MONOLITHIC INTEGRATED SURFACE MICROMACHINED PRESSURE SENSORS WITH ANALOG ON-CHIP LINEARIZATION AND TEMPERATURE COMPENSATION

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ABSTRACT

This paper introduces a noval family of monolithic integrated surface micromachined pressure sensors with both linearization and temperature compensation done on-chip. All sensor parameters are fully programmable and on-chip stored using integrated EEPROM. Surface micromachined capacitive pressure sensors are pre-destinated for monolithic integrated sensor systems due to their compatibility to a standard CMOS process. This enables a cost effective production. Compared with piezoresistive pressure sensors, the surface micro-machined pressure sensors are superior with respect to high overpressure stability [1], simple packaging [2], ease of monolithic integration of signal conditioning electronics [3], low power consumption and small chip size.

INTRODUCTION

The application of MEMS products in the area of automation and automotive electronics is dominated by the requirements of cost reduction, reliability increase, weight and size reduction and the emerge of new funtionalities like self test, accuracy etc. [4]. Therefore today's pressure sensor market demands fully linearized and calibrated sensor systems to avoid the need for additional external components and to enable the replacement of sensors in the field without costly and time-consuming recalibration of the measurement system. In order to satisfy these demands signal conditioning circuits for linearization and temperature compensation have been integrated on-chip.

This paper presents integrated pressure sensors developed and fabricated at IMS that meet these requirements. A description of the sensor principle and the results of the sensor characterization are given below. In particular an analog circuit that compensates for the inherent non-linearity of such capacitive sensors will be described, which overcomes the biggest drawback of sensors based on this principle with grace and stability.

SENSOR REALIZATION

The integrated pressure sensors were fabricated in a standard 1.5 μm/5 V Silicon-Gate CMOS process, where certain specific and CMOS-compatible processing steps have been added. MOSFETs, capacitors and EEPROMs were fabricated along with the pressure sensor, as depicted in figure 1 (see also Ref. [5]).

Figure 1: Cross-section of a monolithic integrated pressure sensor device.

The micromachined pressure sensors transform a pressure into an equivalent capacitance value, which is inversely proportional to the distance between the diaphragm made of polysilicon as the top electrode and a n^+ bottom electrode. Since the cavity is sealed under vacuum the sensor works as an absolute pressure sensor. The pressure range is design controlled by adjusting the diameter of the circular sensor element. Various sensors for low (1.4 *bar* max.) up to high (350 *bar* max.) pressure ranges are available. The corresponding diaphragm diameter are 25 μm for highest pressure applications up to 120 μm diameter for low pressure sensors.

The capacitive sensor consists of an array of circular pressure sensitive diaphragms. The capacitances are switched in parallel. In addition an array of pressure insensitive reference elements has been implemented, which only differ from the sensitive elements in

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diaphragm thickness. The pressure signal is gained by the ratio C_{ref}/C_{sens} of these capacitances, that is almost free from parasitic effects. Figure 2 shows a chip micrograph of a 10 *bar* sensor with the integrated signal conditioning circuit. Tenfold overpressure has applied to these sensors without causing any damages.

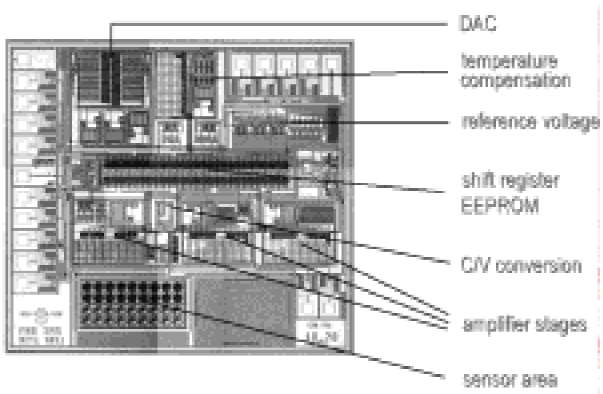

Figure 2: Chip micrograph with illustration of the electronic components.

The readout circuit is designed in switched capacitor technique. The sensor provides an analog and ratio-metric voltage output signal. The power consumption of these devices is 1.6 *mA* at 5 *V* supply voltage. The bare die has a size of 2.9 x 3.1 mm^2, whereas the sensor area shown in figure 2 has a size of only 0.4 x 0.8 mm^2. For normal operation three leads are needed (supply, out, gnd) and additional four leads have to be connected for programming. The other pads seen in figure 2 are I/O´s for certain test cells, which allow to probe each discrete circuit part separately.

SENSOR CALIBRATION

As depicted in the block diagram of the signal path (figure 3) the first stage represents the *C*/*V* converter and performs the linearization via the feedback path with an amplifier of programmable amplification *k*. This stage produces a pressure proportional output signal.

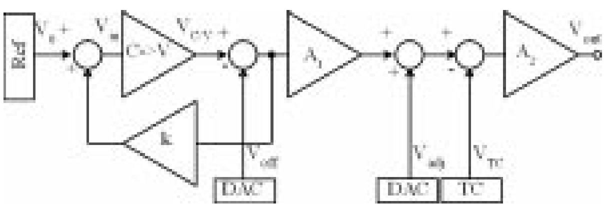

Figure 3: Block diagram of the signal path.

The overall transfer function is shown in figure 4. The output signal V_{out} depends on six programmable parameters A_1, A_2, k, V_{off}, V_{adj} and V_{TC}:

$$V_{out} = \left\{ \frac{\left(V_{Supply} - V_{off}\right) - \left(V_{Supply} - V_0\right)\dfrac{C_{ref}}{C_{sens}}}{1 - k\,\dfrac{C_{ref}}{C_{sens}}} A_1 + V_{adj} - V_{TC} \right\} A_2$$

Figure 4: Transfer function of the integrated pressure sensors.

The correct *k* can be chosen out of 16 available values. Our experiments have shown, that for all sensors of the same pressure range the appropriate *k* needed for optimal linearization is fixed to just one value throughout the automotive temperature range -40°*C*...+125°*C*. So there is no need for installing of a linearization calibration routine. Figure 5 shows the measured output linearity error for four different values of *k*. With the correct choice of the amplification of the feedback loop a linearity error less than 0.1% FSS at room temperature and less than 0.5% FSS over the extended temperature range -40°*C*...+125°*C* has been achieved (figure 6).

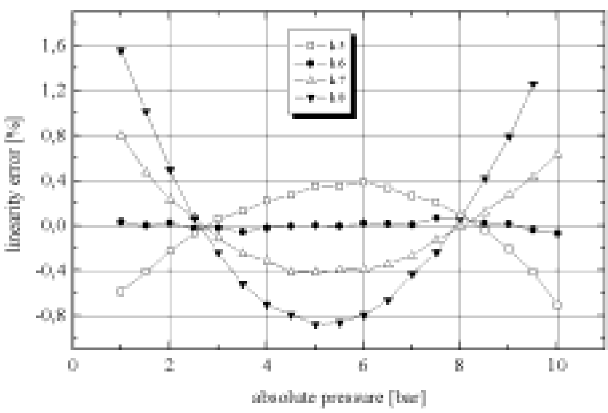

Figure 5: Linearity error at RT in dependence of the programmable linearization parameter *k*.

For offset compensation a voltage V_{off} is added to the signal path. V_{off} is supplied by means of a 8 bit digital to analog converter (DAC) with a resolution of 9.8 *mV*/*LSB*. Further trimming of the output signal makes use of the 6 bit programmable amplifier stages A_1 and A_2. All programmable amplification factors (A_1, A_2, k) and offset voltages (V_{off}, V_{adj}, V_{TC}) are stored in an on-chip EEPROM.

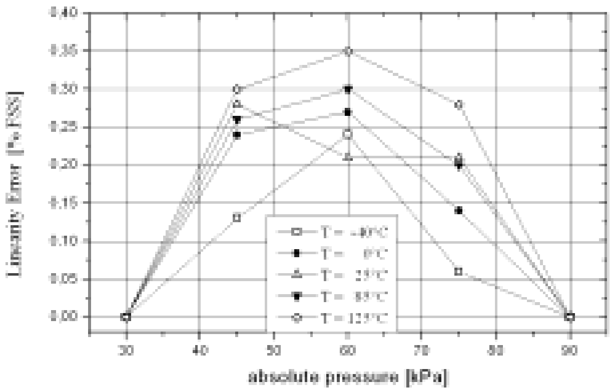

Figure 6: Linearity error of a 1.4 bar sensor in the temperature range [-40°C...+125°C].

The temperature dependence of formerly investigated capacitive pressure sensors was found to be in first order a linear drift in offset voltage (figure 7) [5]. Therefore a compensation voltage V_{TC} based on bandgap reference diodes has been implemented for temperature compensation of the offset drift (TCO). The corresponding block diagram is depicted in figure 8. The temperature coefficient of V_{TC} is adjustable over a wide range by using an amplifier with a 7 bit programmable amplification A_{TC}.

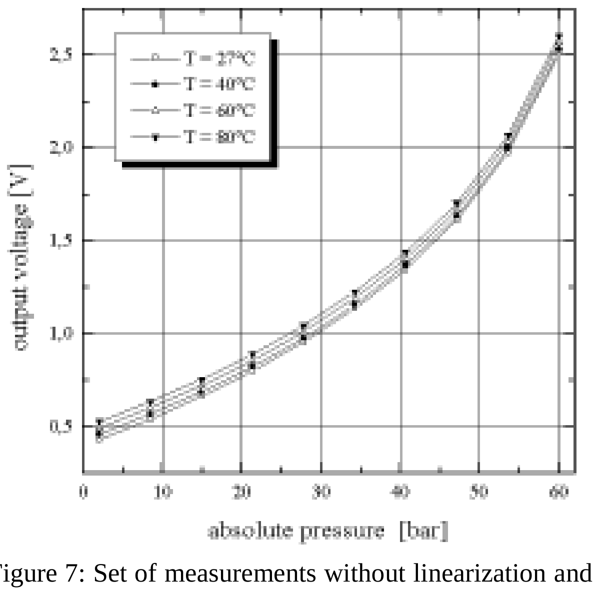

Figure 7: Set of measurements without linearization and temperature compensation.

Obviously, adding V_{TC} to the signal path results in an offset shift of the already adjusted output signal. So a further programmable voltage V_{adj} generated by means of a resistor network is used for readjustment of the output signal offset.

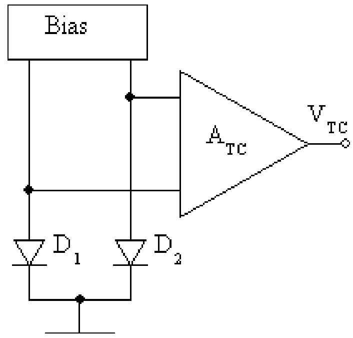

Figure 8: Block diagram of the circuit used for TCO.

With the implemented range of amplification factors a temperature error of less than 100 *ppm/°C* related to the average offset value has been measured. Figure 9 shows a set of measurements with optimized settings for linearization and temperature compensation.

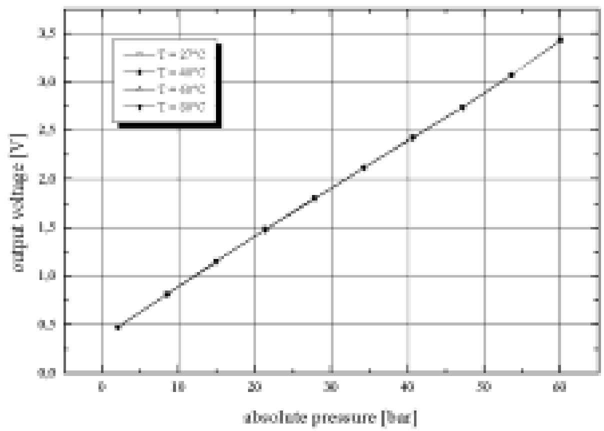

Figure 9: Same sensor as shown in figure 7, with optimal linearization and temperature compensation.

CONCLUSION

The presented micromachined absolute pressure sensors have achieved high accuracy. A linearity error of 0.1 % FSS and a temperature dependend offset drift of less than 100 *ppm/°C* have been measured with these integrated pressure sensors. The pressure range is design controlled by adjusting the diameter of the circular sensor element. Linearization, temperature compensation, amplification and adjustment of offset values were realized by programmable analog circuits. All compensation parameters are stored in an on-chip EEPROM. Various sensors for low (0 *bar*...1.4 *bar*) up to high (0 *bar*...350 *bar*) pressure ranges are available. However, due to its programmability this readout circuitry is applicable for any pressure range. The introduced sensor family provides an analog and ratiometric voltage output signal. These properties make the presented sensors well suited for medical, automotive and mechanical engineering applications as well as advanced aviation systems.

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