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Capacitve pressure sensor with monolithically integrated CMOS readout circuit for high temperature applications

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Abstract

An integrated capacitive surface micromachined pressure sensor for high temperature applications was developed and characterized to work at temperatures up to 250 °C. The sensor and the CMOS readout circuit are processed on separation by implantation of oxygen (SIMOX) substrates. The readout circuit is programmable and allows calibration of linearity, offset and output range. The performance of a 20 and 50 bar sensor is discussed. Even without active temperature compensation the offset temperature coefficient (TCO) referred to full scale output (FSO) is less than 0.03%/°C between 25 and 150 °C and less than 0.09%/°C between 150 and 250 °C. The compensated linearity error is less than 0.4% FSO. © 2002 Published by Elsevier Science B.V.

Keywords: High temperature application; Monolithic integration; Pressure sensor; Surface micromachining; SIMOX; SOI

1. Introduction

There is an increasing need for sensors and electronic devices working at temperatures beyond 125 °C. Typical applications are found in the automotive industry, in avionics and space exploration as well as in the oil drilling industry, industrial measurement and control systems. Several approaches have been made to solve the well known problem of the rising leakage current at high temperatures in conventional silicon devices using isolation by reverse biased p–n-junctions.

A promising approach for high temperature applications is the use of a wide bandgap semiconductor such as silicon carbide (SiC). The excellent electrical and mechanical properties at temperatures far beyond 350 °C make it a suitable material for electromechanical sensors in high temperature applications [1]. However, the rather expensive process technology is still a drawback for many commercial applications. Taking advantage of the highly developed and investigated silicon technology, another promising approach is the silicon on insulator (SOI) technology. Several designs of piezoresistive pressure sensors have already been introduced on different SOI-substrates [2]. However, piezoresistive sensors have the disadvantage of an inherent temperature dependence of the piezoresistive coefficient, which has to be compensated. Using capacitive sensors this step can be avoided, because the pressure is converted to an electrical signal by a vacuum capacitor, which has no inherent temperature dependence. However, capacitive sensors need a readout circuit to convert the capacitance into a voltage. The monolithic integration of a readout circuit with the sensor offers the following advantages compared to a hybrid structure:

- short signal paths between sensor and readout circuit;
- small dimensions of the sensor system;
- omission of the connection technique between sensor and readout circuit, which results in:
  - smaller electrical and mechanical susceptibility to interference of the total system and;
  - reduction of the production costs with high numbers of items.

Within the area of capacitive high temperature pressure sensors with readout circuit the highest application temperature of 200 °C was achieved by a hybrid sensor system [3]. The CMOS-compatibility of the capacitive pressure sensor [4] allows us to integrate a high temperature readout circuit together with the sensing cells.

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68 ## 2. Sensor principle and circuit design

69 The capacitive sensor consists of an array of circular
70 pressure sensitive membranes, which serve as the top elec-
71 trodes. The membranes are switched in parallel to increase
72 the value of the capacitance. The pressure range of the sensor
73 is determined by the diameter of the membranes. There are
74 two arrays of membranes on each chip, which only differ in
75 the membrane thickness. This results in a pressure sensitive
76 sensor array and a pressure insensitive reference array.
77 Hence, the sensor signal is gained by the ratio of reference
78 to sensor capacitance, which is almost free from thermal
79 dependencies of the parasitic capacitances.

80 Fig. 1 shows a cross section of a sensor and a reference
81 element. The bottom electrode is built from a 120 nm silicon
82 layer and electrically isolated from the substrate by the
83 underlying buried silicon oxide layer. Lateral isolation is
84 achieved by a localized oxidation of silicon (LOCOS)
85 process. These dielectrics replace the p–n-junctions used
86 by Dudaicevs et al. [5] and guarantee low leakage currents at
87 temperatures beyond 125 °C.

88 The cavity with a height of 900 nm under the membrane is
89 defined by a sacrificial oxide, which is removed via etch
90 channels by means of hydrofluoric acid. Afterwards it is
91 sealed in an LPCVD deposition process. Due to the LPCVD
92 process the remaining pressure inside the sealed cavity is
93 around 10^{-4} bar. Compared to the pressure ranges of the
94 discussed sensors (20 and 50 bar) this is negligible and we
95 can assume vacuum inside the cavity. Thus, the membranes
96 are sensitive for absolute pressure. The readout circuit has
97 been fabricated in a 1.6 μm separation by implantation of
98 oxygen (SIMOX)-CMOS process technology with 40 nm
99 gate oxide, suitable for high temperature applications [6].

100 In Fig. 2 the comparison of a Bulk CMOS cell with a SOI-
101 CMOS cell is shown. The isolation of the individual tran-
102 sistors of the Bulk CMOS cell is achieved by means of p–n-
103 junctions to the p-substrate (NMOS transistor) or to an n-tub
104 (PMOS transistor). These p–n-junctions serve as a sufficient
105 electrical isolation up to temperatures of approximately
106 150 °C. Beyond this temperature the leakage currents to
107 the substrate caused by the intrinsic conductivity of silicon
108 are rising strongly. Exceeding a certain limit, these leakage
109 currents cause the failure of the whole circuit. The replace-
110 ment of the p–n-junctions by dielectric isolation reduces the
111 leakage currents around 3 to 4 orders of magnitude [7]. In
112 this way the temperature range of the CMOS circuits can be
113 extended well over 150 °C. The boundary of operability is
114 then defined by leakage currents within a transistor. Depend-
115 ing upon the type of circuit this boundary is between 250 and
116 350 °C for analog SOI circuits. While operation amplifier
117 circuits can be operated up to 350 °C, the accuracy of
118 switched capacitor (SC) circuits drops rapidly beyond
119 250 °C. The reason is the strong increase of the drain leakage
120 current in the transmission gates, which amounts to several
121 nanoampere at 300 °C [8].

122 The design of the readout circuit is based on SC techni-
123 que. This technique is used for the capacitance to voltage (*C*/
124 *V*) converter as well as for the linearization and signal
125 conditioning. To get a time continuous output signal the
126 output stage is realized as a sample and hold amplifier. Fig. 3
127 shows a block diagram of the complete sensor system. The
128 first stage represents the *C*/*V* converter (Cr/Cs) and performs

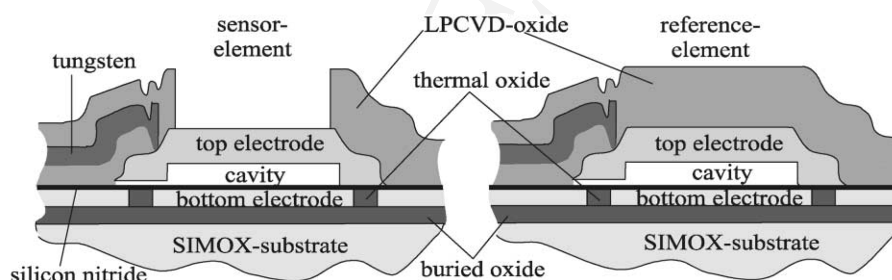

Fig. 1. Schematic cross-section of a sensor and reference element.

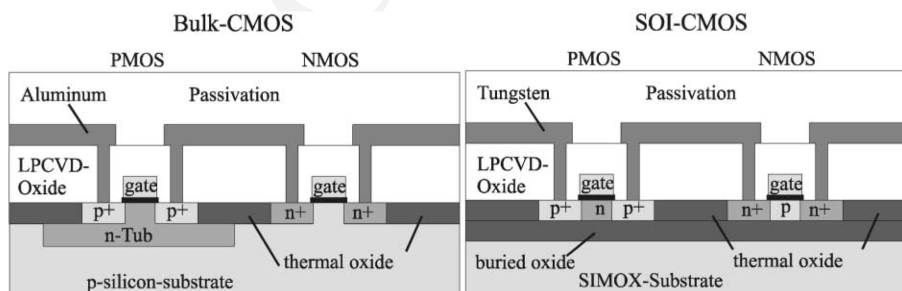

Fig. 2. Schematic cross-section of a bulk CMOS cell and an SOI-CMOS cell.

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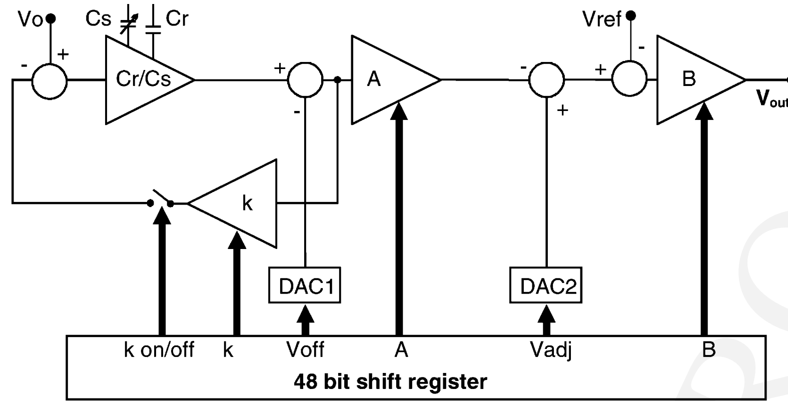

Fig. 3. Block diagram of the sensor system.

the linearization via a feedback path. The feedback path is implemented with an additional operation amplifier (k). This stage creates a pressure proportional output signal. The second and third stage (A, B) are used for further amplification and adjustment of the output range.

All amplification factors (A, B, k) and offset voltages (V_{off}, V_{adj}) are programmable by a 48 bit shift register. This allows the combination of one readout circuit design with various sensor elements to attain different pressure ranges. The output voltage of the first DAC (V_{off}) is used to compensate the zero pressure output signal, which varies due to mismatch between sensor and reference elements. The second DAC (V_{adj}) is added to adjust the range of the output signal. Considering the transfer function of the C/V converter

$$V_{C/V} = V_{DD} - (V_{DD} - V_0)\frac{\mathrm{Cr}}{\mathrm{Cs}} \tag{1}$$

the overall transfer function results to:

$$V_{out} = \left\{\frac{V_{DD} - (V_{DD} - V_0)\mathrm{Cr}/\mathrm{Cs} - V_{off}}{1 - k(\mathrm{Cr}/\mathrm{Cs})}A + V_{adj} - V_{ref}\right\}B \tag{2}$$

Fig. 4 shows a chip photo of the integrated sensor system. On the upper left side there is the array of circular pressure sensitive membranes, while on the right side the same array with thicker membranes can be seen.

3. Experimental results

3.1. Linearization

For the linearization of the pressure sensor, two steps have been taken. Firstly, as the capacitance value is inversely proportional to the distance between the membrane and the bottom electrode, the quotient of the reference capacitance to the sensor capacitance is used. Secondly, to compensate the remaining non-linearity, an analog feedback has been added to the converter stage. Fig. 5 compares the output signals with and without feedback stage of a 20 bar sensor. The curve without feedback stage (non-linearized) has an independent linearity error of 9.42% referred to full scale output (FSO). The linearization by the feedback stage reduces the linearity error to less than 0.4% FSO.

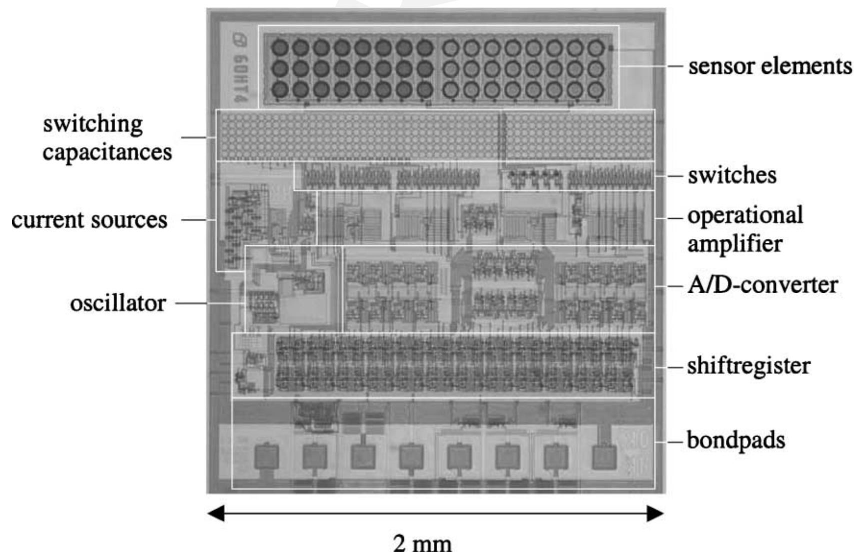

Fig. 4. Chip photo of the integrated sensor. The individual function groups are emphasized and designated.

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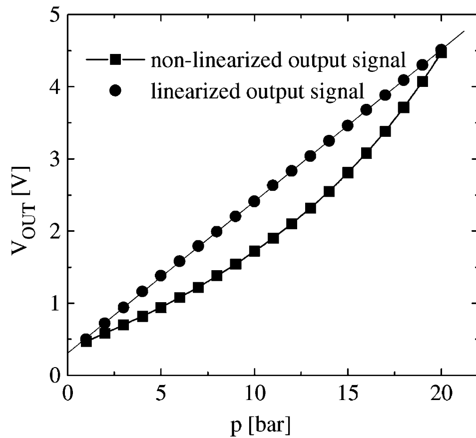

Fig. 5. Linearization of the output signal by means of the feedback stage.

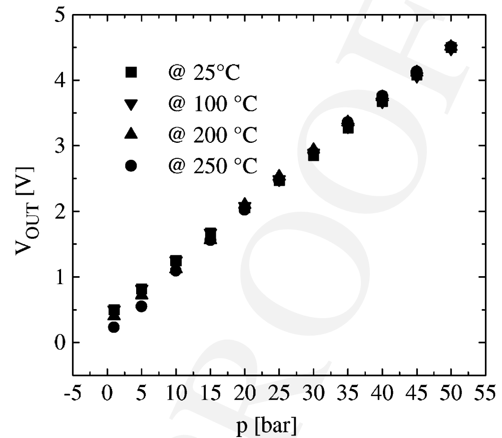

Fig. 7. Linearized output signals at different temperatures.

In order to minimize the linearization error, a highly accurate adjustment of the value k is required. In the presented design k is programmable with a resolution of 6 bit by the shift register. Fig. 6 shows the influence of a gradual modification of k on the linearity error in the proximity of the minimum. In the area ± 1 bit apart from the minimum at 31 the linearization error remains smaller than 0.5% FSO. Therefore the modification of k with the given digital resolution permits a good detection of the minimum.

3.2. Temperature dependencies

In the following the thermal behaviour of a 50 bar sensor in the temperature range between 25 and 250 °C will be discussed. Fig. 7 shows the linearized output signals of a 50 bar sensor at different temperatures. The output signal is adjusted to a range from 0.5 to 4.5 V. The measuring points at different temperatures lie on top of each other well. Only at low pressures and high temperatures there is a recognizable deviation.

To have a closer look at the deviation Fig. 8 plots the temperature dependencies of the output signal at different pressures. The output signals at higher pressures show a very low temperature dependence over the whole temperature range. At a pressure of 1 bar the signal drops at temperatures beyond 150 °C. To quantify this behaviour the offset temperature coefficient (TCO) was determined with the following formula:

$$\mathrm{TCO} = \frac{\partial V_{\mathrm{out}}}{\partial T}\frac{1}{V_{\mathrm{FSO}}} \qquad (3)$$

The TCO equals to the temperature derivative of the output signal referred to the full scale output (V_{FSO}). The full scale output is the difference between the minimum and maximum output signal, which is in this case: $V_{\mathrm{FSO}} = 4.5-0.5 = 4$ V.

Fig. 9 plots the temperature dependencies of the TCO at different pressures. At 50 bar the TCO is less than 0.01% FSO/°C over the whole temperature range. At a pressure of 25 bar the TCO is still less than 0.03% FSO/°C over the whole temperature range. The strongest temperature dependence was observed at the lowest pressure, where sensor and reference capacitance have nearly the same value. Up to a temperature to 150 °C the TCO is still less than 0.03% FSO/

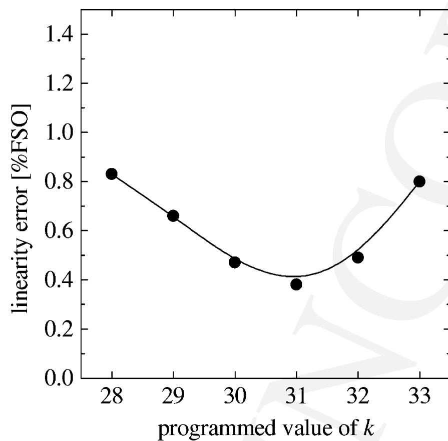

Fig. 6. Linearity error of a 20 bar sensor as a function of the programmed value of the feedback factor k.

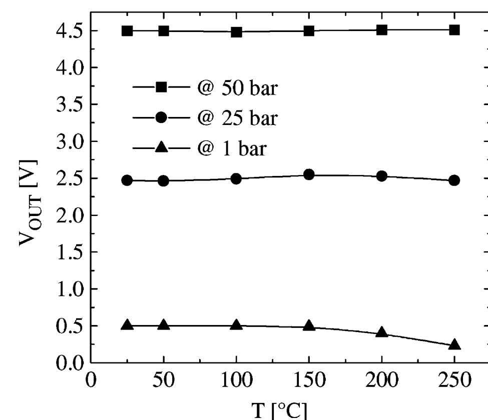

Fig. 8. Temperature dependencies of the output signal at different pressures.

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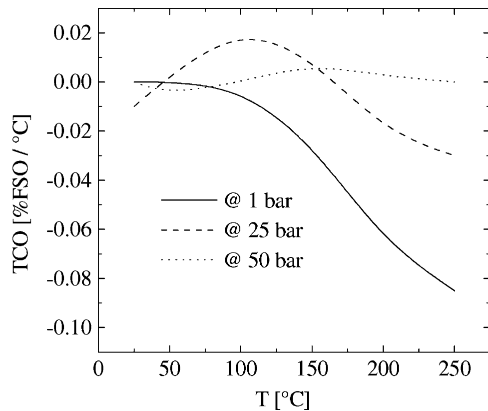

Fig. 9. Temperature dependencies of the offset temperature coefficient at different pressures.

°C, but raises to less than 0.09% FSO/°C at 250 °C. As shown in [4], the offset TCO of the actual sensor elements is less than 0.015% FSO/°C in the temperature range between 25 and 250 °C. This seems to suggest that the temperature dependence at lower pressures and higher temperatures may be caused by the readout circuit.

4. Conclusions and outlook

It has been shown that a surface micromachined pressure sensor with a monolithically integrated CMOS readout circuit is capable of measuring at temperatures up to 250 °C. The linearity error is less than 0.4% FSO at room temperature. Even without active temperature compensation the offset TCO is less than 0.03% FSO/°C between 25 and 150 °C and less than 0.09% FSO/°C between 150 and 250 °C. Future improvements will concentrate on the remaining temperature dependence at low pressures. The next version will also contain a high temperature EEPROM [6] for the permanent storage of calibration data.

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Biographies

Klaus Kasten was born in Gladbeck, Germany, in 1968. He obtained his diploma in electrical engineering from the Technical University (RWTH) of Aachen, Germany, in 1996. He joined the Institute of Materials in Electrical Engineering in 1996, working on the design, packaging and testing of high temperature pressure sensors. Since September 2001 he is with the Robert Bosch GmbH, where he is working on the development of new sensor products for automotive applications.

Norbert Kordas was born in Herten, Germany and received the Diploma in electrical engineering from the University of Dortmund in 1988 and the Doctorater degree in engineering from the University of Duisburg in 1994. He is with the Fraunhofer Institute of Microelectronic Circuits and Systems in Duisburg, where his special interests are mixed mode CMOS circuits and sensor readout electronics.

Holger Kappert was born in 1968. He has received the Diploma in electrical engineering from the University of Bochum in 1993. Since then he is with the Fraunhofer Institute of Microelectronic Circuits and Systems, where he is working on embedded mixed signal systems. His special research interest is the design for testability of those systems.

Wilfried Mokwa was born in 1951. He obtained the Diploma in physics from the Technical University (RWTH) of Aachen, Germany, in 1977 and the Dr. rer. nat. degree in 1981 at the same place. From 1981 he worked at the Department of Experimental Condensed Matter Physics at the RWTH Aachen on catalytic reactions on gas sensor surfaces and joined the Fraunhofer Institute of Microelectronic Circuits and Systems (IMS) in Duisburg in 1985. There he managed a group working on integrated silicon sensor technology. In 1996 he became a full professor in electrical engineering at the RWTH Aachen where he is head of chair 1 of the Institute of Materials for Electrical Engineering with special interests in the field of integration of microsystems. At the same time he is still managing the microsystems activities of the IMS.

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