Infrastructures for Education, Research and Industry: CMOS and MEMS for BioMed

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***Abstract*: Infrastructures to provide access to custom integrated hardware manufacturing facilities are important because they allow Students and Researchers to access professional facilities at a reasonable cost, and they allow Companies to access small volume production, otherwise difficult to obtain directly from manufacturers. This paper is reviewing the most recent developments at CMP, focusing on the manufacturing of various kinds of MEMS. These MEMS are hardware vehicles for many BioMed applications. Various examples are provided in the paper. Such infrastructures may help the BioMed community the same way they helped the Microelectronics community at the time of the VLSI revolution.**

Keywords: Infrastructures, Novel approaches to BME education; Teaching design; Teaching commercialization

I. The need for infrastructures

In Microelectronics in general, infrastructures to provide access to custom integrated hardware manufacturing facilities are important for several reasons:

- they allow Students and Researchers to access professional facilities at a reasonable cost,
- they allow Companies to access small volume production, otherwise difficult to obtain directly from manufacturers.

The needs of Universities, Research Laboratories and Companies can be summarized as follows:

- Universities need to have access to technology for teaching their students. Those students will be in the industry. Therefore they have to be trained at least on the actual state of the art technology processes.
- Research Laboratories usually need to have high performance technologies to validate new concepts. The quality of the research results depends mostly on the quality of the technologies. Accessing to up to date technologies is a necessity.
- Industrial users also need to access to the state of the art of the offered technologies. This is vital for industrial users. The development of a product is usually long (more than 1 or 2 years). It is necessary that an industrial user has access to an up to date process, giving guaranty on product life.

Infrastructures are also important because of the leverage effect they allow. Infrastructures are a means to make it easier the development of many projects, while the funding of individual projects is less efficient (in terms of the number of projects). The major issue is to obtain an affordable cost.

A large number of complex technological operations are required for integrated circuit fabrication, but circuits are cheap, due to the fact that most of those operations are repetitive. Each processed wafer of silicon is cut into hundreds of dice. For some of the slowest and costliest operations, “batches” of hundreds of wafers are processed together. That means that tens of thousands of circuits are fabricated simultaneously.

For non collective operations, such as test and packaging, operations are highly automated, using mass production techniques. These very expensive techniques, aimed primarily at mass production, seem out of reach for research and educational centers for integrated circuit design. However the design of a circuit by students must be pursued to its conclusions, which means fabrication, but a student will only require a few chips and mass production is not necessary. The basic idea of a multiproject chip is to collectively process circuits that are different and dissimilar. High fabrication costs can then be shared. To do so, a great number of elementary circuits are put side by side, to be reproduced on the wafer. The fabrication yield must be excellent, at least constant, since circuits cannot be tested before being sent back to the designer. This good yield is obtained through industrial production processes.

This is pictured in Fig. 1. Prototypes or low volume production is cheap because of a shared wafer cost. This is known in general as Multi-Project Chip / Multi-Project Wafers techniques (MPC/MPW).

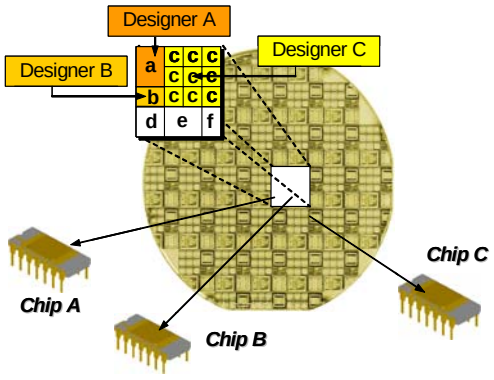

Fig. 1: MPC/MPW techniques

In addition to low cost, an affordable turn-around time should be available. This is pictured in Fig. 2: a total turn-around time of about 12 weeks can be obtained by services like CMP.

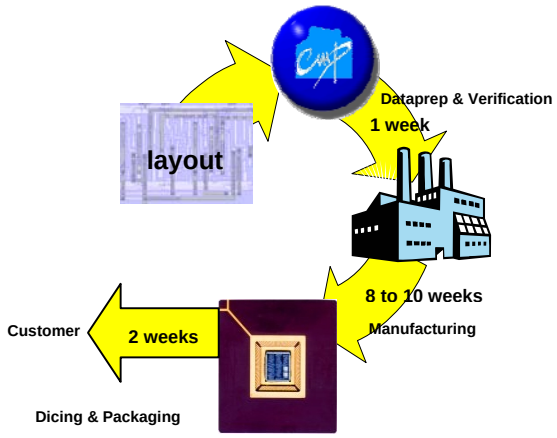

Fig. 2: From layout to packaged chips

Using such industrial processes, CMP could open the service to industry as early as 1990, for prototyping as well as for low volume production. Low volume production is aimed at helping Small and Medium size Enterprises (SMEs) to get relatively small numbers of circuits (say a few hundreds or a few thousands), that they would not obtain directly from manufacturers. A center like CMP is then interfacing the IC manufacturers and the SMEs.

Such an infrastructure allows the design of custom hardware from standard processes, i.e. no custom process development is required. To target an application only requires design capabilities.

II. Integrated circuits manufacturing at CMP

CMP is a non profit Service, reporting to CNRS (the French National Council for Research) and to Universities in Grenoble. A review of early national efforts can be found in [1], and a review of first cooperative initiatives may be found in [2].

Since 1981, several periods may be distinguished at CMP:

Development at CMP

Several periods may be distinguished.

1981–1982 : launching CMP with NMOS
1983–1984 : development of NMOS, launching CMOS
1984–1986 : development of CMOS
1987–1989 : abandon NMOS, increase the frequency of CMOS runs
1990–1994 : launching Bipolar, BiCMOS, GaAs MESFET, GaAs HEMT, advanced CMOS (.5 µ TLM)
1995–1997 : launching CMOS and GaAs compatible MEMS, DOEs, deep-submicron CMOS (.25µ 6LM)
1998 : launching silicon surface micromachining, abandon MESFET GaAs
1999 : launching SiGe, deep submicron CMOS (.18µ 6LM), SOI/SOS CMOS (.5µ)
2000 : launching SiGe BiCMOS (.35µ 5LM)
2001 : launching very deep submicron CMOS (.12µ 6LM)
2002 : launching Inp HBT process
2003 : launching 0.35µ CMOS-Opto
2004 : launching very deep submicron CMOS (90nm, 7LM), HBT Sige:C BiCMOS 0.25µ
2006 : launching CMOS 65nm (7LM)
2008 : launching CMOS 45nm

Processes available

Presently the processes available for ICs manufacturing are depicted in Table 1.

Austriamicrosystems	0.35µ CMOS C35B4C3
	0.35µ CMOS C35B4M3
	0.35µ CMOS-Opto C35B4O1
	0.35µ CMOS Flash C35B4E3
	0.35µ SiGe BiCMOS S35D4M5
	0.35µ HV-CMOS H35B4D3
STMicroelectronics	45nm CMOS CMOS045
	65nm SOI
	65nm CMOS CMOS065
	90nm CMOS CMOS090
	130nm CMOS HCMOS9GP
	130nm SOI
	0.25µ SiGe:C BiCMOS7RF
OMMIC	0.2µ HEMT GaAs ED02AH
CSMC	0.6µ CMOS 2P/2M/HR

Table 1: IC processes available

To be efficient, additional facilities must also be provided, as summarized below.

ICs design kits and CAD software

Design kits and libraries are distributed by CMP for most of the processes and most commonly used CAD tools. CMP sometimes develop design kits, in cooperation with the manufacturers and the CAD vendors. CMP also offers special CAD software conditions from a few CAD vendors. As a focal point, CMP also distributes information on configuration files, converters, etc. About 40 design kits are available for each process and the main CAD tools.

Test and packaging

Packaging and testing services are also offered. Various types of packages are supported, including DIL, SOIC, CQFP, JLCC, PGA, etc. Test of prototypes is usually done by the final user. On request, especially for low volume production, CMP may take over testing together with manufacturing.

III. MEMS manufacturing at CMP

To address BioMed applications, integrated circuits are necessary, but additional features are also often necessary: basically mechanical features. All these features are usually provided by the so-called MEMS, Micro-ElectroMechanical Systems. There are 2 families of MEMS. First the bulk micromachining also called volume micromachining. In that case the substrate is etched in the depth, with a wet or a dry method, front side or back side. These kinds of MEMS are mostly used for beams, bridges and thin structures. Then, the surface micromachining. This method uses sacrificial layers, grown during the fabrication process and then removed during the post process to let structures movable. These kinds of MEMS are often used for capacitive devices. Several types of MEMS are available from CMP, classified in 2 categories. First the bulk micromachining MEMS, based on standard CMOS and BiCMOS processes, for which structures are released with a post process step and without any additional mask. These 2 pairs of process/post process proposed by CMP allow to integrate both electronics and mechanical structures on the same circuit. The second category is the specific MEMS processes such as the MUMPs® family from MEMSCAP and SUMMiT V™ from Sandia, which are

either surface or volume micromachining. On these processes, very advanced systems can be created on moveable platforms.

- Bulk micromachining MEMS

CMP offers the possibility to fabricate MEMS on a low-cost 0.6µ CMOS process, from CSMC, which has 2 poly and 2 metal layers. Structures are released after the circuit fabrication with a humid TMAH solution to etch the silicon as shown in fig. 3. Systems like bridges, micro mirrors, comb drives or sensors can be made.

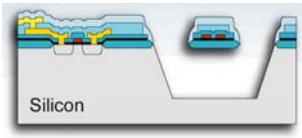

Fig. 3: Bulk micromachining cross section

The second bulk micromachining possibility is based on the 0.25u BiCMOS process from STMicroelectronics. This BiCMOS7RF process has 5 metal layers with top thick metal, vertical NPN with Ft = 55 GHz and is convenient for RF designs. It includes MIM capacitors, inductors and bipolar components. The associated post process is called ASIMPS (Application-Specific Integrated MEMS Process Service) and is made at the Carnegie Mellon University (CMU). Mechanical structures are released by RIE (Reactive Ion Etch) and then by DRIE (Deep Reactive Ion Etch as illustrated in fig. 4). Potential devices to be designed and fabricated in the process include accelerometers, gyroscopes, radio frequency (RF) MEMS communication systems (with resonator oscillators, RF filter and High-Q inductors), infrared sensors and imagers, electro thermal converters and force sensors. Some researches are currently made to develop a “bioacoustic membrane” gravimetric biosensor. This is a chip-based biosensor that is aimed at macromolecular targets. The technology enables integration of multiple devices on the same chip. For example, high-Q inductors and micromechanical resonators can be combined for CMOS RF application. In another example, multiple accelerometers are integrated on chip to create a 3-axis inertial measurement system. Furthermore, both the communications and accelerometer systems can be combined to form a wireless micro sensor system.

Two complementary design kits are provided by CMP, one from STMicroelectronics for the electronic part and one from CMU for the MEMS part.

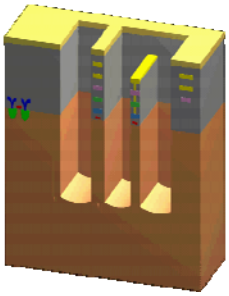

Fig. 4: ASIMPS overview

- MEMS processes

CMP offers processes dedicated for MEMS. First the MUMPs® family (Multi User MEMS Processes) with: PolyMUMPs, which is a Polysilicon / Gold surface micromachining, using sacrificial layers to suspend structures for which the fig. 5 shows the process cross section. SOIMUMPs, which uses the DRIE (Deep Reactive Ion Etch) on SOI (Silicon On Insulator). This process enables to etch front side and back side of the wafer to completely suspend the structures (fig. 6).

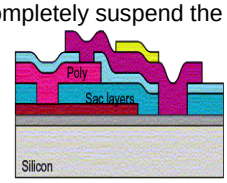

Fig. 5: PolyMUMPS cross section

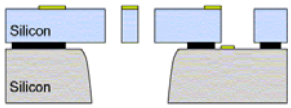

Fig. 6: SOIMUMPS cross section

MetalMUMPs, which uses thick nickel electroplated layer. On these last 2 processes the substrate is etched.

For all MUMPs® processes, CMP provides Cadence and Tanner design kits, with technology files and DRC implementation. Then, the SUMMiT V^{TM} (Sandia Ultra planar Multi level MEMS Technology V) from Sandia is also available. This process uses 5 polysilicon layers, all planarized (fig. 7), offering flexibility and gives a mechanical robustness in the devices.

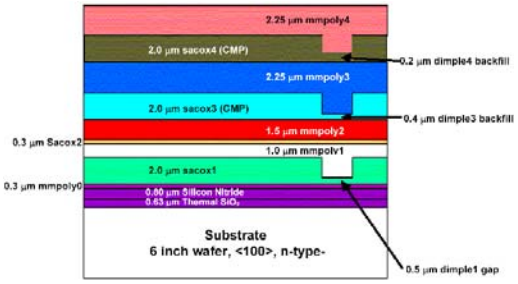

Fig. 7: SUMMit V cross section

Systems like comb actuators, meshing gears and transmissions dynamometers, laminated support springs, steam engines, micro engines and micro machines, motors, mirrors and optical encoders, micro sensors, RF MEMS and linear racks can be fabricated. In the BioMed application, some works are focused on a system that may allow large samples to be handled and processed in micro channel devices that are made in sheet and rolled or stacked. Also, a component that separates nucleic acids by size has already been made.Two design kits are available through CMP. MEMS Pro from SoftMEMS and Autocad 2000. Both enable DRC verification, 2D and 3D visualization. The Table II summarizes the MEMS processes available from CMP. The portfolio is large enough to imagine very complex mechanical structures with a solution for the fabrication. The designs can be complex either with the electronics management and control of the MEMS or in the movable structures. CMP also gives some support on MEMS design and provide the design kits on requests.

Integrated micromachining	Base CSMC .6 µ
	Base STMicroelectronics .25 µ BiCMOS post-process ASIMPS from CMU
Specific MEMS	PolyMUMPS from MEMSCAP
	MetalMUMPS from MEMSCAP
	SOIMUMPS from MEMSCAP
	SUMMiT V from SANDIA

Table II: MEMS processes available

IV. ICs AND MEMS FOR BIOMED

BioMed applications of electronics and MEMS in general range from implant devices to biosensors, DNA-based systems analytical protein arrays and cell based systems [3]. Two basic technological prerequisites are micro-fluidic platforms and separation based tools on chips. The goal of this paper is not to present an exhaustive panorama of all kinds of BioMed applications that can be reached with some types of electronics and MEMS, but only to address a few examples of what can be achieved with standard processes, available for example from CMP. The users do not need to call for specific custom process developments, they only need to design, they do not need to care about the manufacturing.

V. CMOS FOR NEUROSCIENCES

CMOS ICs can be used for interfacing with cells and biological objects. Both ICs and neurons (and more generally electroactive cells) work electrically. Electrons and holes in semiconductors and ions in cells are the information carriers. Neurons transmit information along nerves through the action potential that is the depolarisation of their membrane. Due to differences in ion concentration between sides of the cell membrane, neurons present a negative potential inside the membrane. When membrane proteins open ions channels, a depolarisation occurs and propagates along the nerve, it is the propagation of the action potential. By placing a metallic or insulator/semiconductor structure in the vicinity of a neuron membrane, it is possible to measure the depolarisation and thus to access the electrical activity of cells.

The idea of trying to build an electrical connection between a living cell and an electronic circuit has started in the 70's. This idea is based on the measurement of the extracellular potential instead of the intracellular potential thus being a non-invasive method for accessing the electrical activity of cells. Micro Electrode Arrays (MEAs) have then been developed and succeeded in not only measuring the electrical activity of neurons and tissues (the spikes) but also to interfere and initiate action potentials in neurons. Needle shaped microelectrodes have also been developed in order to be implanted *in vivo* in cerebral tissue and then to record its electrical activity. Despite these remarkable results, MEAs were suffering form limitations in terms of signal / noise ratio and integration possibilities.

In 1991, Peter Fromherz [4] has been working on silicon/neuron junction and then developed the first real connection between a neuron and an integrated circuit. These works have been pursued toward a greater integration and soon a real communication between an IC and a neuron [5-6] has been shown. By communication we mean initiation of an action potential in a neuron, propagation to other neurons and then reading of the signals in these other neurons through other microelectrodes in the IC.

The integration of real neuron networks with integrated circuits is a very promising technique for neuroscience. However some specific care must be taken for the coupling. For biocompatibility reasons, it is not possible to directly connect a culture medium to the surface of an integrated circuit. The aluminum as an example of metal present in ICs connection pads is not compatible with neurons. Several techniques have been develop to overcome this problem including the use of capacitive electrodes (silicon dioxyde is biocomptabile) or the covering of metal electrodes with noble metals such as Platinum. It is shown as an example in the fig. 8 where a square platinum plate covers the top metal opening.

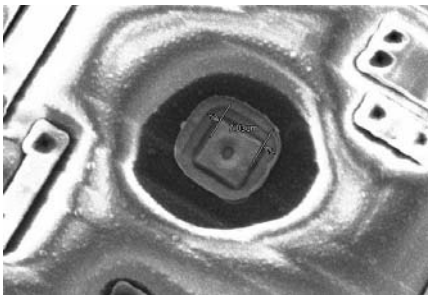

Fig. 8: SEM picture of the grid electrode of an ISFET covered with a platinum layer. This electrode is a part of an ISFET sensor matrix implemented on CMOS.

Apart from an electrical interface with electrically active cells, ICs have been used in several other bio applications such as the measure of ion concentration in the vicinity of cells. This has been done in the purpose to study ionic activity of cells (through membrane proteins) regarding the presence of drugs in the culture medium. In this case, several studies report the use of Ion Sensitive Field Effect Transistors to measure ionic concentration. Another application in cell biology has been to use an IC for localisation and immobilisation of cells. In reference [7], authors have created an array of photodiodes / electrodes included in a microfluidic system. Once a cell is detected through the array of photodetectors it is kept trapped by means of a vertical dielectrophoretic well. This system allows the control of cells population on top of an integrated circuit.

All previously described applications have been developed to establish a measure of electrical or ionic activity of living neurons. On another hand, there is an intense research activity on the field of mimicking the behaviour of neurons and synapses in the goal of building artificial analog neuron networks. Neuron networks have been intensively studied and modelled using computers. In the case of neuromorphic ICs [8], a physical implementation of a neuron is made on silicon. It has the advantage of being real time and could be used both for the study of computing techniques and also in the goal of hybridation with a real neuron network. The figure 8 is an example of such an analog neuron network, it has been made by researchers in University of Bordeaux [8]. This chip emulates neurons electrical activity using a biophysical model (Hodgkin-Huxley formalism). Five neurons have been integrated and are fully tunable. Their model cards are stored in an analog memory cell array. Such ASICs, as shown in Figure 9, form the computation core of a complete simulation system dedicated to the investigation of the dynamics of biomimetic neural networks.

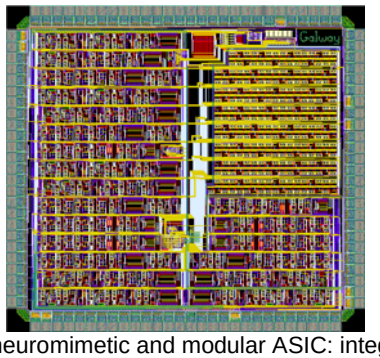

Fig. 9: A neuromimetic and modular ASIC: integration of biomimetic neurons

VI. Bulk Micromachining for BioMed

Bulk micromachining allows the fabrication of various types of sensors for BioMed applications. In the following, an acoustic sensor for ORL surgery is briefly described.

Acoustic sensor for ORL surgery

This project is under development jointly at the TIMA Laboratory in Grenoble and at the Hopital Nord in Grenoble. In Oto-Rhino-Laryngology (ORL), the middle ear surgery aims at correcting certain types of hearing loss or in treating certain diseases. Among different kinds of techniques, the ossiculoplasty attempts to re-establish a connection between the tympanic membrane and the oval window. This surgery involves ossicular chain reparation or reconstruction with appropriate replacement prosthesis. Three elements of the ossicular chain (stapes, incus, and malleus), the smallest bones of the human body, provide the sound energy transfer between the tympanic membrane and the inner ear. Successful surgery can lead to the correction of hearing loss due to tympanic membrane anomalies or to a discontinuity or fractures of ear bones. There exists a number of different techniques leading to the ossicular chain reconstruction using either biomaterials or various other materials such as titanium, gold or ceramics. In spite of all this progress, the surgical act in the middle ear remains difficult because of a large number of factors influencing its success. Moreover, there is no available means enabling per-operatory monitoring and thus giving necessary feedback to the surgeon.

The project is aimed at the development of a micromachined vibration sensor working in the audible frequency range from 1 to 5 kHz is required by ORL surgeons. Such a sensor, used during a surgery, will make easier to a surgeon to take a decision whether the realized ossiculoplasty is providing an optimal transfer of the acoustic signal from the tympanic membrane to the inner ear. The simplified picture showing the human ear main parts as well as the procedure using the vibration sensor is in Fig. 10. A sound source located in front of the patient's outer ear generates a test signal that propagates through the external ear to the tympanic membrane. The movement of the tympanic membrane is transferred via the ossicular chain to the input of the inner ear represented by the oval window. The vibration sensor put in contact with any part of the ossicular chain will thus provide real-time information about its degree of mobility and about the quality of the propagated sound signal.

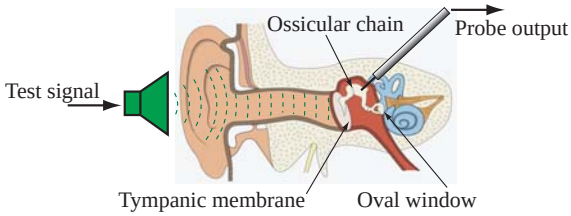

Fig. 10: Illustration of the basic parts of the human ear and of the use of the sensor.

The MEMS-based approach to the sensor design is motivated by the small size and low mechanical impedance of the ossicular chain. A micro-machined sensor tip will provide a possibility of the vibration measurement by a physical contact with no side effects to the ear function. A careful design of the sensor is required in order to overcome the ultra-low level of vibrations (see Fig. 11). The curve in Fig. 10 shows middle-ear displacement values generated by the sound pressure level of 80 dB on the tympanic membrane as obtained from the behavioral model of the ear.

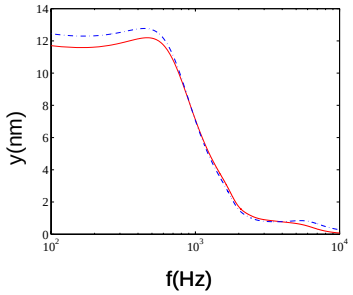

Fig. 11: Middle-ear bones displacements as a result of the behavioral model of the ear (sound level 80dB).

Different possible arrangements of the sensor are investigated. The sensor with a contact tip placed perpendicularly to the sensitive element composed of four arms equipped with piezoresistive gauges is shown in Fig. 12.

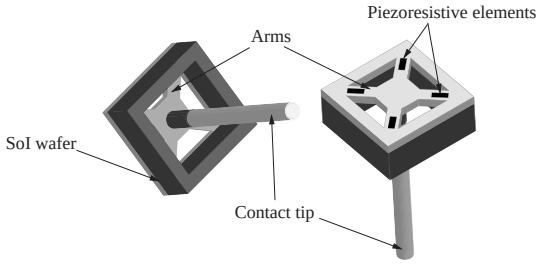

Fig. 12: Principle of the sensor structure.

The sensitive element of the sensor is made from the silicon-on-insulator (SoI) wafer. This kind of substrate facilitates the fabrication of arms with uniform thickness. The silicon arms are made by the front side micromachining. The whole sensitive structure is suspended on the cavity obtained with the deep reactive ion etch (DRIE) from the back side of the wafer. The contact tip is formed by a glass fiber attached with a central stem obtained after the patterning and the etching of the bulk silicon layer. Attention must be paid to the resulting characteristics of the mechanical structure. Especially, the mechanical impedance at the end of the tip must match that

of the middle ear ossicular chain. Too high value of the mechanical impedance may result in affecting the function or even in damaging the structure of the ear; too low impedance value would not ensure the optimal transfer of the tip movement towards the piezoresistive gauges. One of the results of the sensor structure FE modeling is shown in Fig. 13. The zones of maximal stress on the arms as a result of force load at the end of the tip can be identified here.

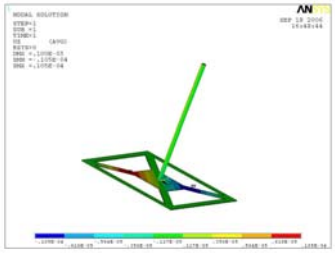

Fig. 13: Piezoresistive sensor structure FE modeling.

Another important issue consists in piezoresistive gauges optimization. Extremely low displacement values require high signal-to-noise ratio achieved by optimal geometry and placement of the gauges, by proper doping of the silicon layer and by low-noise electronics applied at the front-end.

VII. MUMPS FOR BIOMED

MUMPS allow the manufacturing of devices in view of various BioMed applications. In the following are addressed successively research applications and commercial applications.

VI.1. Research applications

The following examples are coming from Canadian Universities. The projects have been collected by CMC. CMC is the Canadian Microelectronics Corporation, a Service similar to CMP, servicing the Canadian Universities. The first example is coming from the University of Calgary, Electrical & Computer Eng. (Karan Kaler, Martin P. Mintchev, Electronic Mosquito: A Semi-Invasive MEMS for Blood Sampling and Analysis".). The device would extract blood like a mosquito would, electronically analyze the sample and then transmit it to a wireless device to monitor and control the insulin infusion pump so that the glucose balance in the body of a diabetic patient is maintained throughout the day. The Fig. 14 depicts more in detail the device. The following is taken from the designers.

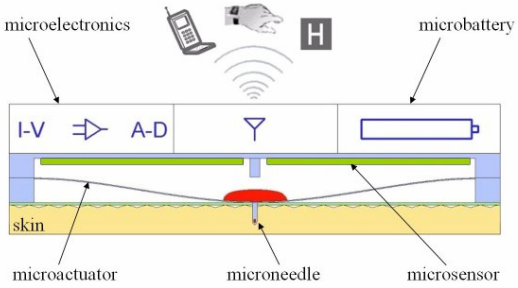

Fig. 14: The e-Mosquito™ cell: device building blocks include microneedle, microactuator, microsensor, microelectronics, and microbattery
[courtesy from the University of Calgary]

The very small volume of blood (<1ml) delivered by the sampling process is stored in a miniature blood compartment, where the microsensor converts the blood element of interest (for example, the glucose level) into an electrical signal. This automated and self-calibrated procedure is performed by a microsensor integrated inside the blood compartment.

The major building blocks consist of: (1) a microneedle; (2) a microactuator integrated with the microneedle; (3) a microsensor implemented inside a blood-collecting compartment; (4) a microelectronic stage including analog signal conditioning, analog-to-digital converter, controlling electronic circuitry, and digital radio-frequency transceiver; (5) a microbattery providing the energy to operate the MEMS device; (6) an associated packaging to protect the delicate microsystem inside; (7) an adhesive and antiseptic layer placed between the skin surface and the device; and (8) an enclosing band-aid to attach the e-Mosquito™ patch safely onto the skin. An array of single-use and individually actuated e-Mosquito™ cells form the disposable patch and a matrix of 180 e-Mosquito™ cells can provide periodic blood sampling for up to one week, assuming that blood monitoring is required every hour.

An other example comes from Dalhousie University, Mechanical Engineering Department, Ted Hubbard et al., developed a microgripper in view of mechanical testing of cells and bacteria, cell manipulation, medical screening. Initial designs were made on MUMPS, they next moved to Micragem, a SOI MEMS technology from Micralyne, that is available from CMC. The following is taken from [9]. An electrothermal microgripper is used. Typical displacements for chevron actuators are in the range of a few micrometres, so mechanical amplifiers are needed to increase the motion. Fig. 15 shows a chevron actuator with a set of two closed-toggle-style amplifiers, one for each jaw of the gripper. A small displacement downward (along the y- axis) at the centre of the chevron actuator (3) draws in the gripper jaws (6) significantly. The amplifiers (5) are mechanically connected to the actuators (3), and therefore current also flows through them. This means that they will also heat up and thermally expand. To take advantage of his current, the amplifiers are designed to act as hot/cold-arm-type thermal actuators, where the thin-finned hot arm of the actuator is on the outside, contributing to the inward, closing motion of the jaws (6).

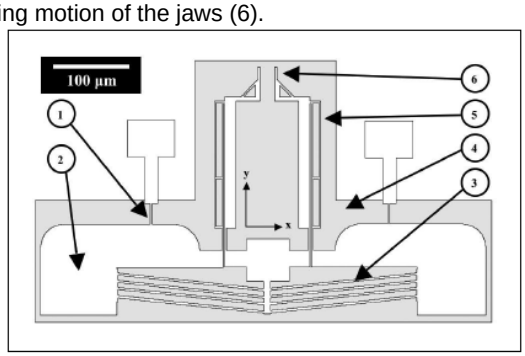

Fig. 15: Design of an off-chip gripper: (1) breakable tether; (2) bonding pad; (3) chevron actuator; (4) cavity; (5) amplifiers; (6) jaws [9]

The gripper is able to grasp 5 µm spheres.

VI.2. Commercial applications

The following examples are coming from MEMSCAP. The products did not come directly from MUMPS, but MUMPS have served as test vehicles to test various components . The first example is a pressure sensor MEMSCAP is manufacturing for CardioMEMS. The wireless pressure sensor is inserted during the minimally invasive repair of abdominal aortic aneurysms (AAA) or thoracic aortic aneurysms (TAA), via a catheter into a patient's aneurysm sac. The small size, durability, and lack of wires and batteries enable system to last for, and transmit data over, the lifetime of the patient without requiring repeated procedures (Fig. 16).

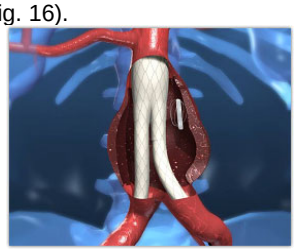

Fig. 16: Wireless AAA pressure sensor from CARDIOMEMS

The second example is a wireless imaging system made for Given Imaging in view of endoscopy. The tiny camera contained in a capsule captures images of the gastrointestinal tract as it travels through the body and transmits the images to a computer so a physician can view them and make a diagnosis (Fig. 17).

Fig. 17: PillCam Capsule from Given Imaging

VIII. ASIMPS FOR BIOMED

ASIMPS from Carnegie-Mellon University allow the design of BioMed applications. Here is an example: a bone implantable stress sensor. The following is taken from [10]. The clinical management of skeletal trauma and disease relies on radiographic imaging to infer bone quality. However, bone strength does not necessarily correlate well with image intensity. There is a need for a safe and convenient way to measure bone strength in situ. The goal is to present a new technique to directly measure bone strength in situ at a micro-level scale through a MEMS sensor. The proposed MEMS stress imager comprises an array of piezoresistive sensor "pixels" to detect stress across the interfacial area between the MEMS chip and bone with resolution to 100 Pa, in 1 sec averaging. The sensors are integrated within a textured surface to accommodate sensor integration into bone. From initial research, surface topography with 30-60 µm features was found to be conducive to guiding new cell growth. Finite Element Analysis (FEA) has led to a sensor design for normal and shear stress detection.

The Fig. 18 pictures the MEMS device that includes the piezoresistive sensor array, and a coil antenna for RF power and telemetry. The interest for clinicians is that if they had a practical means to directly measure and quantify biomechanical properties of healing or diseased bone in situ, within bone, this capability could provide improved and timely information for treatment management options, including drugs, fixation adjustments, rehabilitation regiments, or pre-emptive surgical intervention.

In contrast to the local nature of the validation in single sensor experiments, an array of piezoresistive elements offers the possibility of global data over an entire surface on the order of 1-4 mm^2.

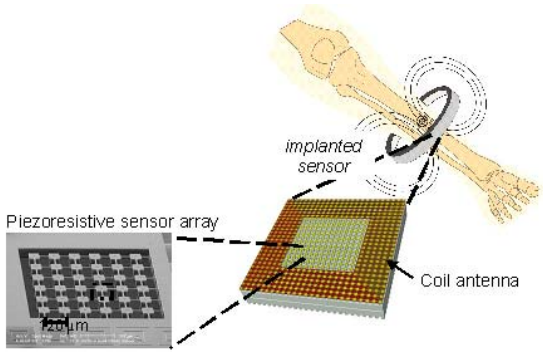

Fig. 18: Bone Implantable Stress Sensor [10]

IX. A SYSTEM VIEW: BIOMED SCIENCE AND BEAUTY

This last section gives a detailed example of a whole system including various kinds of sensors, ASICs for signal processing, data acquisition, expert systems, etc. It is coming from IntuiSkin, a wholly owned subsidiary of the MEMSCAP Group. IntuiSkin is focused on innovative, technology based skin care solutions. These solutions provide an answer to the new and strong consumer demand for technology based cosmetology. They allow to characterize the skin in general, in order to recommend suitable cosmetic treatments. The general concept of IntuiSkin is depicted in Fig. 19 [11]. The various MEMS sensors are grouped into 2 probes measuring many basic parameters of the skin.

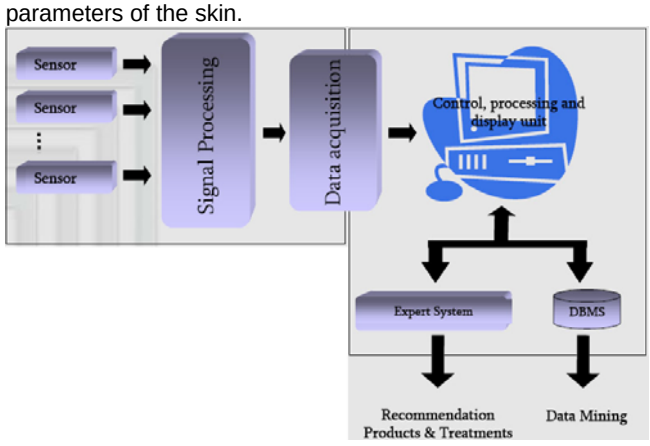

Fig. 19: IntuiSkin general concept [11]

The Visio probe uses its sensors to capture with an extreme precision the skin images. The system enables many measurements including wrinkles, sebum, hairiness, dark spots and clogged pores/bacterial infection. The Physio probe contains sensors and extracts in vivo the key characteristics of the skin. This probe measures, among other parameters, the hydration, the trans-epidermal water loss (TEWL), and the skin temperature. The 2 probes and a few examples of the measured parameters are depicted in Fig. 20.

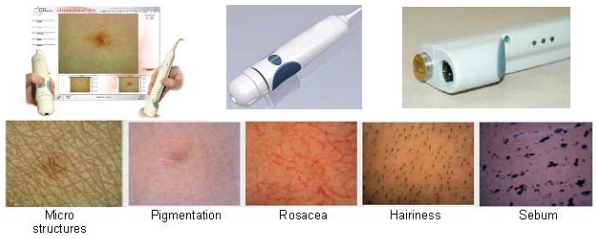

Fig. 20: The probes and examples of measured parameters [11]

Several equipments and products have been derived by IntuiSkin to address various needs. The Skin Evidence is addressing the medical market. It is an answer to the practician needs in cure and detection as well as in specific treatments (peeling, injection, fillers,…) as well as to the clinician in pre and post surgical support. It is expected that the system will be used by skin specialists, dermatologists, dermato-cosmeticians, plastic surgeons in their clinics or in their office.

The other market addressed by the general concept of intuiSkin is the beauty market. The IOMA Beauty Diag™ is measuring the 7 main dysfunctions of the skin: hydration and UV damage, fine lines, wrinkles and elasticity, redness, bacterial infection, sebum, dark spots. It is expected that aestheticians will use the equipment to recommend the best treatments.

The last exemplified systems are portable systems for consumer use: the Sensicards™. Sensicards enable to optimize the use of cosmetic products, to watch and check the skin evolution, so as to enjoy the sun benefits with no constraints. SensiCards are systems equipped with sensors, micro-electronics, data displays, batteries, communications interface and data analysis and management. They are custom made and integrated in a light and resistant packaging the size of a credit card. The UV-SensiCard is expected to be used for skin protection against the sun. Once the sun protection factor (SPF) of the available sun cream is selected, this card enables to measure and display the intensity of the ambient UV, and to recommend for each skin type the time to reapplication of this sun cream. Other SensiCards have been developed along the same general concept.

X. Conclusions

Many kinds of BioMed applications have been addressed in this paper, ranging from neurosciences to surgery aid, to endoscopy, to skin treatment. Many other kinds of applications might be devised in the future. Going further from dermatology for example, hardware devices might be designed in view of the coming market dealing with dermonutrition or nutricosmetics, depending on the way companies are coming from. Danone is offering yoghurts “nourishing the skin from inside”, and L’Oreal is offering with Nestle nutritional food fighting the skin aging:nutraceuticals with cosmetic benefits(the so-called beauty pills). In both cases, the efficiency can be scientifically measured by specific devices.

Services like CMP offer facilities to Students, Researchers, Small Companies in order to address many types of BioMed applications. Such facilities are efficient if and only if they are based on top level (advanced) industrial processes. Such efficient facilities are available from CMP: CMOS down to 45 nm, MUMPS from MEMSCAP, ASIMPS from CMU, etc. This is important in order to stay ahead of others, at the time of the globalization, when every country or continent is a low-cost country or continent to another one. Since it is difficult for a single service like CMP to offer many high-tech processes, a cooperation has started already years ago between a few such services. There are basically 7 such services in the world: CIC in Taiwan, CMC in Canada, CMP in France, ICC in China, IDEC in Korea, MOSIS in the USA, VDEC in Japan. Presently, the major cooperative effort is undertaken by CMC, CMP and MOSIS. These 3 infrastructure services announced it in June 2002. Since then, the cooperation has been steadily expanding [12]. CMP has also set up cooperations with ICC in China and with IDEC in Korea. Separately, CMP has also set up a number of bilateral cooperation with infrastructure services, with special groups in various countries, and has established distributors in several parts of the world.

More general comments can be made. The major services are going global in terms of cooperation, acting worldwide. The more advanced services are also going global in terms of technologies, addressing in the future electronics, photonics, mechanics, fluidics, as CMC-CMP-MOSIS plan to do. It is worth to note that the 7 major infrastructure services share the same legal status (services hosted by a University). The most advanced of these services shared the same development in extending their services from Universities to Companies and evolving from a subsidized service (by Ministries, Agencies, etc.) to a non-profit non subsidized kind of service.

What is important for the BioMed community is that Education and Research should take advantage of these infrastructures, in the same way as Education and Research in microelectronics have taken advantage of these infrastructures in the 80s. At that time, these infrastructures offered the possibility to EE and CS students, teachers, researchers, to focus on the design of complex circuits hence to focus on the applications, because these infrastructures gave them the opportunity not to be burden by the manufacturing processes, nor by the cost of their projects. Today, various CMOS and MEMS processes can allow students, teachers, researchers to focus on BioMed applications. Not all possible applications can be reached by standard processes offered by service organizations like CMP, but these service organizations are continuously expanding their portfolios. CMC from Canada recently introduced, for example, access to a microfluidics platform. In addition to fixtures for custom fluidic microchips, it gains advantage from multiple technologies--

photonics, electronics and embedded software, and pushes further the set of BioMed applications targeted by teachers, researchers and students.

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