CMOS INTEGRATION OF A THERMAL PRESSURE SENSOR SYSTEM

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ABSTRACT

We report the integration of a CMOS thermal pressure sensor system for the range of 10^2 to 10^6 Pa. The operating principle of the sensor is based on the pressure-dependent heat transfer across the air gap separating a heat source from a heat sink. After completion of the double metal CMOS process the sensor structure is obtained by a fully CMOS-compatible sacrificial metal etching. The microsystem includes both sensor and a readout circuit. The interface circuit compensates for temperature effects and provides a bitstream at the system output representing the ambient pressure.

1. INTRODUCTION

Conventional Pirani type thermal vacuum sensors have been used for many years for total pressure measurement. Their operating principle involves a resistively heated wire with a high temperature coefficient of resistance. This filament is usually part of a Wheatstone bridge. Molecular collisions with the heat source transfer thermal energy to a heat sink which results in cooling of the wire. This lowers its resistivity, unbalances the bridge and hence generates a voltage proportional to the temperature variation of the wire. The collision rate varies with pressure and therefore leads to a pressure dependent output.

In this paper we describe a system based on a recently reported miniaturized Pirani gauge [1]. This thermal pressure sensor conforms to the entire set of CMOS design rules. The separating air gap between the heat source and the heat sink is obtained by a sacrificial metal etching. We exploited the CMOS compatibility of the sensor by the cointegration of a biasing and readout circuit. For the filament the standard upper metallization of the CMOS process is used, having only a modest temperature coefficient and low resistivity. The biasing circuit enables operation of the sensor at constant relative temperature ΔT. The information about the ambient pressure is obtained by evaluating the power required to maintain ΔT. This is done by simultaneously measuring the voltage drop over the filament and the current through it. Two on-chip incremental ADCs transform the voltage and the current into the digital domain, providing two bitstreams at the output of the microsystem. Due to the small size of the sensor (300 µm in diameter) an increased sensitivity with the same power consumption is obtained by connecting four sensors in series.

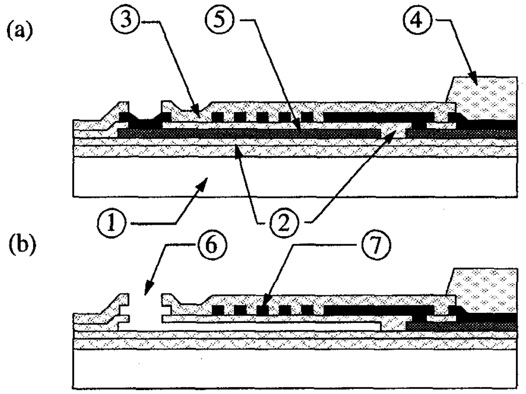

Fig. 1 Pressure sensor after CMOS process (a) and after sacrificial metal etch (b) consisting of silicon (1), SiO_2 (2), passivation (3), pad with gold bump (4), sacrificial metal (5), access window for etchant and gas (6), heater (7).

2. THERMAL PRESSURE SENSOR

Thermal pressure sensors are based on the pressure-dependent heat transfer across the gap separating a heat source from a heat sink. The sensor in the system reported here builds on the first metal layer, the intermetal dielectric, the second metal layer, and the passivation layer. As shown schematically in Fig. 1, after completion of the CMOS process, the final structure is obtained by the local removal of the lower CMOS metallization by a commercial wet etchant. Such sacrificial micromachining is achieved by providing pad-like structures in the design layout that give access to the sacrificial metal structure. The 2 µm CMOS process used to fabricate these devices routinely offers gold bumps which cover the bonding pads. Therefore, the pads are not affected by the sacrificial metal etching and no photolithography has to be carried out to protect the bonding pads. The postprocessing results in a suspended dielectric membrane composed of the intermetal dielectric and the passivation layer. A meandering line of the second metal layer is sandwiched between these dielectrics. It is used as the heating element. The suspended membrane is separated from the substrate by a narrow gap, of a nominal width of 0.6 µm, which communicates with the surrounding atmosphere through the cleared etch windows. A mi-

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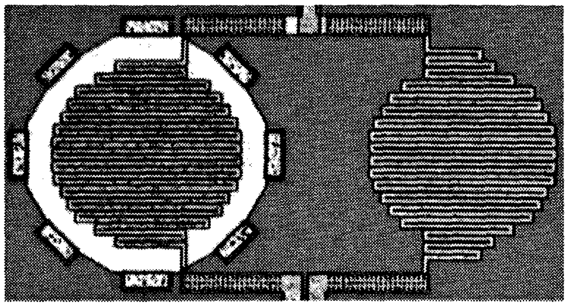

Fig. 2 Microphotograph of the thermal pressure sensor (left) and reference structure (right) before postprocessing. Note the circular membrane (300 µm in diameter), eight access openings, and meandering heater.

crophotograph is shown in Fig. 2.

A thermal power P dissipated by the heater causes a temperature increase ΔT of the membrane given by

$$P = G(p)\Delta T, \qquad (1)$$

where the thermal conductance $G(p)$ of the device describes the pressure-dependent heat transfer across the micromachined gap and through the sensor materials. Fig. 3 shows experimental values of $G(p)$ as a function of pressure.

3. READOUT CIRCUIT

The pressure information is extracted by keeping the temperature difference ΔT in Eq. (1) constant. By evaluating the power required to maintain ΔT, the information about the ambient pressure is obtained. Two controlled current sources $M1$ and $M2$ force the sensor R_S to track the resistance of a reference resistor R_R (Fig. 4).

This reference consists of a structure similar to the sensor, without air gap, however. Hence its thermal resistance to the silicon substrate is low and its electrical resistance does not depend on the pressure.

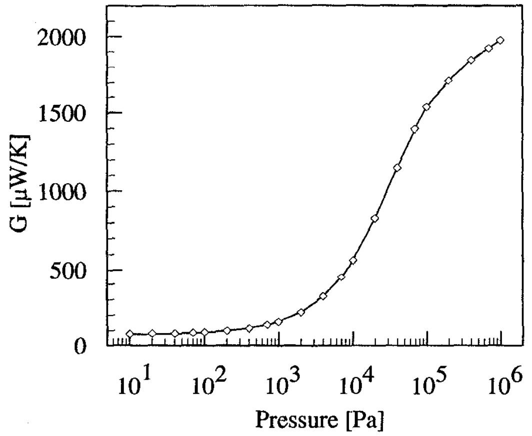

Fig. 3 Measured thermal conductance as a function of pressure of an individual pressure sensor.

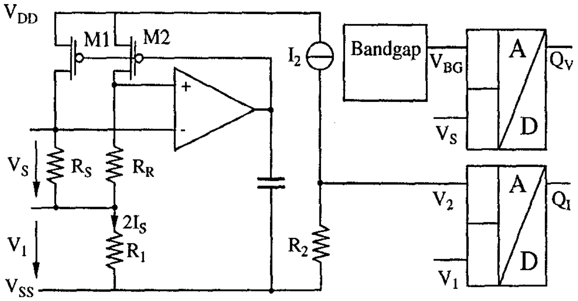

Fig. 4 Block diagram of the implemented pressure sensor system consisting of the biasing circuit, a bandgap reference cell and two incremental ADCs.

A well-controlled difference R_R - R_S was achieved by symmetrical layout with a reference filament longer than the heater. This results in a temperature difference

$$\Delta T = (R_R - R_S)/(\alpha R_R), \qquad (2)$$

where α denotes the temperature coefficient (4300 ppm/K) of the reference resistor R_R and sensor resistor R_S.

The dissipated power P required to maintain the temperature difference ΔT is obtained by simultaneously measuring the current I_S and the voltage V_S. The current measurement is done with the shunt resistor R_1. Since R_1 is made of polysilicon a significant temperature coefficient occurs. The temperature compensation is performed by generating the reference voltage V_2 of the current measuring incremental ADC with the help of a constant current source I_2 and the poly-resistor R_2 having the same temperature coefficient as R_1. Taking into account the conversion equation of the incremental ADC [2] this leads to a temperature compensated current measurement

$$N = \frac{V_1}{V_2} \cdot 2^n = \frac{2I_S R_1 (1+\beta T)}{I_2 R_2 (1+\beta T)} \cdot 2^n \sim I_S, \qquad (3)$$

where N is the (n-1) bit representation of the input voltage V_1 after 2^n conversion cycles, and β denotes the temperature coefficient of R_1 and R_2.

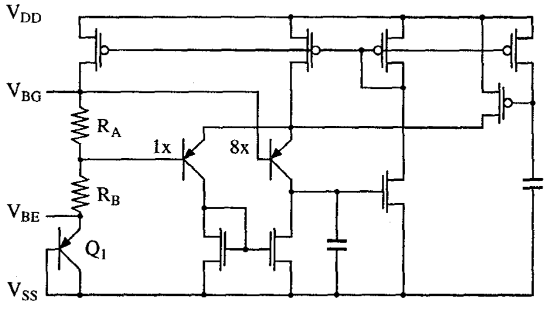

Fig. 5 Bandgap reference cell.

In contrast, the reference voltage for measuring the sensor voltage V_S is generated by a bandgap reference cell which provides a constant voltage V_{BG}. The decimation of the bitstreams Q_V, Q_I and their multiplication, which is required to obtain the power information, is done off-chip by a central processing unit.

4. IMPLEMENTATION

We increased the sensitivity of the thermal pressure sensor system by connecting four pressure sensors in series. The temperature difference is set by design according to Eq. (2) in the order of 2 K. Increasing ΔT would offer an enhanced sensitivity, at the expense, however, of a decreased lifetime of the sensor due to electromigration. In our implementation the maximum current through the sensor does not exceed 10 mA, which ensures long term reliability. The system has two stable points, one of which corresponds to $I_S = 0$ mA. A settling at this point can easily be avoided by ensuring a positive V_S.

The schematic of the bandgap reference [3] is shown in Fig. 5. The reference voltage V_{BG} consists of two terms

$$V_{BG} = \frac{kT}{q}\ln(8)\left(1+\frac{R_A}{R_B}\right)+V_{BE} \qquad (4)$$

where T, k, and q denote the absolute temperature, the Boltzmann constant, and the elementary charge, respectively. Choosing the appropriate ratio R_A/R_B in the first term which has a positive temperature coefficient allows to compensate the negative temperature coefficient of the second term V_{BE}.

Two incremental ADCs [2] are integrated for the conversion of the voltage and the current of the thermal pressure sensor. They are based on the switched capacitor technique implemented in fully differential architecture providing improved noise immunity. A schematic of the ADC is shown in Fig. 6. The converter consists of an integrator and a comparator performing a $\Sigma\Delta$ modulation of the input voltage V_S. The integrator is offset compensated which necessitates a sample and hold block in order to store the output of the integrator until in phase $K1$ the comparison takes place. In contrast with the more usual first-order oversampled $\Sigma\Delta$ ADC the integrator is reset before each conversion cycle. This leads to deterministic behavior of the conversion allowing the bitstream to be decimated by a simple counter. The decimated value N of the counter after 2^n integration steps is

$$N = \frac{V_S}{V_{BG}}\cdot 2^n . \qquad (5)$$

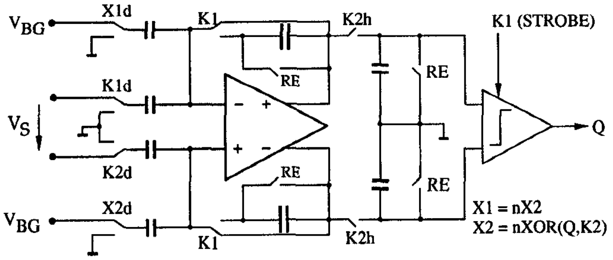

Fig. 6 Incremental ADC converting the sensors voltage V_S into a bitstream Q. A similar ADC is used to convert simultaneously the sensor current.

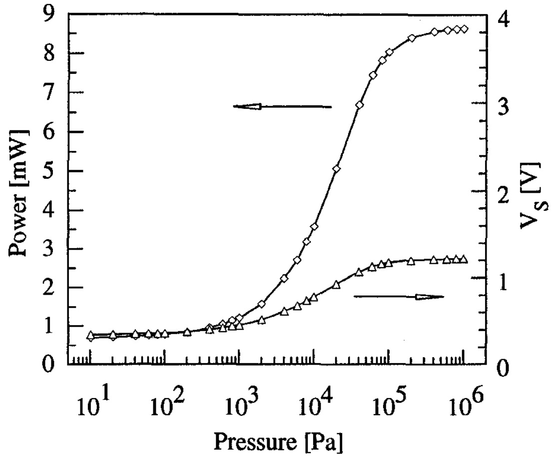

Fig. 7 Measured system response where (Δ) is the sensor voltage V_S and (◇) the power P required to keep ΔT constant.

5. MEASUREMENTS

The offset of the OTA in the front-end interface is equivalent to an additional difference between R_S and R_R and can cause instability or saturation. Compensation of the offset which allows the fine tuning of the temperature difference ΔT and the calibration of the system response is done with an off-chip resistor parallel to the reference resistor R_R.

We successfully tested the pressure sensor together with the readout circuitry. Fig. 7 shows the pressure dependent voltage signal V_S and the dissipated power P. The nominal value of R_S is 170 Ω. According to Fig. 3 and Eq. (1) the temperature difference ΔT for this measurement was 1.3 K.

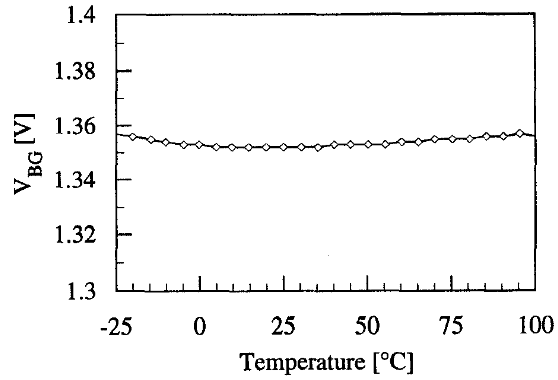

Fig. 8 Measured voltage V_{BG} of the bandgap reference cell as a function temperature.

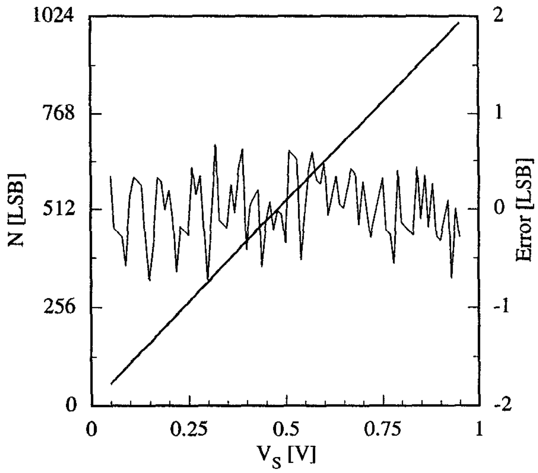

Fig. 9 Transfer characteristic and non-linearity of the implemented incremental ADC with a reference voltage of 1 V running at a clock frequency of 50 kHz.

A measurement of the performance of the bandgap reference cell is given in Fig. 8.

For the incremental ADC we obtained a resolution and linearity of 10 bits which is well suited for the sensor performance (Fig. 9). A micrograph of the integrated system is shown in Fig. 10. In order to increase the sensitivity and the matching of the sensor-reference structure we designed arrays of four sensors and four reference structures.

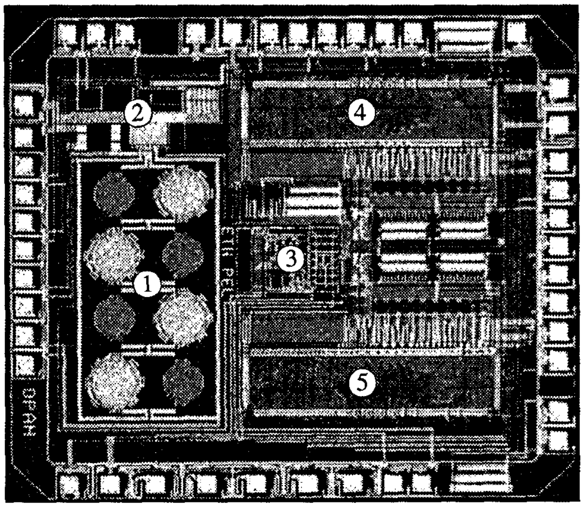

Fig. 10 Microphotograph of the integrated microsystem consisting of pressure and reference sensor arrays (1), front-end interface (2), bandgap reference (3), two incremental ADCs for current (4) and voltage (5) measurement. Four pressure sensors are connected in series for sensitivity improvement.

The chip was produced using the double metal, double poly 2 μm CMOS process of EM Microelectronic Marin Switzerland and covers an area of 3.3 x 2.8 mm^2

CONCLUSION

We have reported a thermal pressure system for the range of 10^2 to 10^6 Pa. The microsystem is realized in an industrial CMOS technology consisting of an array of miniaturized thermal pressure sensors with interface circuitry for appropriate biasing and readout of the ambient pressure. The sensor structure is obtained by the local removal of the lower metallization layer after completion of the CMOS process. An interface circuitry drives the sensor at constant relative temperature. The power required to maintain this condition is read out and converted by two incremental ADCs. Each of them provides a bitstream with 10 bit resolution. The power consumption of the complete system is dominated by the sensor biasing and amounts to 80 mW at 10^5 Pa with a power supply of 6 V. The chip covers an area of 3.3 x 2.8 mm^2.

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