# Pressure sensor elements integrated with CMOS

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## ABSTRACT

We report the measurement and fabrication results of monolithically integrated capacitive pressure sensor elements. The device fabrication process is based on novel plug-up process [1], which enables monolithic integration of sensors and CMOS in a modular fashion.

The electrical measurement results including pressure dependence, temperature dependencies of the various sensor geometries, and the effects of pre-bond tailoring of SOI wafers are presented in this paper.

***Keywords***: MEMS, SOI, monolithic integration

## 1 INTRODUCTION

Monolithic integration of MEMS and electronics is sought for miniaturization of microsystems. Single chip realization of a pressure sensor and its interface circuitry could be suitable for applications such as handheld devices, where small size is of great importance.

A simple monolithically integrated pressure sensor circuit fabricated on SOI was presented in previous work [2]. The capacitive sensors are made from the vacuum cavities embedded in the SOI structure, a schematic cross-section of a cavity is shown in Fig.1.

## 2 FABRICATION

The integration approach used in this work is ´MEMS first´, where the cavities for sensor elements are fabricated before CMOS. SOI wafers are used as starting material. The substrate and structure layer doping level were selected to simultaneously obtain good sensor performance and to facilitate CMOS fabrication. A non-patterned SOI substrate was used. For improving the performance of capacitive sensors a pre-bond boron implant was performed on some of the wafers during the SOI manufacturing process. The enhanced surface doping of MEMS devices is desired to void formation of voltage and temperature sensitive depletion regions and other phenomena associated with low doping.

### 2.1 Cavity formation

The key issue in this process is the controlled formation of hermetically sealed cavities in the SOI structure and the resulting smooth single crystal surface after etchback steps, which enables versatile backend processing.

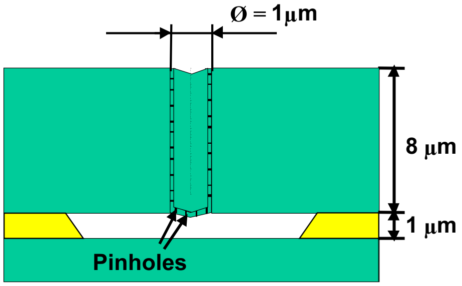

Figure 1: Cross-section and dimensions of a polysilicon plug and SOI structure used in this work.

The cavities are wet etched through a thin permeable polysilicon film [3], which contains small holes. The polysilicon deposition conditions are controlled in such a way that deposition occurs between amorphous and polycrystalline deposition regimes. The obtained film contains enough pinholes when the film thickness does not exceed the grain size [4]. A SEM micrograph of the thin polysilicon film grain structure is shown in Fig. 2.

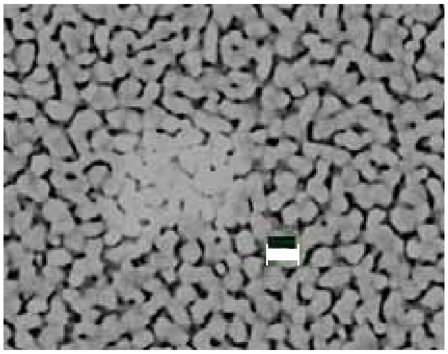

Figure 2: Grain structure of a permeable polysilicon film. The white marker shown is 200 nm.

The cavities are then closed by depositing a thick conformal polysilicon film, which blocks the pinholes as well as the one micron sized dry etched holes forming polysilicon plugs in the SOI structure layer.

## 2.2 CMOS

The CMOS used in this work is 1.2 μm gate length analog oriented molybdenum gate bulk CMOS. Besides CMOS this process contains bipolar transistors, thin film resistors, capacitors and optional EEPROM, and high voltage NMOS [5].

# 3 DEVICE DESIGN

The MEMS part of the device requires four extra mask layers to conventional CMOS: 1) the cavity defining the array of polysilicon plugs, 2) substrate contact, 3) trench for dielectric isolation, and 4) removal of extra layers from micromechanical device areas after CMOS.

A top view of a circular sensor and reference capacitor structures are shown in Figs. 3a and 3b. The ambient pressure deflects the structure layer of the vacuum cavity in the sensor, which appears as a darker area in the central parts of the sensor, while the vented reference structure is not deflected.

## 3.1 Pressure sensors

The pressure sensors are circular shaped cavities. The diameter of the cavity is about 300 μm, the size at which the used structure touches the substrate when an external pressure of 6 bar is applied. The cavities are isolated from the environment with dielectric isolation, a trench etched through the structure layer and refilled with silicon dioxide. The sensor element is surrounded by a hexagonal guard ring formed between two isolation trenches. The CMOS metallizations and substrate contacts are used for interconnecting the pressure sensors.

## 3.2 Reference elements

The integrated reference for temperature compensation of the capacitive element can be an oxide capacitor or any structure that does not change with the applied pressure, but where capacitance changes similarly to a pressure sensor with temperature. We made simple reference devices by opening the pressure sensor cavity using a lithographically defined and etched vent hole. A reference with an open cavity may not be optimal in real device that can be exposed to dirt and moisture, but measurements of the opened device provide interesting information about the structure when comparing the measurements with the closed structure.

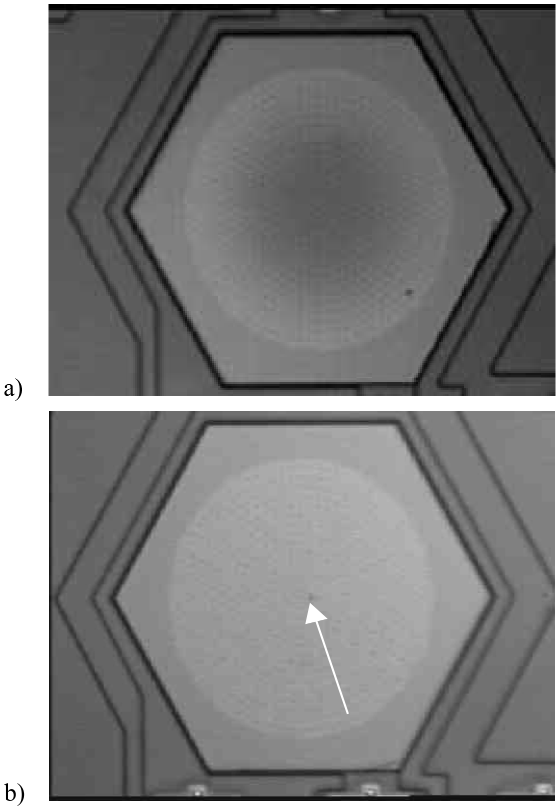

Figure 3: IR photographs of a pressure a) sensor cavity and b) reference element with vent hole in the center (indicated by the arrow).

# 4 MEASUREMENT RESULTS

## 4.1 CMOS

The properties of CMOS were not affected by the fabrication of MEMS elements. The leakage currents remained at low level. The relatively thick SOI layer did not change the process results significantly. Only the breakdown voltages of some inherent diode structures were lower in the SOI realization when compared to bulk wafers.

## 4.2 Pre-bond implant

The non-implanted wafers showed higher sensitivity to temperature and stronger asymmetric bias dependence than the devices with pre-bond implantation. The C-V curves of buried oxide capacitances are shown in Figs. 4a and 4b.

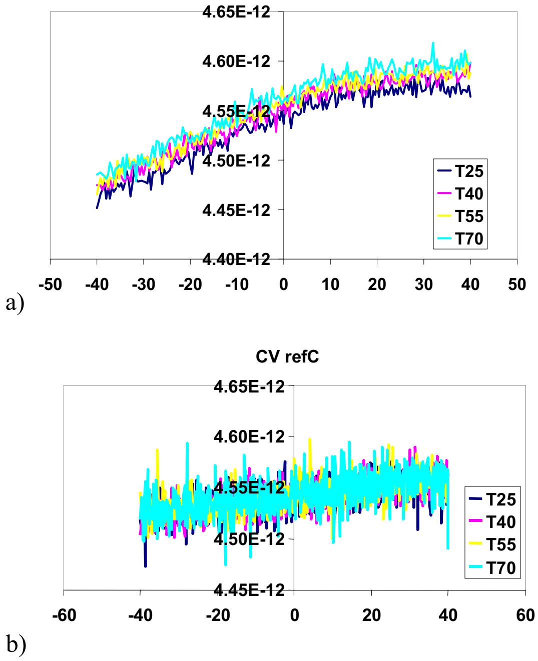

Figure 4: a) C-V characteristics of an oxide capacitor made made a) on standard SOI, b) on pre-bond implanted SOI. Temperature (°C) is used as a parameter.

## 4.3 Pressure sensors and references

The diced and encapsulated pressure sensor devices were measured in a weather chamber at VTI Technologies. The external pressure and temperature were controlled and the sensor capacitance was measured with an LCR bridge.

A typical measured pressure dependence of a sensor element is shown in Fig. 5a and the temperature stability of the reference element in Fig. 5b. The achieved temperature sensitivity of the sensor elements was excellent, limited only by material the properties of silicon and silicon dioxide.

The pressure dependence of the capacitance can be satisfactorily modeled with a modified parallel plate capacitor model using the following equation:

$$C = C_{00} + \frac{C_0}{1 - C_0 p / K} + \frac{aC_0}{1 - C_0 p / bK}, \qquad (1)$$

where $C_{00}$ is the pressure independent stray capacitance, $C_0$ the pressure dependent capacitance, $p$ pressure, $K$ reduced sensitivity, and $a$ and $b$ are sensor geometry dependent constants (the fitted parameters for the device of Fig. 5a. are as follows $C_{00}$ = 2,453 pF, $C_0$ = 0.112 pF, $K$ = 83.2 kPa·pF, $a$ = 3.15 and $b$ = 2.2).

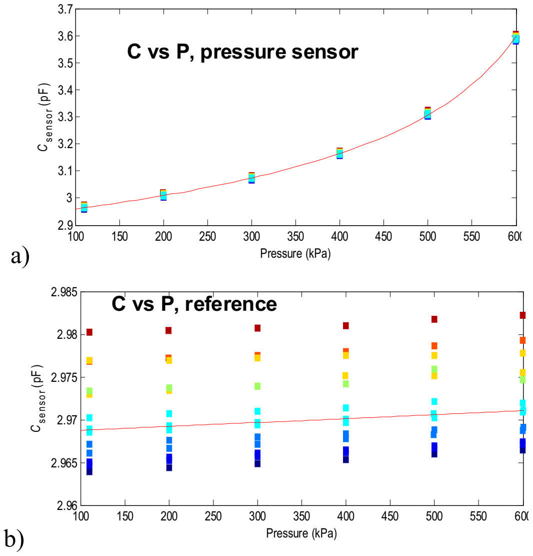

Figure 5: a) Pressure dependence of sensor element. a) pressure dependence of reference element. Temperature as a parameter, from -40ºC to +125ºC.

The temperature dependence of the sensor capacitance at 5 bar pressure is shown more closely in Fig 6. The capacitance sensitivity is about 43 ppm/K at 5 bar pressure and about 30 ppm/K at atmospheric pressure. The temperature sensitivity of thevented structure is about 30 ppm/K throughout the measurement range.

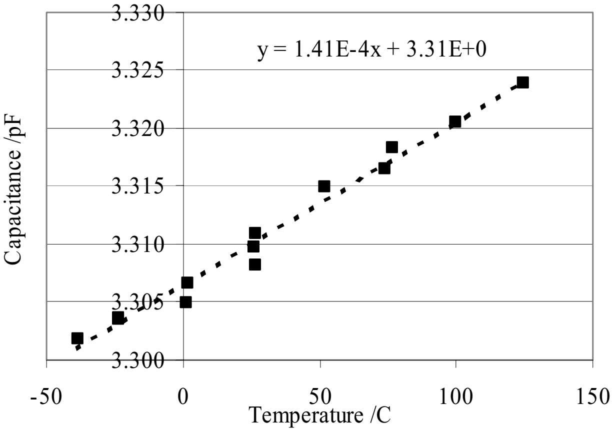

Figure 6: Temperature dependence of sensor capacitance at 5 bar pressure.

In the future temperature effects will be minimized with monolithic integration of readout electronics and temperature compensation circuitry.

The resonance frequency of another pressure sensor as a function of external pressure was measured at room temperature using an impedance analyzer. The measurement result is shown in Fig. 7. The resonance frequency of the closed cavity decreases as the pressure is increased, because of the electrostatic spring softening effect. The applied constant bias produces a higher electric field strength between the electrodes at higher pressure as the membrane is deflected closer to the bottom electrode. With the open reference structure the gap remains unaltered by the pressure. Instead, the effective spring constant increases with pressure, because the air in the gap acts like a spring. The change of resonance frequency or damping factor can be used for pressure sensing in applications where capacitive sensing is not applicable.

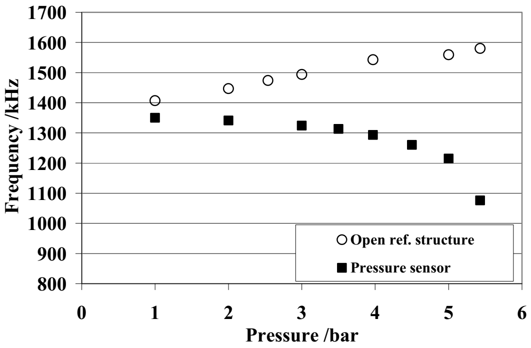

Figure 7: Resonance frequency of sensor and vented reference structures as a function of applied pressure, DC-bias 50 V.

Besides the circular sensor, oval shaped sensors were also designed. The pressure response of the oval shaped resonator is plotted in Fig. 8. The large structure touches the substrate at a low pressure of about 3.5 bar. The pressure dependence of the long sensor has improved linearity and dynamic range compared to a circular sensor.

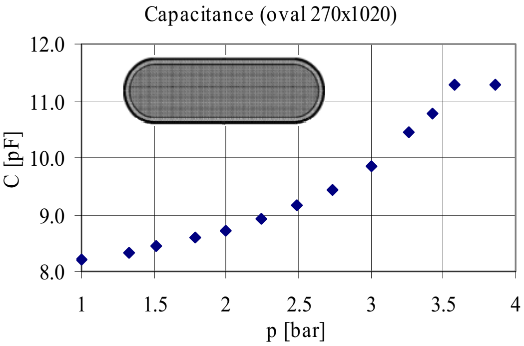

Figure 8: Pressure dependence of an oval shaped cavity (length 1020 and width 270 micrometers).

## 5 CONCLUSIONS

The fabricated pressure sensor elements show excellent electrical performance. The temperature sensitivity of the capacitance is below 50 ppm/K, which is very near the theoretical minimum value that can be obtained using silicon and silicon dioxide as structural material. The operation of the co-processed CMOS did not show any signs of degradation due to sensor fabrication. Fabrication of monolithically integrated pressure sensors is technically feasible using the plug-up integration concept.

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## ACKNOWLEDGEMENTS

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