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A monolithic integrated MEMS in a 350 nm technology for filter monitoring applications

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Abstract

This paper presents a system which combines a modern 350 nm mixed-signal CMOS technology with a MEMS technology for monitoring of the filter contamination level of suction and filtering systems. Therefore the system includes a piezoresistive pressure sensor, a controller core, a power management, a digital and analog signal processing with a variable gain up to 270 and an 8 bit autonomous offset adjust as well as a RFID interface to allow wireless transfer of energy and data.

Key words: CMOS technology, MEMS, 350 nm, pressure sensor, RFID interface

1 INTRODUCTION

In various production techniques, e.g. in metal and wood processing or electronics industry, the prevention of air pollution becomes more important. Especially the occupational health and the climate protection require this prevention. For this reasons suction and filtering systems provided with exchangeable filter cartridges are used. In most cases the filter pollution is examined by means of observing differential pressure. The differential pressure between raw air side and clean air side depends on the filter filling level, like demonstrated in fig. 1.

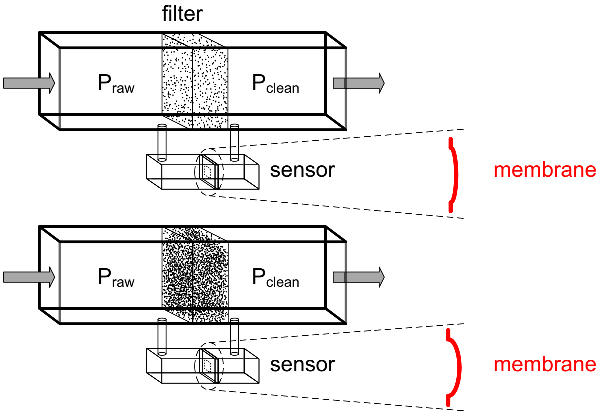

Fig. 1: Rise in differential pressure with increasing filter pollution

Typically the pressure sensor is mounted on a printed circuit board and connected with the filter by silicone tubes. Drawbacks of this solution are high expenses in assembly and service. Furthermore, the cartridges can be replaced by non certificated filters with incorrect filter classification. There are no control mechanisms to prevent the consequences on the air pollution.

Objective of the current research project is the monolithic integration of pressure sensor, sensor control and electronics within new MEMS. For the future the MEMS should be nonexchangeable parts of the filter cartridges with the possibility of individualization by absolute coding. Energy and data are transferred wireless via RFID (Radio Frequency Identification) interface [1]. Therefore the housing contains an antenna. Because the MEMS have to be protected from thermal and mechanical influences the research of suitable assembling and housing methods is necessary.

Basis of innovation is the integration of a pressure sensor fabrication module into a modern 350 nm CMOS mixed-signal standard semiconductor technology, available for customers using the foundry service of the semiconductor manufacturer. Compared to available processes the conjunction of MEMS technologies with the minimum feature size of 350 nm allows undreamed-of possibilities for complex circuit designs with less area consumption. In this way cost-efficient more intelligence and adaptations to the intended use can be concentrated in the filter.

However, combining CMOS and MEMS technologies is challenging because several MEMS process steps, e.g. silicon etching by KOH, are incompatible with the requirements of CMOS technology. To avoid contaminations MEMS process steps are arranged at the back end of the whole flow.

2 SYSTEM DESIGN

The complete “SmartFilter”-system consists of the RFID frontend with antenna, adjustment capacitor and energy storage capacitor, sensors for pressure and temperature, the analog to digital converter and a controller unit with working memory and program counter. Fig. 2 gives a system overview.

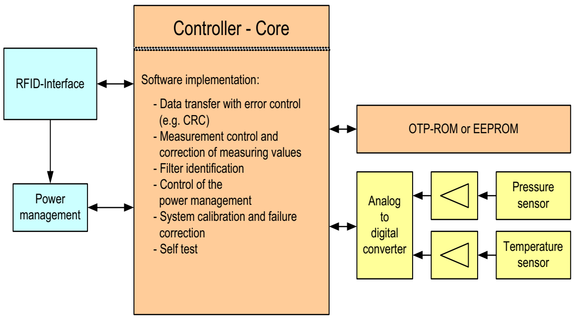

Fig. 2: System overview

All components are monolithic integrated in the MEMS but the adjustment capacitor, the energy storage capacitor and antenna are discrete elements and placed on a small printed circuit board (PCB) along with the MEMS. The PCB is the non expensive but flexible configurable conduction base plate for the system package. The RFID frontend communicates with the suction and filtering control system. As working frequency the 13.56 MHz band was selected, an international permitted ISM band [2].

This frequency band allows exchanging data, e.g. measurement commands, measurement values, device identification and failure codes. Additionally the energy transfer over a small distance is enabled to grant an operation of the “SmartFilter” system without needing a battery or an accumulator. The power management observes the energy transfer and generates all necessary supply voltages for the analog and digital circuit components.

The analog to digital converter (ADC) converts the appropriate prepared analog measurement signals of the temperature and pressure sensors into digital data format for the controller core. The operation principle allows only one conversion per time step, either the temperature or the pressure value. This principle permits low-energy operation. The energy aspect has more importance than the time critical measurement value extraction.

The controller core is an 8051 based implementation. It executes the complex control algorithms for data transfer, MEMS identification, power management, measurement procedure as well as monitoring and failure observation. For an energy-saving operation the cycle frequency can be reduced from 10 MHz down to the kHz range.

The monolithic integration of sensors/actors and electronics makes it possible to join high volume production at low costs with an enhanced level of reliability due to a considerable reduction of bond wire connections. Otherwise for the integrated circuit design it is a challenge to cope with the restrictions of the post CMOS MEMS process. FEM calculations for sensor dimensioning, sensor manufacturing, possible designs of piezoresistors as well as characterizations will be discussed within another paper.

3 RFID-FRONTEND

The energy supply of the SmartFilter system has to be provided for distances in the range of about 5-10 mm dependent on the mechanical installation of tag and reader. Furthermore the RFID interface is used for data communication. To maintain a stable power supply for the integrated circuits and the resistance bridge an RFID-Frontend was developed (fig. 3).

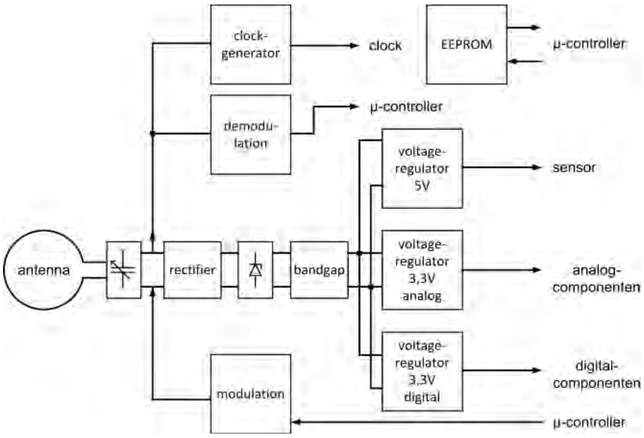

Fig. 3, Block diagram of the RFID-Frontend

The RFID-Frontend consists of several sub-building blocks which represent a tuning circuit for the adjustment of the operating frequency, the rectifier, a voltage limiter circuit, a bandgap source, three voltage regulators and a circuit for generating several system clocks. There are also the sub-building blocks for modulation and demodulation to handle the data transfer.

A correct adaptation of the antennas operating frequency is necessary to reach an optimal energy transfer. The combination of a discrete capacitor and an integrated 4-bit capacitor array is to be destined for this purpose (see fig. 4).

The application of this combination has several advantages. On the one hand it is possible to tune the resonant circuit of the

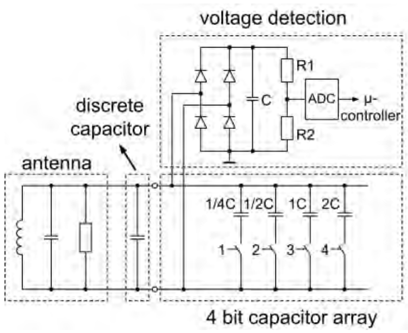

Fig. 4, Structure of the Antenna Adaption Circuitry

antenna to the operating frequency by the integrated microcontroller and on the other hand it enables to minimize the effect of too high coupling factors caused by small distances between the antennas.

A high coupling factor causes a current which antagonizes the current through the reader antenna and hence decreases the transmission power. This decrease could affect the data transmission. By means of the capacitor array it is possible to change the frequency of the resonant circuit in such a way that the coupling factor will be reduced to ensure an optimal data transfer.

The voltage detection was implemented to compare the induced voltage while tuning the frequency by use of the integrated 4 bit capacitor array and searching the maximum voltage.

The rectifier is equipped with 4 integrated diodes and a discrete smoothing capacitor. The implementation of the limiter is based on a shunt-regulator which compares the rectified voltage with a reference voltage. If the voltages are equal, the output of the comparator enables a path between the rectified voltage and ground. The current through this path reduces the factor of quality of the antenna and so the induced voltage decreases.

For the voltage regulators it is necessary to generate a stable reference voltage independent on both, temperature and power supply. Therefore a bandgap voltage reference based on [3] was used. In comparison to conventional circuits this bandgap is able to improve the PSRR (Power Supply Rejection Ratio) around the operating frequency about 30 dB. The voltage regulators generate the three required supply voltages of 5 V for the resistance bridge and 3.3 V for the analog and digital circuits, respectively. The circuits of these regulators base on [4].

In addition to the supply voltages it is necessary to generate several clocks for the implemented microcontroller and the ADCs. Furthermore for data transfer a frequency of 423.75 kHz is required. The implementation of these clocks occurs by a frequency divider which divides the operating frequency of 13.56 MHz.

The data transfer for this RFID interface bases on the ISO-15693 standard, which demands a transfer using an amplitude modulation (AM) by a subcarrier of 423.75 kHz. The AM is excited by a resistor parallel to the antenna that is switched on and off. The resistor reduces the factor of quality of the antenna whereby the coupling factor between the antennas varies. This variation is detected by the reader. For an optimal data transfer the resistor is implemented as a 4 bit array similar to the capacitor array. Thus it is possible to choose the right resistance value for the desired degree of modulation. A demodulation circuit detects the data received from the reader.

4 SENSOR

A precise manufacturing of discrete pressure sensor membranes is possible using etch stop techniques. However after the preceding CMOS process membranes have to be manufactured by multi-stage time etching. For this reason one has to cope with larger fluctuations of the membrane thicknesses.

These fluctuations have directly influence to the sensitivity, the offset and the linearity of the sensor. For a precise analysis of the filter contamination level it is necessary to have a small offset, a high linearity and a high sensitivity.

The V(p) characteristic of the manufactured sensor is shown in Figure 5 and in addition the important values in table 1.

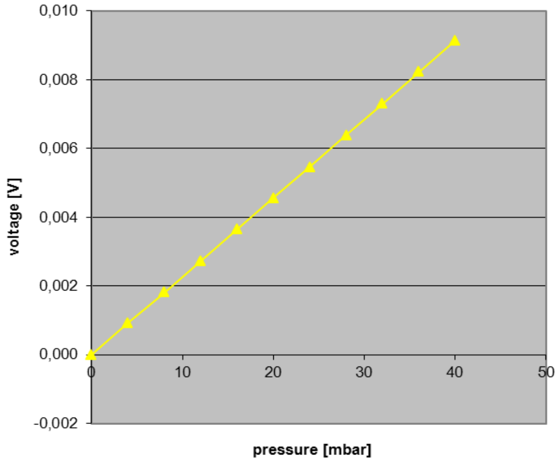

Fig. 5, V(p) characteristic without offset

Offset [mV]	FSO [mV]	S [mV/(V*bar)]	max.L-Error [%FS]
-9,87	9,15	45,74	0,26

Table 1, characteristic data of the manufactured sensor

5 ANALOG SIGNAL PROCESSING

Due to the fluctuating sensitivities the signal of the differential pressure sensor cannot be digitized directly. Depending on the supply voltage of the resistance bridge and the applied differential pressure only a maximum signal of a few 10 mV/V could be expected. Because the offset of the sensor signal obtains the same magnitude of order balancing before amplification is indispensable (see Fig. 6).

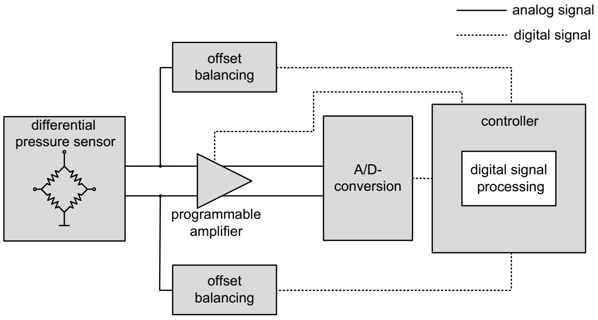

Fig. 6, Analog and digital signal processing

The potentials for both output nodes of the sensors resistance bridge are independently controlled by means of an autonomous calibration routine, respectively. For offset balancing D/A converters using the W-2W current steering principle are designated [5]. With a bridge voltage of 5 V and the designated resolution of 8 bit a maximum offset as large as 80 mV can be compensated. The minimum resolution of 0.31 mV is sufficient for an adjustment to the input of the fully differential amplifier.

Figure 7: Offset adjust plot

Its programmable amplification enables in conjunction with another controller routine the compensation of sensitivity fluctuations to fit the sensor output to the fixed input range of the A/D converter.

The mechanical stress of the membrane is dependent on temperature. Due to this behavior the resistances of the bridge change their values without applying a differential pressure and cause an offset of the sensor signal. Furthermore the pressure sensitivity decreases with rising temperature caused by the piezoresistive effect. Both influences are compensated using digital calibration routines, respectively.

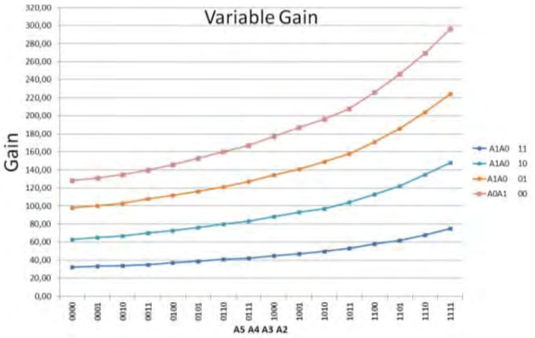

Figure 8: Variable gain plot

The requirements of the analog to digital conversion are mainly defined by the dynamic properties of the sensor signal and the limited available power. Fortunately the variation of the average pressure in time is a very slow process and therefor a low power Delta Sigma architecture will perfectly fulfill the specifications. To ensure that the slope of modulator's noise transfer function is strong enough for small signals a second order system was chosen. In consideration of the power specification a feed forward architecture (Cascaded Resonator Feed Forward) is preferred because of the reduced overall capacitances.

Figure 9 shows the layout of the integrated system with four functional blocks. The dimensions of the ASIC are 3.5 mm x 7.5 mm including the sensor with a size of 3.5 mm x 3.5 mm.

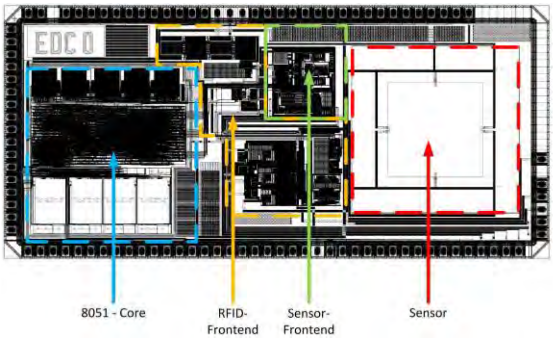

Fig. 9, Layout of the System

6 PACKAGING

The most important demand of packaging is to find low-cost solutions applicable for high volume customization while maintaining sufficient flexibility. Further requested properties concern a robust and simple assembly, the prevention of additional thermal influences on the pressure sensor and a maintenance-free use of the module. An integration of the module in various filtering units and other applications should be possible.

To achieve these aims low-cost material, e.g. FR4 should be used for the PCB. The PCB serves as a flexible configurable base plate for the monolithic MEMS, the complementary discrete circuitry with some discrete components and the RFID antenna as well.

Fig. 10 shows the corresponding model design.

In order to protect the MEMS and the discrete circuitry from mechanical influences a cap is placed to the front-side of the board which is embedded into the filter cartridge. On the back-side of the PCB is placed the antenna.

The SmartFilter module can be mounted directly into the sled wall as a fixed part of the filter cartridge.

In addition to the module for filter monitoring described above a RFID reader unit has to be developed which acts as communication interface between the filter monitoring and the control unit of the complete suction and filtering unit.

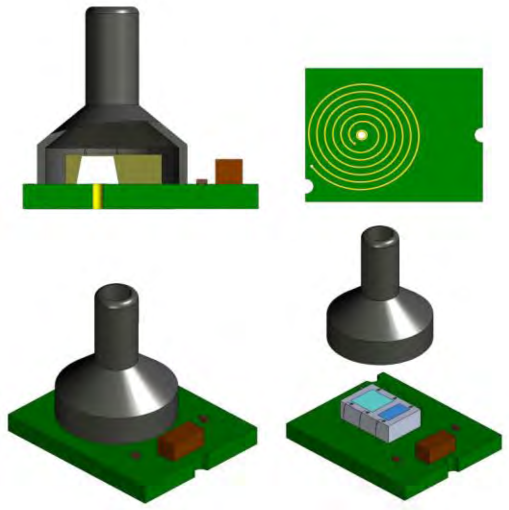

Fig. 10, Package of the System

ACKNOWLEDGMENT

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