MICROSYSTEMS AND SMART SENSOR INTERFACES

F. Maloberti
Integrated Microsystems Laboratory
Department of Electronics, University of Pavia
Via Ferrata 1, 27100, Pavia, Italy
Tel. +39 382 505 205, Fax. +39 382 505 677, e-mail franco@ispp4.unipv.it

Abstract
Future integrated microsystems will benefit significantly from the progress in the VLSI field. Two key elements will boost the implementation of new micro-integrated architectures: the progress in batch-manufactured silicon sensors and the introduction of new circuit techniques for designing interface circuits. These two factors will be essential in favoring the transition from the present “research driven speculations” to “customer driven activities”. This paper discusses the key issues for realizing post-processed sensors and the most suitable circuit techniques for interfacing and processing their output signals. A number of examples of integrated structures will illustrate present problems and possible solutions.

1. INTRODUCTION
Conventional integrated circuit (IC) technologies and, when necessary, a few additional post-processing steps allow us to realize (within a silicon chip and with a reasonable sensitivity) a number of sensing structures capable of detecting various physical and chemical quantities. The same materials (silicon, polysilicon, aluminum and dielectrics) used to fabricate integrated circuits are employed in realizing sensors. If the processing steps of a conventional IC process are not sufficient, the additional operations required to fabricate the sensor should be realized after the completion of the conventional IC process flow (post-processing steps) and preserve the integrity of the IC features unchanged. This approach, on one hand allows batch manufacturing of the integrated circuit and, on the other hand, permits us to work out wafers for achieving sensing elements at the batch manufacturing level as well. Therefore, since this leads to the production of cost effective devices, the method opens new perspective markets. Challenges arise from the cost effective technology, the level of the sensor signals, the packaging requests, the testing of physical-electrical (or chemical-electrical) systems, the aggressive environment and even the signal processing functions required.

The possibilities for a profitable use of smart sensors in real products depends strongly on a number of issues. Among them the most relevant are: cost-effective production, the achievement of reliable devices, easy and inexpensive testing, the availability of digital correction and compensation of non-idealities. All of these issues will be kept in account in the following discussion.

2. MICRO-SYSTEM DESIGN
The development of an integrated microsystem is, in any respect, a system development, thus requiring the same attentions required to realize conventional electronic systems. In addition, the design of a microsystem requires an interdisciplinary knowledge: sensor technology, analog signal conditioning, signal processing, digital interfacing and/or actuator techniques. Each of the system development is the definition of the system’s needs or, rather, filling the customer’s needs. In this paper we will discuss the contribution of experts in silicon microsystem design, and signal processing is essential.

Once the specifications of the system are outlined, possible silicon sensors and transducers must be defined. Moreover, the testing issues (reliability, de-bugging, testing procedures) should be considered already at this early stage. We have seen that realizing a system is quite a different issue than testing an integrated circuit; if we have to handle electrical variables, in the former case, we have inputs (and, outputs) which are physical or chemical quantities. Fortunately, the bandwidth of the signals is fairly low, but the amplitude is often limited and corrupted by noise. Moreover, most of the system operates can be harsh with severe conditions of use (high temperatures, high humidity, high pressure, ...).

An important concern for integrated microsystem production is encapsulation: function of an integrated circuit package is the circuit protection. Dissipation power and shielding from EM interferences can be secondary needs. By contrast, the quantity to be measured must (selectively) enter the system itself and the system’s problems in rejecting undesired signal or aggressive quantities.

Cost is another important issue. Batch manufacturing allows us to reduce the cost, the miniaturization of the system, a lower voltage and power consumption of the micro-integrated system even more attractive. However, the cost/benefit ratio is the key selling to the customer. It is worth specifying that low cost does not mean only but easy use, reliability and superior performances at well.

All the arguments above clearly show that a breakthrough in microsystems sensors does not only depend on the technological progress but also on a proper focus on the industrial issues that should expand the area of interest of researchers to what we call “customer driven investigation”.

3. SILICON SENSOR TECHNOLOGIES
In this section, we discuss the possible post-processing steps used to fabricate sensor steps can be classified in two major categories:
- Micromachining
- Deposition of material

In micromachining, we remove part of the material forming the chip (silicon, poly-silicon oxide, ... ) to realize mobile structures or to create a thermal insulation (somatic machining is used to lower parasitic capacitances).

Deposition of special materials in the form of thin layers helps in procuring or enhancing sensitivity to some specific quantities. Examples are the deposition of polymers, gases and humidity or the use of magnetic coating to concentrate the magnetic field.

Etching is used to manufacture micromachined structures. As we well know, we distinguish between isotropic etching and anisotropic etching. In the following, we quickly review these techniques and their specific use in micromachining.

Isotropic Etching
The etching is called isotropic when it proceeds uniformly in all crystal directions. Anisotropic etching is not very positive for modern IC processes since it causes the so-cal...
Diffusion realizes the lower electrode

Capacitance oxide achieved by silicon nitride and sacrificial layer made by p-doped silicon dioxide

Polysilicon pattern defines the micro-bridge

Lateral etching removes the sacrificial layer
Metal contacts the top plate

Fig. 1 - Post-process steps for a polysilicon micro-bridge realization

...effect, which is responsible for mismatch between capacitors having same area but different layers. By contrast, isotropic etching is beneficial in sensor technology since it permits removal of underlying material with the help of sacrificial layers, when necessary. To understand this point, Fig. 1 shows the steps necessary to realize a capacitive micro-bridge. On the top of a diffused pattern, a passivation layer made by silicon nitride and a sacrificial layer made of a p-doped silicon dioxide are deposited. A successive polysilicon pattern defines the microbridge structure. Finally, the lateral isotropic etching removes the sacrificial layer, thus allowing the polysilicon micro-bridge which becomes movable. Isotropic etching is carried out with reactive ion etching and hydrofluoric acid (HFA), and is followed by the chemical reaction

\[ \text{SiO}_2 + 6\text{HF} \rightarrow \text{SiF}_6^2- + 2\text{H}_2\text{O} + 2\text{H}^+ \]  

Isotropic etching allows us to remove sacrificial layers under structures as wide as 20-30 um, whereas, the etching rate is normally low (at low temperature); several hours for releasing metal a few tens of um can be required. Moreover, of course, the etchant used must be chosen: it must not attack other parts of the structure or the protective photoresist.

Anisotropic etching

Anisotropic etching produces a material cut with an etching-rate that depends on the crystal orientation. For example, the EDP (Ethylene diamine pyrocatechol water solution) etchant shows a higher etching rate in the (110) or (100) directions which 20 or 45 times (respectively) larger than etching rate in the (111) direction. Higher index planes (like the (211)) are highly attacked by the etchant. The exploitation of these features leads to the fabrication of predictable 3-D structures. For example, Fig. 2a, represents the result of the anisotropic etching of a square window in (100) silicon. The etching rate in the (111) directions is negligible; the chemical erosion of the material mainly proceeds perpendicularly to the (111) graphic planes (54.7° slope). When the depth reaches \( d = L/\left(2 \tan(54.7°)\right) \), the metallization of the two (111) planes brings the etching-rate to a negligible value and etching stops.

If the mask has convex corners, the etching in the (100) and (110) directions exerts planes with high index to the etch rate of the etchant, thus leading to underetching under these corners. This effect is shown in Fig. 2b [1].

A key point in designing etched structures concerns the capability of stopping etching at a given depth. Etch-stop is obtained with various techniques:

- by controlling the etching time: a fresh etchant with a low etching rate produces a depth controllable with acceptable accuracy
- by exploiting the etch-stop at a given interface: some etchants are selective with respect to other layers the etching-rate drops to negligible values (for example EDP do not attack highly doped p-type silicon)
- electrochemical etch-stop: when the etching reaches an electrochemical barrier (like a p-n junction) an electrical “signal” indicates that such a barrier has been reached.

The techniques described above allow us to perform both bulk micromachining and micromachining. In bulk micromachining, silicon is post-processed from the back of the wafer allowing us to achieve thin membranes like the one shown in Fig. 3. The bulk silicon is moved up to the etch-stop interface, usually, silicon dioxide or a p+ layer. With surfac...
Optical Sensor Systems

Conventional CMOS technologies allow us to design optical photodiodes with good sensitivity in the visible and near infrared spectrum. A photodiode is made by a p-n junction with a resistive and the diode is a junction of an MOS transistor. Lightwaves in the region of the p-n junction generate photo-voltaic output immediately below the surface. The electric field generated by this output can be collected. Fig. 4 shows an array of photodiodes arranged in a matrix. As the light passes through the matrix, the photo-currents are stored in the parasitic capacitance of the photodiode. When the diode is periodically biased, its stored charge is measured and, at the appropriate time, the diode biasing of the photodiode is established. The circuit requires either digital or analog interface units. The digital section controls the diode selection, while the analog performs the photo-current into a voltage by means of one or more charge pre-amplifiers.

Deposition of Materials

Deposition of thin layers of material is a common operation in microelectronics technology. For sensor applications, the only difference is that the temperature of the process must be low in order to preserve the features of the material. The techniques used are: evaporation, sputtering, and chemical vapor deposition. For deposition, the materials are:

- Metal films
- Dielectrics
- Semiconductors
- Oxides
- Polymers

Deposition processes can be divided into two categories: physical vapor deposition (PVD) and chemical vapor deposition (CVD). PVD processes include sputtering, evaporation, and ion beam deposition. CVD processes include plasma-enhanced CVD, pyrolytic CVD, and low-pressure CVD.

4. SENSOR INTERFACES

A sensor, similarly to all conventional sensors, generates an electrical signal in the form of current, resistance, or capacitance variation. The desired signal must be measured, amplified, and converted to a voltage or current signal. The amplified signal can then be processed by a microcontroller or other signal processing unit. The signal processing needs are determined by the characteristics of the sensor and the environment in which it is used. The signal processing requirements can be divided into the following categories:

- Sensors that require no signal processing
- Sensors that require simple signal processing
- Sensors that require complex signal processing
- Sensors that require signal conditioning

Fig. 5 - Photodiode array and control circuits
Magnetic sensors in CMOS technology: a) top view of a Lorentz device; b) LMT

diagram of a charge pre-amplifier is shown in Fig. 5 b). The read-phase is divided in two
stages, the charge on the photo-diode is integrated on capacitor CREF while the voltage
photo-diode approaches VREF. Then, capacitor CP is discharged (to be ready for a
second cycle), settling the photodiode voltage at VREF. The error caused by the finite
gain stage A is, therefore, cancelled.

Magnetic Sensors

A physical quantity that we can detect with an unchanged conventional IC technology
is the magnetic field. Two possible devices based on the Lorentz effect are shown in Fig. 6. The
detection is sensitive to a magnetic field orthogonal to the chip [5]. The current I1 injected from
the terminals is split into two parts: the major part, I2, flows through the central terminal
and a small fraction goes through two lateral terminals. The magnetic field produces an
effect on the two lateral components which is measured by the on-board electronics.

A lateral bipolar magnetotransistor (LBTM) device [4] is an extension of the parasitic bipolar
transistor available in the CMOS technology (p+ diffusion-well-substrate); in addition to the
LTM, the LBTM includes two lateral p-n-p transistors. The magnetic field parallel to the
substrate induces lateral collector currents that are measured by the on-board interface. Both
transistors are capable of detecting magnetic fields in the mT range

A structure can be made bi-dimensional [5]. This, in combination with a permanent
magnet, is suitable for accurate contactless angle measurements in wear-free angular position
sensing systems. Fig. 7 shows the microphotograph of a 2D- LTM. It has one central emitter
and lateral collectors. A suitable processing of the four collector currents permits the
measurement of the magnetic field direction. The block diagram of the sensor interface used is
shown in Fig. 8. It consists of a 2D magnetic microsensor, a circuit for biasing and common
depletion, two 10 bit D/A converters performing offset compensation and a signal pro-
cessing circuit capable of calculating the ratio of the two field components parallel to the
plane. The output of the system is a bit-stream which represents the angular position of
the magnet. The angle is measured over the full 360° range with a resolution of one
degree.

It is worthwhile observing that the circuit interface uses the oversampling technique to
declare the analog signal in the digital domain. The oversampling approach is very com-
mon when processing band-limited signals: speed is traded with accuracy and high resolution
is achieved without requiring precise components. Moreover, the oversampling approach
on sensor interfaces is motivated by additional goals, i.e., avoiding complex anti-aliasing filter
moving as fast as possible in the digital domain. Moreover, in this specific case, since the
measurement of the ratio between the x and y component of the magnetic field is required,
the post-stage of the oversampling module (Fig. 9) switches between the two inputs using
the input and reference voltages. The larger of the two input signals acts as the
reference and the output becomes the digital representation of the ratio between the larger
and the smaller one.

Fig. 7 - Microphotograph of a 2D magnetic sensor

IR Sensor

We have seen that bulk micromachining allows us to realize a thermally insulated memb.
A selected part of a chip can be heated by an infrared flow and the temperature of the mem-
brane rises compared to the silicon bulk (Fig. 10). The achieved temperature difference
the IR flow. A convenient device for on-chip temperature detection is the thermister which is the sample connection of a large number of thermocouples made by a p-doped poly2 (p-doped) junction. The signal resulting from a small IR flow (like that from the human body) is in the lV range. Therefore, the task of the electronic circuitry is to provide low noise and low offset amplification. This is achieved by using CMOS technology by assuming the signal band to be fairly low \([6]\). The use of this technique and the successive low frequency filtering of out-band noise contributes to the target sensitivity. Fig. 11 shows the input stage of the sensor including four-input transconductance stage; two inputs of the transconductor are used for gain and two for the autozero cancellation. During the autozero phase, the transconductor is connected in series and parallel branches of the offset and low frequency noise in the input terminals. During the measurement phase, the output of the stage is a signal current: its (over a large number of clock periods) on the capacitor of the following stage is required low filtering action.

![Fig. 11 - Autozero pre-amplifier for the IR sensor](image)

**Pressure Sensor Interface**

The Pirani vacuum sensor will show the potential features of a surface micromachined Pirani gauge involves a resistively heated wire. The sensor is attached to the heat source to transfer thermal energy to a heat sink which results in a decrease in the wire temperature. The output of the wire varies with pressure and, therefore, the sensor is used to measure pressure. The thermal coefficient of the wire is not the temperature (measured through the thermal coefficient of the wire). The actual CMOS Pirani gauge has been recently fabricated. Fig. 12 shows a sketch of the sensor. The air gap which separates the heat source and the heat sink is obtained by a metal etching. The post-processing results in a suspended dielectric membrane made of a metal dielectric and passivation layer. A meandering second metal layer sandwiched between the dielectrics is the heating element. The suspended membrane is separated from the substrate by a narrow gap, with a nominal width of 0.6 \(\mu m\), which communicates with the surface through the cleared etch windows. The standard upper metallization of the CMOS process is used for the membrane. A microphotograph of the sensor is shown in Fig. 13.

![Fig. 12 - Pressure sensor before (a) and after micromachining (b) silicon (1), SiO2 (2) passivation (3), poly(4), sacrificial metal (5), access window for gas (6), heater (7)](image)

**Humidity Sensor**

The deposition of materials using a conventional CMOS process allows us to sense the relative humidity the variation of the dielectric constant in polysilicon layers is normally exploited. A variation in the capacitance of a humidity sensor using minimum area elements is 0.01 \(\mu m^2\), in the range of a fraction of one percent. A variation of a few percentage points of the relative humidity produces a change in the capacitance.
5. CONCLUSIONS

The paper discussed some key research issues for the mass production of microsystems and sensor systems. The design and the co-integration of sensors and electronics on the same substrate is very important for batch manufacturing and the consequent cost reduction.

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