluated, as shown by the third curve on this figure, by integrating current over time and dividing by electrode active area (400μm^2 in our case). Charge injection threshold is found to be 0.08μC/cm^2. This has been verified in ten different preparations. Depending on time in culture, threshold can vary by one order of magnitude. This value is nevertheless much lower than the threshold usually found for neural implants, such as the retinal, because of the controlled environment. Aiming at determining lower baseline for neural prosthesis, one can start by looking at the cultured cells thresholds.

MEMS

Usual processes for MEMS fabrication are revised for specific applications such as: microsystems for use in the cellular biology field, localized temperature control and gas sensors. In this work, contributions were made to the development of sensors and microsystems, following the current trend of miniaturization and integration of electronic and mechanical devices (microelectromechanical systems – MEMS) for applications in several areas. In this study, microsystems for biological applications are, basically, microstructures for neuron culture including microelectrodes for electrical access and integrated electrical devices for culture temperature control. For localized temperature control, microsystems composed by heating devices (micro-hotplates) and integrated thermal sensors (such as thermopiles) are developed.

HYDROGEN IMPLANTATION – POROUS SILICON TECHNIQUE (HI-PS)

Focusing on low cost alternatives and local infrastructure available in our laboratory, another implementation was the exploration of a promising combination of processes to obtain silicon membranes useful for microstructures. Such combinations included the hydrogen ion implantation process for “masking” porous silicon (PS) over selective areas, and the use of PS as a sacrificial layer.

This work intended to study the hydrogen ion implantation, aiming to obtain a stable structure formed by an improved quality surface region over a damaged high resistivity buried layer. Firstly, many hydrogen sources were tried to obtain an operational condition for hydrogen implantation. Afterwards, hydrogen implantations were followed by rapid and conventional thermal annealing over the samples. The presence of a high resistivity buried layer was verified by “spreading resistance probe” technique. Next, the implanted and annealed samples are submitted to anodization into HF in order to form porous silicon (PS) in selected regions without hydrogen implantation, where the silicon resistivity remains low.

Afterwards, PS sacrificial layer can be removed, resulting in several kinds of microstructures, depending on the geometry of the implantation masks as shown in Fig. 1.

The advantages of this Si microstructures fabrication procedure are presented and compared with the main fabrication techniques currently used. Microstructures such as bridges, membranes and cantilevers, conventionally used in sensor devices, were designed and implemented to define design rules to be used with this technology [8].

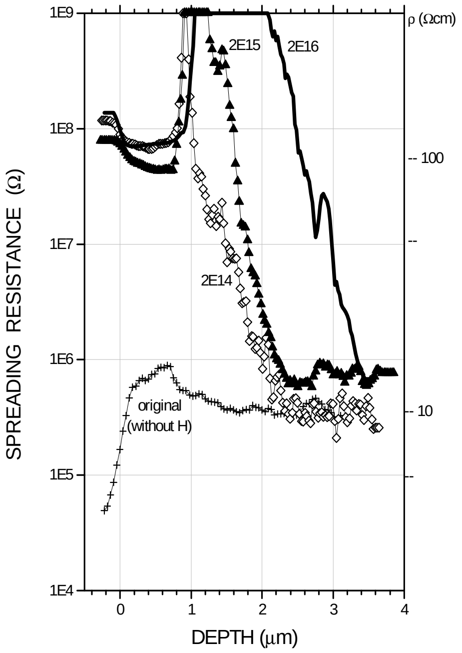

FIGURE 1
SPREADING RESISTANCE PROFILES FOR HYDROGEN IMPLANTED.

The major success was obtaining conical and pyramidal Si microtips with heights of about 50 μm, that can be extended to greater heights, and diameters lesser than 0.2 μm in the end, as shown in Figures 2 and 3. It has also been demonstrated that this technique allows getting Si membranes with different thicknesses, by just adjusting the H$^+$ implantation dose and adding conventional thermal annealing (CTA) processes after the RTA process.

Therefore, the HI-PS technology has shown to be a promising alternative for micromechanics manufacture, presenting advantages with relation to the major current techniques used for such purpose. This is a simple process that allows an excellent definition of microstructures.

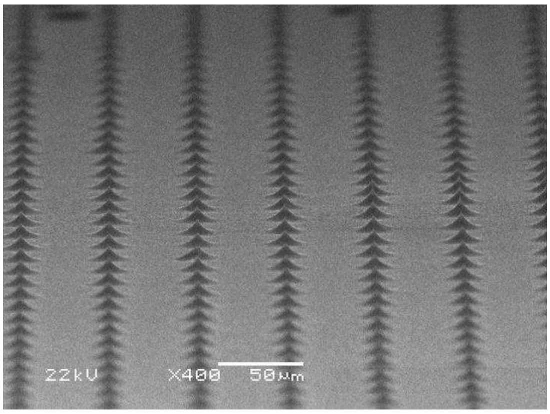

FIGURE 2
MICROTIP ARRAY OBTAINED BY HI-PS TECHNIQUE.

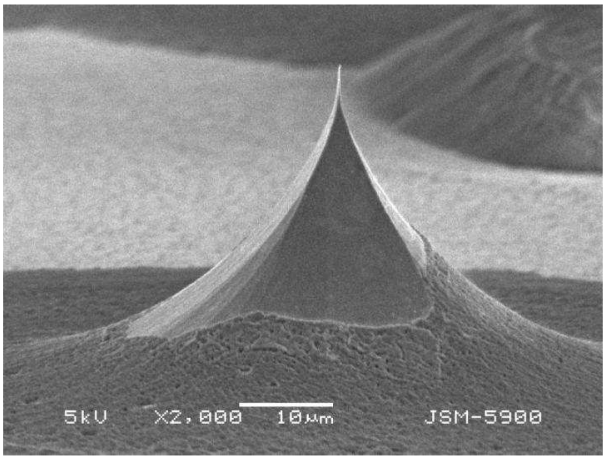

FIGURE 3
DETAIL OF A SILICON MICROTIP.

NANO-COMPOSITE OF POROUS SILICON FOR OPTICAL GAS SENSOR APPLICATION

Optical properties of porous silicon (PS) can be used as an excellent material for photonic device fabrication [9]. The high surface area of PS and their surface sensitivity to optical properties were used in order to fabricate an optical gas sensor [10]. Many efforts were devoted to the elaboration of nano-composites based on PS. The purpose could be to improve the electro-luminescence efficiency, or also the realization of particular sensing properties [11].

In this work, the photoluminescence (PL) behavior of thermal oxidized porous silicon/blue methylene (Ox-PS/BM) nano-composite, submitted to different organic ambients, was studied. The Ox-PS/BM structure was initially setup into a chamber vacuum (10^{-5} bar), followed by the injection of organic gas vapor (benzene, Methanol, Butanol, Hexane) and O_2 ambient, respectively. Figure 4 shows the PL emission of Ox-PS/MB after benzene vapor injection in the chamber, in which these intensities were normalized relative to PL intensity before gas injection as I/I_0, where I represented the PL intensity after gas injection and I_0 represent the intensity before gas injection.

From the experimental results, it could be observed that the PL emission increases after gas injection in all cases. Such behavior can be explained as follows: the gas molecules adsorbed on the Ox-PS/MB surface promote cavity, which avoided the non-radiative recombination of excited states in the MB molecules, increasing the quantum efficiency of radiative recombination.

Considering the behavior of the relative intensity spectra from the OX-PS/MB after exposed to different organic gas moities, it is suggested that the Ox-PS/MB film can be used as an excellent optical gas sensor, which can be implemented in optical systems as an optical nose after the principal component and pattern recognition obtained by signal processing from the relative intensity spectra.

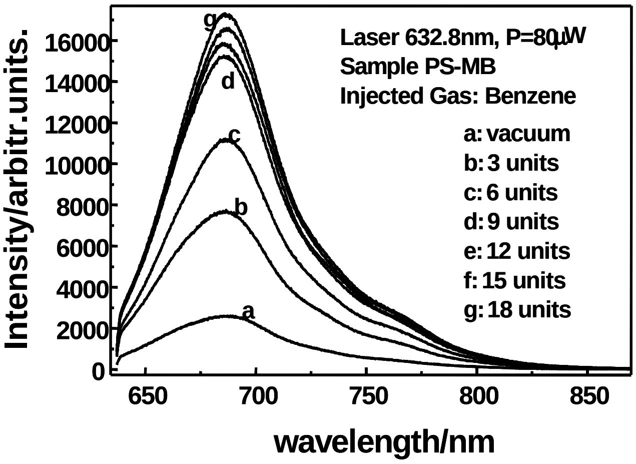

FIGURE 4
PL SPECTRA OF OX-PS/MB FILM WITH BENZENE VAPOR INJECTION

GAS SENSOR TECHNOLOGY - ELECTRONIC NOSE

Nowadays, there is an increasing interest in the monitoring and controlling of environmental conditions, such as air pollution levels and hazardous gases. Therefore, there is also an increasing demand for environmental monitoring by means of selective, fast, compact, easy to operate and low cost systems. In this context, materials nanofabricated for sensing application that are compatible with integrated circuits technology can be a solution. Several materials can be applied as gas sensors including Pd, Al_2O_3, and SnO_2. These materials have attractive characteristics, such as high specific area and high chemical surface activity. Nevertheless, these materials show elevated sensitivity, and selectivity and stability properties need to be improved, which is the focus of the present investigation. Our option to develop a gas sensor technology was first for Pd and then by SnO_2.

A portable system to identify aromatic substances, acquire and store signals of sensors was developed as the first experience to build advanced instrumentation. The system is based on the 80C552 microcontroller and on an array of tin oxide gas sensors, which are not very selective. Results obtained in the discrimination of alcoholic substances of equivalent chemical composition and mixtures of alcoholic substances are presented. The methodology considers the sensor operation under a variable temperature condition so as to obtain a reduction in sensor response time, as well as in error rate to gaseous compound recognition with relation to the behavior presented by the same system under a constant operation temperature. By periodically varying the sensor operation temperature, it is possible to increase the number of extracted parameters for substance discrimination. The sensor response, analyzed with Fast Fourier Transform (FFT), allows discriminating substances with the first six harmonics. Trials with chemical substances were carried out in different groups.

INTERFACE FOR SENSOR MICROSYSTEMS

The development of advanced instrumentation, such as the electronic nose, used in a number of scientific and industrial applications, was possible by combining artificial neural networks related to a sensor. Several electronic blocks were built, including multiplier, weight storage capacitor as a solution that constitutes the synaptic matrix in VLSI and the projected neurons with commercial integrated circuits.

The synaptic matrix blocks were projected with 0.6 µm CMOS technology to obtain circuits with small power consumption and a reduced silicon area. The projected multiplier has several advantages compared with those commonly used in the literature, since this has simple inputs, consumes little power and is based on an algebraic identity in such a way that the transistors are working in the saturation region that can be fulfilled with this condition.

One of the main application fields of this type of circuit is the on-chip sensors generated signal conditioning. There are many limitations for its development: hard trends to digitalize the electronic processes, poor performance when conventional techniques are used to design circuits, lack of appropriate models for simulating programs. In order to overcome these problems, this work presents some adequate design techniques for designing low-power low-voltage circuits. Some strategies in the design of CMOS interfaces for developing sensor Microsystems or MEMS were developed. The main goal is to provide a compatible output sensor with microprocessor systems on the same chip or in a hybrid way. Particularly, a CMOS interface for a resistive gas sensor with a bridge configuration is presented in Figure 5. The interface includes an appropriate circuit for compensating any temperature dependence of the offset voltage and sensibility of the output signal [12].

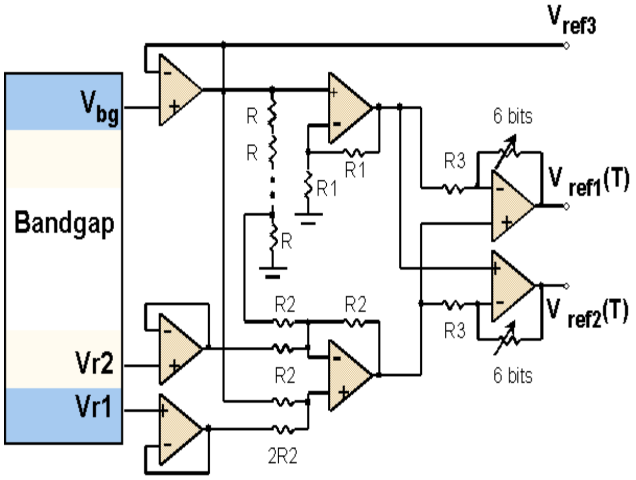

FIGURE 5.
THERMAL COMPENSATION.

PLUG AND PLAY SENSOR NETWORK

Embedded electronic systems are very useful for diagnosing sensor networks, and are cost-effective systems that can help to improve the efficiency and detection speed and to prevent faults. Additionally, it easily parameterizes to any Electronic Control Units (ECU), among other functions. There is no agreement between systems on which diagnostic protocol should be used and any new model even adds new protocol commands; therefore, it becomes more difficult to develop a "universal" diagnostic tool [13]. A telematic module developed in this work uses a FPGA as the core of the system, in which a protocol processor has been implemented, and it has the ability of adapting its output ports to establish communication with a sensors network, no matter what electric interface, diagnostic protocol or additional commands are been used, as shown in Figure 6. This architecture can be employed in any multiprotocole application to control intelligent sensors networks, greenhouses, environment monitoring, among others.

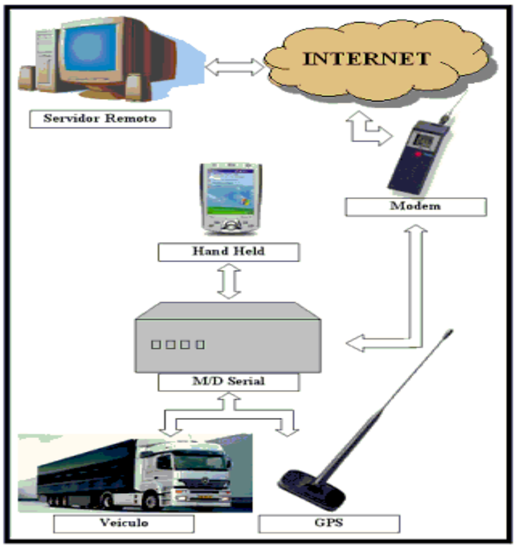

FIGURE 6.
TELEMATIC MODULE.

In this work, an intelligent network sensor architecture was developed based on the IEEE1451 standard for plug and play transducers. It is a Network Capable Application Processor (NCAP) connected to the Internet by a wired connection, and to Smart Transducer Interface Modules (STIM) by a wireless Zigbee communication channel. A web server is the interface between each NCAP node and a remote client. A Transducer Electronic Data Sheet (TEDS) is a set of electronic data in a standardized format stored in the STIM module, therefore allowing the transducer to identify and describe itself to the network, facilitating interface and the signal conditioning. Once a TEDS is read, the NCAP knows how fast it can communicate with a STIM, how many channels a STIM contains, and the data format of each STIM transducer [14]. This architecture can be used in biological research, meteorology, intelligent environments, and other remote monitoring applications.

CONCLUSIONS

This paper synthesizes our experience in microelectronic and electronic engineering education, focalized on the development of nanomaterials for sensors, alternatives for MEMs fabrication and dedicated systems for network sensor, joining students of different areas. The results presented in this work led us to draw the conclusions that follow related to microelectrode array, micromechanical systems, porous silicon, gas integrated sensor, interface for microsystems and advanced instrumentation to data acquisition from a network sensors. Microelectrode arrays were applied in cellular biology field as tools for probing electrophysiologic activity either *in vitro* or *in vivo*. Moreover, the miniaturization of sensors that can be implemented along with the electrodes, such as temperature and pH sensors, enables the production of microsystems that will eventually bypass the current biomedical equipment and provide enough data to define neuronal activity and system status. The HI-PS technology is a promising alternative for micromechanics manufacture, presenting advantages with relation to the main current techniques used for such purpose. It is a simple processing that allows an excellent definition of microstructures. It has also been demonstrated that this technique allows getting Si membranes with different thicknesses, by just adjusting the H^+ implantation dose and adding conventional thermal annealing processes. The porous silicon film can be used as a good host material in order to obtain silicon – organic dye molecules nano-composites and gas sensors.

With the design rules from 0.6 μm CMOS technology, integrated circuits with little power consumption and a reduced silicon area were fabricated. The multiplier has several advantages compared with the current ones in the literature, since this one has simple inputs, consumes little power and is based on an algebraic identity in such a way that the transistors are working in the saturation region that can fulfill with this. One of the main application fields of this type of circuits is the on-chip sensors generated signal conditioning. There are many limitations for its development: hard trends to digitalize the electronic processes, poor performance when conventional techniques are used to design circuits, lack of appropriate models for simulation programs. Aiming to overcome these problems, this work presents some design techniques for designing low-power low-voltage circuits. Some strategies in the design of CMOS interfaces for developing sensor Microsystems or MEMS were developed. The main goal is to provide a compatible output sensor with microprocessor systems on the same chip or in a hybrid way.

A telematic module was developed by means of a Field Programming Gate Array (FPGA) as the core of the system, in which it has implemented a protocol processor that has the ability of adapting its output ports to establish communication with a sensors network, no matter what electric interface, diagnostic protocol or additional commands it uses. The developed architecture can be employed in any multiprotocole application to the control of intelligent sensors network, greenhouses, environment monitoring, among others.

ACKNOWLEDGMENT

The authors acknowledge partial support from Brazilian agencies FAPESP, CAPES and the Laboratório de Microscopia Eletrônica LNLS, Campinas. This work was developed under the NANOSENSIM Nano-Sensores Integrados e Microssistemas network (contract number 400619/2004-0 CNPq).

REFERENCES

[1] Tom, K., Alvandpour, A., “Curvature compensated CMOS bandgap with sub 1V supply”. Proceeding of Third IEEE International Workshop on Electronic Design, Test and Applications, DELTA 2006. Jan. 2006, pp 1-4.

[2] Pina, C.A., “Evolution of the MOSIS VLSI educational program”, Proceedings of The First IEEE International Workshop on Electronic Design, Test and Applications, 2002, pp.187-191.

[3] Manic, D., Schuring, E., Ramirez-Fernandez, F. J., Popovic, R., “Post-processing Approach to Reduce the Influence of Assembling Procedure on parameters of Integrated Sensors”, Proceeding of the International Conference on Microelectronics and Packaging ICMP99, v.1, 1999, pp. .81 – 84.

[4] Giansanti, D., Giansanti, D., Maccioni, G., Maccioni, G., Development and testing of a wearable Integrated Thermometer sensor for skin contact thermography. Medical Engineering & Physics 29 (5): Jun 2007, pp. 556-565.

[5] N. Peixoto, “Matrizes neuroeletrônicas” Thesis, Escola Politécnica, Universidade de São Paulo, 2001.

[6] Thomas, C.A., Springer, P.A., Loeb, G.E., Berwald-Netter, Y., Okun, L.M. “A miniature microelectrode array to monitor the bioelectric activity of cultured cells”. Experimental Cell Research, v. 74, 1972, pp. 61-66.

[7] Eckmiller, R. “Learning retina implants with epiretinal contacts”, Ophthalmic Research, v. 29, 1997, pp. 281-289.

[8] M. Dantas, E. Galeazzo, H. E. M. Peres, F. J. Ramirez-Fernandez, Silicon micromechanical structures fabricated by electrochemical process, IEEE Sensors Journal, Vol.3, nº 6, 2003, pp. 722-727.

[9] V. Parkhutik, Porous silicon—mechanisms of growth and applications, Sol. Stat. Electron. 43, 1999, pp. 1121-1141.

[10] W. J. Salcedo, F. J. R. Fernadez, and J. C. Rubim, “Photoluminescence quenching effect on porous silicon films for gas sensors application”, Spectrochem. Act. A 60, 2004, pp.1065-1070.

[11] L. T. Canham, “Laser dye impregnation of oxidized porous silicon on silicon wafers”, Appl. Phys. Lett. 63,1993, pp. 337-339.

[12] F. Chaves, “Strategies in the design of CMOS interfaces for developing sensor Microsystems or MEMS” Thesis, Escola Politécnica, Universidade de São Paulo, 2004.

[13] Lee, K. (2000), IEEE 1451: “A standard in support of smart transducer networking”, in 'Instrumentation and Measurement Technology Conference, IMTC 2000. Proceedings of the 17th IEEE', vol.2, 2000, pp. 525—528.

[14] Ramos, H.; Pereira, J.; Viegas, V.; Postolache, O. & Girao, P., “A virtual instrument to test smart transducer interface modules (STIMs)”, Instrumentation and Measurement, IEEE Transactions on 53 (4), 2004, pp. 1232--1239.