INTELLIGENT CMOS SENSORS

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ABSTRACT

CMOS including micromechanics using polysilicon structures as functional layers is a promising technology for production of Intelligent CMOS Sensors. Its cost and performance advantages allow to address volume markets like monolithic integrated sensors for automotive application.

Using modern silicon processes and their potential for large scale integration, new functions like on-chip calibration and diagnosis are possible. Furthermore, it offers direct digital output signals which is ideal for data processing in microcontrollers. In this technology, the non electric functional blocks (e.g. membranes for pressure sensors) can be miniaturized in a way so that they do not impose a chip real-estate penalty. This immediately reduces the production cost immensely. We will demonstrate the superiority of CMOS as technology for integrated sensors by two examples: An integrated pressure sensor and an integrated fingertip sensor system.

INTRODUCTION AND MARKET

The basic motivation for the integration of sensor functions and electronic functional blocks with standard (Bi)CMOS processes is driven by the necessity to provide high reliable and adaptable smart sensor products at low manufacturing costs. Low cost is the key indicator for the economical success of sensors in the rapidly growing sensor market, which is accompanied by an average prize reduction of 30 % in ten years. This prize reduction will even be accelerated in application fields that are known for the high demand for quality, reliability and system innovations, like the automotive market segment. Intechno Consulting [1] claims that the automotive market will still be the fastest growing segment in the next ten years, starting with 6 bill. USD world market in 1998 to 12,6 bill. USD in 2008.

Sensors for safety applications like dynamic vehicle control, tire pressure and side airbag will show the fastest growth, followed by sensors for the motor management (e.g. MAP: manifold air pressure). Sensors for ABS and driver airbag will saturate.

Besides the automotive segments, the market for sensors in home appliances, consumer applications and in information & communication, e.g. acoustic sensors, will grow as well.

Coming from a technology point of view, the semi-conductor sensors will be the class with the highest potential for innovations. Fig. 1 shows that most of the growth of the pressure sensor market is covered by silicon micromachined sensors.

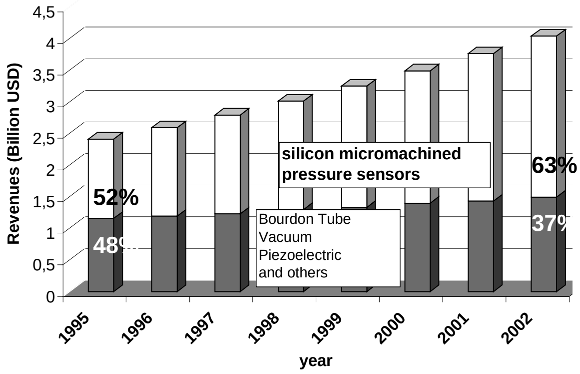

Figure 1: Micromachined pressure sensor world market [2].

The major benefits of integrated semiconductor sensors are: Reliability, flexibility, plug & play through digital interfaces, simple calibration, self test, miniaturization and low cost. Intelligent CMOS Sensors have the potential to meet all these requirements. The manufacture of CMOS sensors can be made rather cost-effective, at the same time providing high quality and reliability. Furthermore they can easily be assembled on PCBs (Printed Circuit Board) through the application of SMD (Surface Mounted Device) packaging technology. Nevertheless, the development of additional process steps for the non-electronic components, for example micromechanical structuring techniques like etching of sacrificial layers and anti-sticking procedures, is rather cost-intensive.

This additional cost for monolithic integration must be justified either through a gain in system performance, like low power consumption and ultra small size for medical applications [3], or through volume production, taking advantages of IC batch processing. A reasonable number for volume production is around ten million units per year for a product family. This is the kind of volume which is expected for certain applications.

Famous examples for integrated micromechanical systems are given by Analog Devices and Texas Instruments. The acceleration sensor ADXL 50 and family (Analog Devices [4]) shows that the seismic mass is no longer determining the chip area as compared to the electronic circuitry. Miniaturization also allows to integrate a multitude of mechanical components on one

MEMS. TI's DMD (*D*igital *M*irror *D*evice) is an impressive example of a highly integrated MEMS [5], featuring 10^5-10^6 individually addressable micromechanical mirrors. The DMD is the basic element of high-resolution and high-contrast digital projection systems that are on the market today.

The product examples mentioned above are based on CMOS or related processes, with add-ons in surface micromachining. The structural layers for the seismic mass (polycrystalline silicon) or the mirrors (metal) are in both cases added after completion of the microelectronic part.

CMOS MICROMACHINING

The next consequential step, suggested by Parameswaran, Baltes et al. [6] is the use of existing layers of the CMOS mainstream technology for the building of non-electronic components in CMOS sensors. Beyond that the goal is to use also IC packaging technology as long as interfaces to the environment are feasible.

As pointed out above, the basic principle of CMOS compatible surface micromachining is to use layers and processes of mainstream silicon technologies. The few necessary additional process steps for the non-electric components are also performed using standard CMOS process steps. The wafers do not leave the production line for these steps.

The additional process steps for surface micromachining are in general:
- Etching of sacrificial layer (mostly wet etch) to release the moving mechanical part (e.g. membrane or seismic mass),
- drying of the structure with special processes (e.g. critical point drying with CO_2 [7]) to prevent sticking of the moving part on the substrate,
- or instead of this two steps, applying a dry etch with gaseous hydrofluoric acid (HF) [8],
- coating with special layers for chip protection, if the chip surface is directly exposed to the environment, e.g. for pressure sensors.

Due to the small gaps between surface micromachined electrodes, the electric sensor signal can be deduced from capacitance measurements. In Fig. 2a, an n-doped well is located below the movable membrane of a pressure sensor as counter electrode. The vertical deflection of the membrane is detected as a change in capacitance between the membrane and the counter electrode.

Vertical deflected membranes are the basic sensor elements of Infineon's pressure sensors IC. A micromachining process module, comprising only one additional photo lithography step, sacrificial layer etching and cavity sealing was developed for integration into a standard 0.8 µm (5V) (Bi)CMOS process [9]. The micromachining processes have been inserted between the front end (active devices) and back end (metalization) parts of the process.

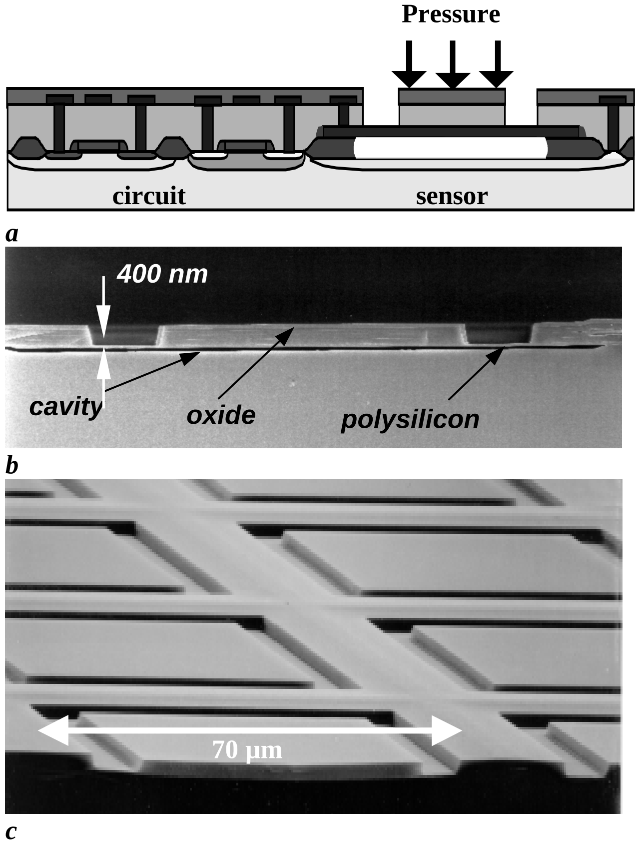

Figure 2: Surface micromachined capacitive absolute pressure sensor. a: Basic concept, b: Bossed membrane (polysilicon, 400 nm thick), c: sensor array out of 14 basic membranes, connected in parallel [3, 10].

The membranes with dimensions of 70 x 70µm and a thickness of approximately 400 nm are manufactured completely in a standard 6-inch BiCMOS production line. A field oxide is first generated over the lower electrode of the capacitor (substrate) and this is covered by a doped polysilicon layer in the next process step. The polysilicon forms the counter-electrode of the capacitor and is initially perforated in a dry etching step. The oxide (sacrificial layer) lying below is etched away via the holes using hydrofluoric acid, leaving an exposed polysilicon membrane. When the holes have been closed, an oxide seal is applied to the membrane to increase its rigidity and to hermetically seal the cavity with a defined pressure.
The sensitivity of the sensor is determined by the thickness of the polysilicon layer and the size of the oxide boss, which is etched at the very end of the process flow. As this process steps are well controlled, the sensor membranes can be manufactured with good reproducibility.

Table 1: Material properties of standard CMOS materials

material	Young's modulus [GPa]	stress (as deposited) [MPa]	stress (400°C, 30min, H_2&N_2) [MPa]	stress (85°C / 85%r.h., 600h) [MPa]	fracture strength [GPa]	aging (10^6 cycles) [GPa]
polysilicon 400nm, P 10^{16}	**162..169** **169 ± 6 [1]**	**19 ± 7**	**18 ± 7** ⇨	**18 ± 7** ⇨		
polysilicon 400nm, B 10^{16}	**162..169**	**203 ± 7**	**203 ± 7** ⇨	**203 ± 7** ⇨		
polysilicon 800nm, P 10^{16}	**162 ± 10**	**30 ± 10**	⇨	⇨		
polysilicon 4µm, P in-situ 10^{20}	**162 ± 10**	**-20 ± 7**	⇨	⇨	**3,1 ± 0,5** **1.2 .. 4.0 [1],[5]**	**2,5 ± 0,4** ⬂
SiO_2 600nm	**68 ± 6** **57..73 [2],[3],[6]**	**-255 ± 26**	⇨	⇨		
PE-Silan-oxide 700nm	**60 ± 5**	**-96 ± 9**	**-68 ± 5** ⬂	**-160 ± 5** ⇧		
PE-TEOS-oxide 700nm	**60 ± 5**	**-103 ± 24**	**-96 ± 21** ⬂	**-252 ± 21** ⇧		
BPSG 1µm, 4%B, 4%P	**57 ± 5**	**-27 ± 3**	**-26 ± 3** ⇨	**-147 ± 3** ⇧		
PE-nitride 600nm	**132 ± 8** **130 [2]**	**-44 ± 5**	**-24 ± 5** ⬂	**-24 ± 5** ⇨		
LP-nitride 250nm	**146 ± 9** **146..190 [2],[7]**	**1150 ± 146**	**1150 ± 146** ⇨	**1150 ± 146** ⇨		
aluminum 800nm	**69 ± 6** **70 [4]**	**232 ± 24**	**167 ± 17** ⬂	**167 ± 17** ⇨		

⇨ **unchanged** ⬂, ⇩ **decreasing** ⬀, ⇧ **increasing**

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The packaging of the pressure sensor, that must provide a direct interface to the environment is very important in terms of media compatibility and costs. To allow inexpensive assembly of the sensor in high volume applications, the component is encapsulated in a new developed SMD package. This P-DSOF8-1 plastic package is open on its upper side.

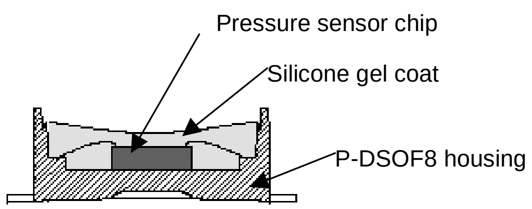


Figure 3: Pressure sensor housing [12]

After the chip has been glued using an isolating epoxy adhesive and contacted with gold wires, it is covered with a silicone gel through which the ambient pressure is transmitted to the sensor surface [11]. The package is well designed for the automatic placement on PCBs and thus offers a real cost advantage over conventional packages.

MATERIAL CHARACTERIZATION

The knowledge of mechanical parameters like Young's modulus and intrinsic stress of materials used in MEMS is essential for the design of the integrated sensors. In order to guarantee a high reliability the long-term stability of these materials has to be proven. Because most of the micromachined systems are in direct contact with surrounding media additional investigations are necessary.

We investigated [13] the properties of standard CMOS materials (Young's modulus, stress, fracture strength and aging) for surface-micromachined applications after deposition, and under accelerating conditions like high temperature (400°C, 30 min, H_2&N_2) and humidity (85% r.h. @ 85°C, 600 h). We investigated P- and B-doped polysilicon, Silan- and TEOS-oxide, BPSG, plasma nitride and aluminum The results are summarized in Tab. 1 and compared with results found in the literature.

Storing BPSG, silan- and TEOS-plasma oxide layers under humid conditions (85% relative humidity @ 85°C) leads to a significant exponential increase in compressive stress (Fig. 4). The analysis of transmission-IR-spectroscopy showed that the bindings with atoms of water increase when storing in humid environment.

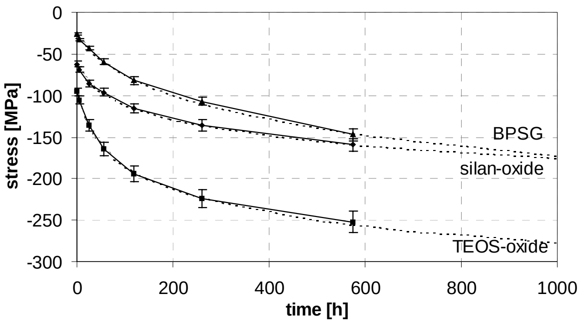


Figure 4: Measurement results for change of stress by storage in 85° C / 85% relative humidity [13].

No change in material properties of polysilicon, nitride and aluminum could be found during all measurements. This proved nitride coating to be a good protection for MEMS devices with a direct interface to the environment (Fig. 5).

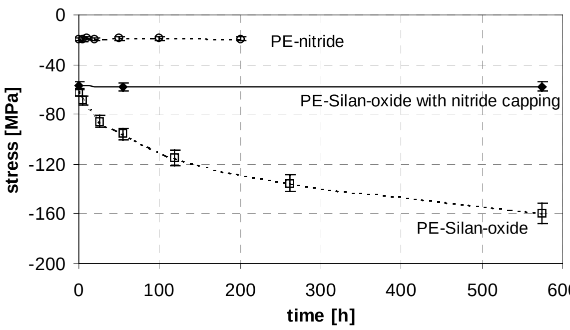


Figure 5: Change in intrinsic stress of nitride coated silan-plasma oxide, nitride and oxide.

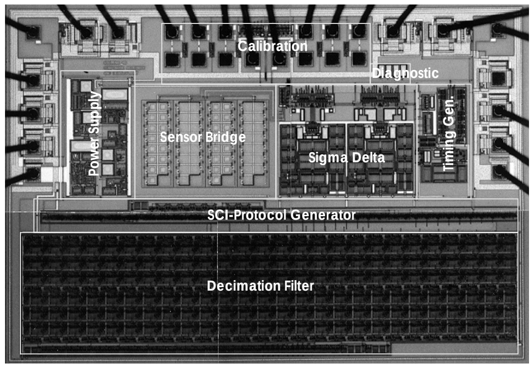
EXAMPLES

Integrated pressure sensor

An example for an intelligent CMOS sensor is the monolithic integrated absolute pressure sensor (Demonstrator: Fig. 6a, block diagram KP100 Fig. 6b). It is equipped with an on-chip ∑Δ-modulator, digital filter and a digital serial output. Offset control and diagnosis functions are integrated on the chip [10].

Due to the integration of sensor and circuit into one intelligent sensor system, additional features like diagnostic modes are easily provided to fulfil – for example - the safety requirements of automotive electronics. KP 100 comes with three different diagnostic modes. A self-test can be performed and the sensor's operational reliability can be continuously monitored [11]:

- Signal section: A fixed capacitance integrated on the chip is read into the signal path instead of the sensor capacitance. As this capacitance is independent of the pressure, the sensor will supply a defined digital value at the output as long as the electronics is operating correctly.
- Membrane arrays: After the sensor has been completely assembled, an offset results between the pressure-sensitive sensor arrays and the reference arrays. This offset is characteristic for each sensor and can be read out and stored. A change in the offset indicates possible mechanical damage of the sensor membrane.
- Digital section: Defined codes are generated and read into the digital decimation filter. The 16-bit words available at the output must be identical to those defined in the specification. These diagnostic modes allow the sensor to be monitored for correct operation.



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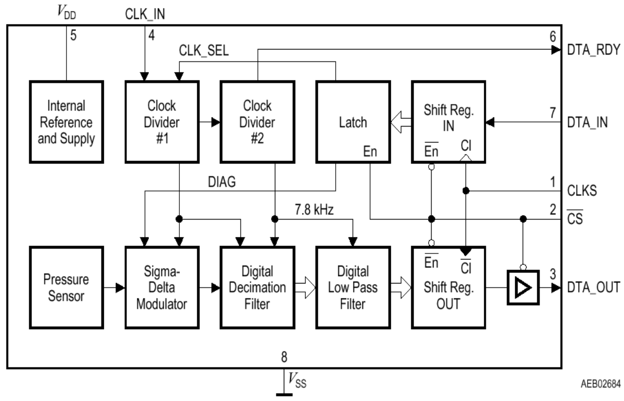


b

Figure 6:
a: Chip photo of a pressure sensor system (demonstrator). Two of the sensor arrays form the active part of a full bridge circuit with two reference arrays which are not pressure sensitive. The signal is then fed into the ∑Δ modulator [9].
b: Block diagram of IC sensor KP100 [12]

These sensors are mainly designed for applications like low cost sensors for airbag systems [10]. The same concept can, however, be applied to a host of other applications. Examples range from manifold air pressure (MAP) or high pressure (20 MPa) in automotive applications to medical applications [3].

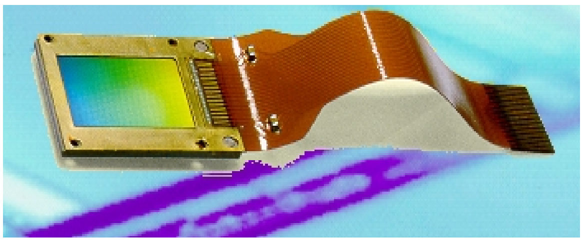
Table 2: Performance data of the pressure sensor KP100 [12]

Pressure range	60kPa - 130kPa
Sensitivity	145 digits / 1 kPa
Accuracy	11-12 bit
Noise	0.03 kPa
Supply	1.8 mA @ 5V

Integrated CMOS FingerTIP™ sensor system

The second example for an Intelligent CMOS Sensor is the recently developed Biometric System FingerTIP™ [15], that is manufactured in a two metal layer, 0.5 µm CMOS process.

The FingerTIP™ sensor (Fig. 7a) does not contain any moveable parts and is therefore not a classical MEMS device. However, as the chip surface is touched directly by the human skin, this mechanical interface is of essential importance for the system function. The sensor is designed to sustain 8kV air discharge.



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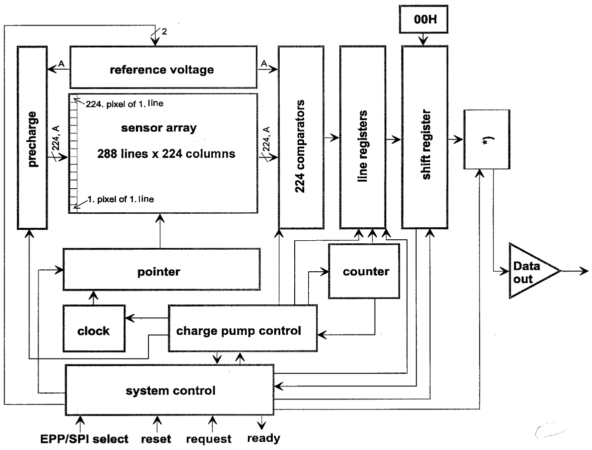

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Figure 7:
a: FingerTIP™ module ready for assembly into applications like mobile phones or keyboards.
b: Block diagram of the Biometric Sensor FingerTIP™ The pixel signal is converted on chip into 8 bit digital data, which are transmitted via a parallel (EPP1.9) or serial (SPI) interface. No additional devices are necessary for sensor operation.

The FingerTIP™ sensor is a fingerprint scanner, measuring the distance between the finger ridges and the chip surface capacitively. The chip includes data acquisition by the sensor array, direct A/D conversion of the measured signal, a controller unit, a parallel (EPP1.9) and serial (SPI) interface that transmits the 8 bit digital data to a microprocessor directly (Fig. 7b).

The basic operation principle of the sensor is explained in Fig. 8. The two dimensional pixel array of the fingerprint sensor measures the capacitance between chip surface (pixel) and the finger's surface locally. One single capacitor C_p is shown in Fig. 8. The value of this capacitor depends on the distance of the finger's surface from the chip surface. In the case of a finger ridge the distance is small and the capacitance is large.

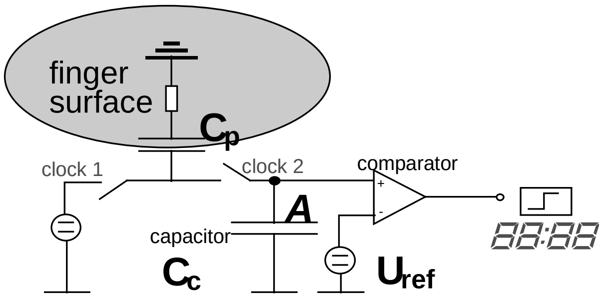

Figure 8: Basic principle of sensor operation: The number of clock counts until Cc is charged to Uref at node A is a direct measure of the distance of the finger's surface to the chip surface.

For a valley the capacitance is small. The capacitor C_p is measured by the shown circuit: During clock 1 C_p is charged. During clock 2 the charge on C_p is transferred to the capacitor C_c, which is much larger than C_p. After a number of clock cycles, the reference voltage is reached at node A and the counter is stopped by the comparator. The number of clock cycles is a means for C_p. The number of cycles is low for a large C_p corresponding to a small distance between chip and finger surface (finger ridge = dark) and vice versa. The sensor is ready to use simply by connecting the parallel interface to the parallel port of a PC.

Tab. 3 summarizes the performance and specification of the CMOS FingerTIP™ sensor.

Table 3: Performance data of the FingerTIP™ sensor [16]

Number of pixels	224 * 288
Pitch	50 µm
Lateral resolution	513 dpi
Sensor area	160 mm^2
Resolution	8 bit
Gray scale dynamics (accuracy)	30 ,70 (selectable)
Image capture time	< 100 ms (EPP @ 5V)
V_{CC}	5 V
I_{CC}	12 mA (1 mA sleep mode)
ESD (air discharge)	8 kV

CONCLUSIONS

Miniaturization, integration and batch processing are necessary to meet the market requirements for CMOS sensors in high volume applications in terms of costs, performance and system integration.

Beyond the given examples for Intelligent CMOS Sensor, the highest demand for micromechanical sensors comes from the automotive market. This market asks for calibrated sensors with signal pre-conditioning and convenient interfaces, for diagnostic features (especially in safety applications), for small packages, and for further and future system level integration potential. In addition, excellent quality is needed in high volumes at low prices.

Intelligent CMOS sensors provide a seamless and appealing way of integrating micromechanical structures and microelectronic devices on a single chip. This approach essentially offers enormous advantages across the entire value chain:

- Reduced cost by simple processing and reduced area through miniaturization,
- portability of processes to different CMOS manufacturing lines,
- high reproducibility through on-chip, on-wafer calibration of offset, sensitivity, and temperature coefficient, if necessary,
- simplified test on wafer- and on chip-level,
- less sensitive to assembly specific impacts, like stress induction by adhesive and package,
- cost effective assembly on PCBs by SMD technology.

Intelligent CMOS Sensors can benefit from existing production lines and processes in many ways because equipment and processes are available and qualified, no specific investment is required, and conventional products serve as base load during ramp-up of production. For process control new test structures must be developed [14] to monitor process quality for the mechanical parts of the sensor system. Notwithstanding the substantial advantage of strictly CMOS compatible surface micromechanics, there are also some disadvantages for certain applications. This is particularly true for some types of actuators because surface micromechanics does not allow large deflections or volume changes (e.g. for micro pumps). In addition, large aspect ratio structures which are often required, cannot easily be realized using standard processes.

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