An A/D Interface for Resonant Piezoresistive MEMS Sensor

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Abstract

This paper introduces an original architecture to measure and convert into digital data the oscillations of a resonant beam. An electromechanical CMOS magnetic field sensor is considered here for the purpose of a case study. The proposed architecture is based on counting the periods of an oscillator signal, whose frequency depends on the deformation of the mechanical structure. In order to cancel drifts, the structure implements a differential measure by counting both up and down within a mechanical vibration period, using the actuation signal for synchronization. Simulation results demonstrate that high resolution can be achieved with acceptable integration time. Such a signal processing architecture is particularly suitable for low-cost CMOS mechanical structures.

Keywords
CMOS, MEMS, Magnetic field Sensor

INTRODUCTION

Recent publications in the field of microsystems reveal an increased attention concerning the monolithic fabrication of sensing devices with dedicated CMOS signal processing circuits. A regular low-cost fabrication flow to manufacture monolithic systems usually relies on an industrial CMOS foundry followed by specific micromachining post-processes [1] that basically release suspended structures for thermal or mechanical applications.

Among the available post-processes, the bulk wet etching of CMOS dies from the front side (FSBM) appears to be the cheapest. There are however some limitations in the use of this fabrication approach. For example, capacitive actuation and capacitive sensing are not possible because of the large gaps separating the moving parts from the substrate or other moving parts. Thermal or electromagnetic actuation can be used instead while mechanical deformations can be measured by using the available polysilicon in a piezoresistive strain gauge configuration.

In the use of a standard microelectronic technology to implement mechanical functions, there are many non-optimized parameters and many constraints to deal with. For example, the designer has no control on the thickness of the various layers in the suspended structure. Also, the polysilicon gauge factor, which is not under concern for the purpose of transistor making, is not optimized. Consequently, the performance of the so-obtained mechanical part is usually intrinsically modest. The purpose of on-chip electronic is then to compensate the sensor weaknesses in order to reach the required level of performance at the system level.

This study concerns an original approach for the measurement and the analog-to-digital conversion of the oscillations of a resonant CMOS beam. Various applications of such resonant beams have been reported including chemical (or mass) sensors and inertial sensors [2]. In this work, a magnetic field sensor is used as a case study. The paper is organized as follows: in a first part, the monolithic fabrication approach is briefly described; the second part is dedicated to the mechanical device that is used for magnetic field sensing. Basic operating principles are described with resonant characteristics; the proposed circuit architecture is then detailed, including design and post-layout simulation results.

FABRICATION APPROACH

The Front Side Bulk Micromachining (FSBM) post-process allows the fabrication of micrometric mechanical structures using a silicon wafer issued from a standard CMOS industrial process. This MEMS technology can be easily addressed through Multi-Project Wafer services. CMOS is currently a 0.8µm or 0.6µm standard process with two or three metal layers by Austria Mikro Systems [3].

Figure 1 represents a cross-sectional schematic view of a CMOS process where polysilicon, metal and oxide layers are deposited on a substrate. According to designer requirements several etching masks can be superimposed to leave the silicon bulk uncovered at the end of the standard CMOS process. Then, the post-process operates as an anisotropic silicon etching that uses the various oxide layers as self-aligned masks. <100> substrate planes can then be etched leaving the <111> planes of silicon substrate unaltered. In this way, suspended structures can be obtained as a heterogeneous stacking of various materials (namely Silicon Oxides, Polysilicon, Aluminum, Silicon nitrides).

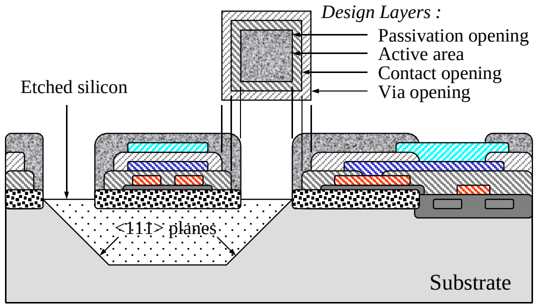


Figure 1. Cross section of a typical CMOS suspended structure

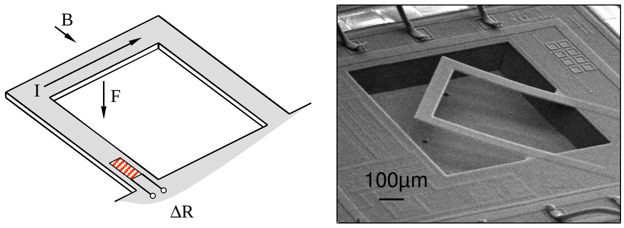
Considering the important distance (typically 200µm) between the suspended structure and the substrate, electrostatic actuation would require oversized voltage. Both thermal or electromagnetic actuation have been reported for such structures. These actuation methods are easy to apply since polysilicon can be used to implement heater and metal layers provide an embedded current path. The mechanical deformations can then be measured by means of polysilicon resistors that exhibit a piezoresistive behavior.

THE MAGNETIC FIELD SENSING DEVICE

The basic mechanical structure (Figure 2) consists in a U-shaped cantilever embedding an aluminum planar coil. The coil is supplied with an electrical current *I* that can be continuous (static mode) or alternative (dynamic mode). When an external magnetic field *B* is present, cantilever beam is therefore deflected due to the action of the Lorentz force *F* applied to its free side. Polysilicon strain gauges are located into the mechanical structure close to anchor points in order to detect such deflections with a maximum sensitivity. The interaction between the current and the external unknown magnetic field produces a Lorentz force given by:

$$\vec{F} = \left(\vec{I} \cdot W_c\right) \otimes \vec{B}$$

Where *Wc* represents the length of the cantilever free standing length placed in a perpendicular magnetic field. In figure 2.b, the cantilever width is $Wc=520\mu m$.



(a) (b)

Figure 2: The "U-Shape" magnetic field sensor :
(a) operation principles
(b) SEM picture of a fabricated device

The sensor has been characterized with both static and dynamic actuation signals in a calibrated magnetic field [4]. The static sensitivity is reported in figure 3, as a relative change in the resistor value (gauge) as a function of the applied force. Figure 4 plots the device frequency response in the resonance neighborhood (with $B=40mT$ and $I=80mA$).

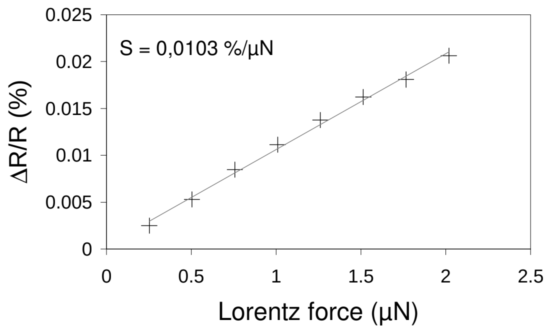


Figure 3: Cantilever static sensitivity to Lorentz force

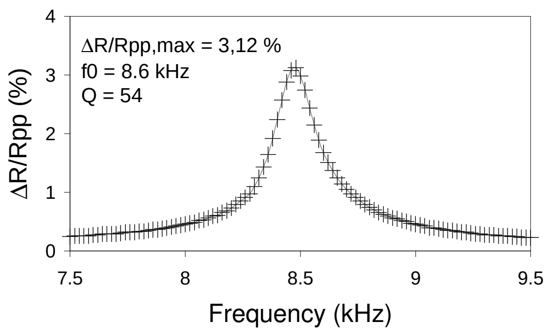


Figure 4: Cantilever frequency response

The best sensor sensitivity is obtained by operating the mechanical structure at its resonant frequency. In the following, an electronic architecture, to measure the oscillation amplitude of the resonant cantilever, is therefore proposed.

SIGNAL PROCESSING

Conventional approach

A common approach for the signal processing of resistive sensor is depicted in figure 5. First, a Wheatstone bridge is used to bias the gauges. Such an arrangement provides a good ratio between the output voltage and the relative changes of the gauge resistance value. It is furthermore insensitive to temperature variations. The signal is then amplified and filtered before it enters into an analog-to-digital converter.

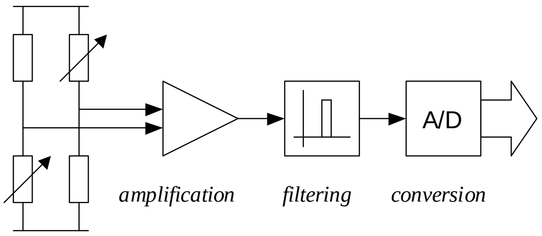


Figure 5: Standard approach for signal conditioning and A/D converting circuit

This conventional solution is currently evaluated [5] together with the alternative approach presented in this paper. Design difficulties have been identified for the various stages. Let's mention few:

- The drawing of matched resistors do not totally avoid an offset voltage at the Wheatstone bridge output. This is a problem since amplification gain has to be high in order to reach the required sensor sensitivity.
- The first amplification stage has to be designed with special care regarding noise. This is a decisive point regarding the final sensor resolution.
- By driving the sensor at its resonant frequency, the signal bandwidth is in the range of few hundreds Hertz (see figure 4). The best resolution is achieved using a narrow band-pass filter which is difficult to integrate.

The purpose of the proposed alternative signal processing architecture is to convert the analog information, i.e. the gauge resistance, into a digital signal as soon as possible in order to avoid the previously mentioned problems. Amplification and filtering is therefore directly performed in the digital domain.

Alternative approach

The proposed measurement circuit, which is shown in figure 6, consists in using the gauge in an RC based oscillator. The variations of the gauge resistance value produces a change in the oscillator frequency (*osc_out*). Given that the cantilever is driven at the resonant frequency, the oscillator output signal is therefore a frequency modulated square wave. The frequency shift represents the signal to be measured.

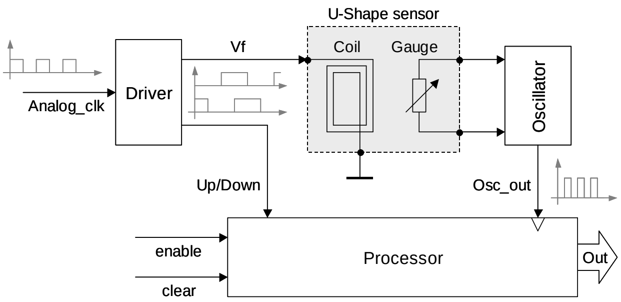


Figure 6: Architecture of the proposed circuit

The cantilever is actuated by means of the signal *Vf* which is applied to the embedded planar coil and produces the required Lorentz force. This signal is generated by the driver module. The driver receives an analog clock signal (*analog_clk*), whose frequency is exactly twice the mechanical resonant frequency. Using two flip-flops and an inverter arrangement, this clock is divided into two signals at the resonant frequency with a phase difference of 90° : *Vf* and *up/down*.

In the resonant mode, the cantilever oscillations exhibit a phase shift of 90° from the actuation signal *Vf*. Consequently, the *up/down* signal represents the sign of the signal to be measured (i.e. the sign of the frequency modulation in the *osc_out* signal). In order to summarize this part, an overview of these transient signals is given in figure 7.

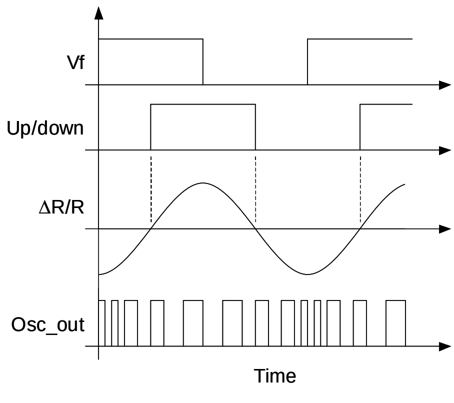


Figure 7: Overview of transient signals

The processor includes an up-and-down counter and a register to store the partial results as shown in figure 8.

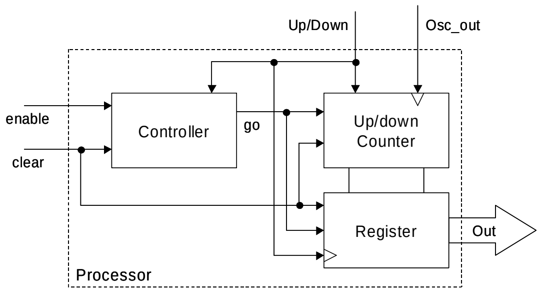


Figure 8: Processor architecture

Figure 9 details a complete measurement cycle. First, a *clear* pulse is applied to reset the counter. Note here that the reset value can be used to compensate offsets. Then the *enable* signal is toggled. The controller starts the counter (using the *go* signal) when the first rising edge occurs on the *up/down* line. This mechanism is used to run the counter during an integer number of *osc_out* periods. The measurement is performed by incrementing the counter during a half period, and decrementing the counter during another half period. The counter is clocked by the *osc_out* signal. The measure is possible because, as in the example of figure 9, during the up-counting half period the average clock frequency of the counter is higher than in down-counting. In fact, the average resistance of the gauge is smaller during this half period. A difference is therefore cumulated in the counter during the measurement window. After each period, the actual difference is latched in the register. After the *enable* signal falling edge, the controller waits for a rising edge on *up/down* and the content the register is read.

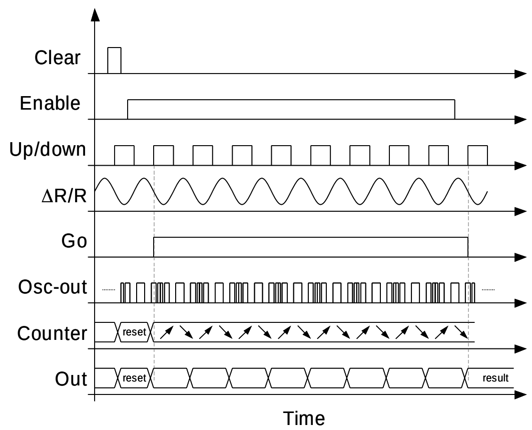


Figure 9: Processor signals

The sensor performance depends on design parameters which are here:

- The nominal RC oscillator frequency. It has to be high enough, in comparison with the resonant frequency to permit a counting difference to appear for each single mechanical oscillation period.
- The duration of the measurement window since the result is directly proportional to this time. The size of the counter also depends on that time.

The choice of these parameters is discussed later on in the simulation result section.

OSCILLATOR DESIGN

The oscillator translates the strain gauge value (i.e. the cantilever bending) into a frequency. So, the variations of the gauge resistance modulate the frequency of the oscillator. The proposed design is depicted in figure 10. This design has been chosen because it is simple to integrate.

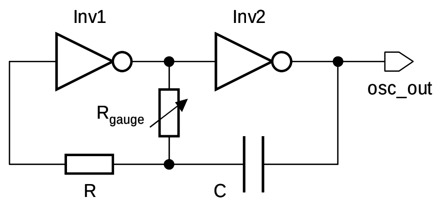


Figure 10: Oscillator design

Figure 11 gives a transient simulation result for an oscillator using the following design parameters : *R=100kΩ*, *C=2.2pF*, R_{gauge} = *4kΩ* (nominal value). Both inverters are taken from the foundry design library : *L=0.8µm*, W_P*=36µm* and W_N*=20µm*.

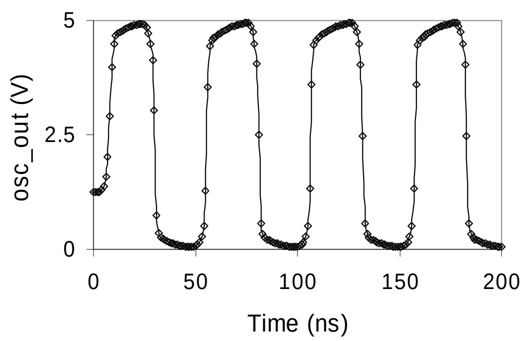


Figure 11: Transient simulation of the oscillator

This oscillator provides a digital signal (0-5V) at a frequency of about 20MHz when the structure is not deformed. In figure 12, a parametric analysis is reported to study the response of the oscillator frequency as a function of the gauge resistance deviation. We observe a linear response with a negative frequency shift of about 100KHz/%.

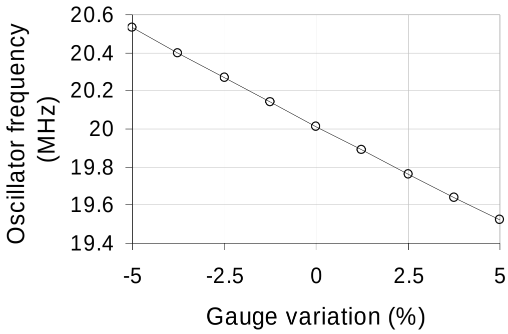


Figure 12: Oscillator frequency shift as a function of the gauge variation.

The effect of temperature, the jitter and other imperfect behaviors of this oscillator have not been studied. Because of the measurement principle, it is supposed that only the variation of R_{gauge} from one half-period to another will produce the differential result to be accumulated. All other random behavior (i.e. non correlated with the resonant frequency) are assumed to be cancelled by the averaging process.

Finally, note that the nominal frequency of 20MHz is an arbitrary choice. The proposed oscillator has been validated for frequencies above 30Mhz by decreasing the value of the capacitor. Since this signal is used for the clocking of the digital part, higher frequencies need to be validated at the system level. At higher frequency the sensitivity of the sensor is higher, but it requires a bigger counter.

SYSTEM EVALUATION

The purpose of this section is to evaluate the performance of a magnetic field sensor using the proposed architecture. For this let us calculate the system output for a 1mT magnetic field.

Given that a maximum current of *80mA* can flow into the cantilever shown in figure 2, the static force applied on the structure is:

$$F = 80 \cdot 10^{-3} \times 1 \cdot 10^{-3} \times 520 \cdot 10^{-6} = 41.6 \cdot 10^{-9} N$$

When using the resonant node, an equivalent force can be considered, taking into account the quality factor Q:

$$F_{eq} = Q \cdot F = 54 \times 41.6 \cdot 10^{-9} = 2.25 \mu N$$

According to figure 3, the relative change in the gauge resistance is therefore:

$$\Delta R / R = 0.0103 \times 2.25 = 0.023\%$$

With such a resistance change, the oscillator frequency variation is ±2300 Hz.

The cantilever resonant frequency is 8.6kHz. The duration of an up-counting phase (or a down-counting phase) is then 58.14µs. Consequently, there is a difference of only 0.27 pulses between the up-counting phase and the down-counting phase. From a practical point of view, it means that most of the time, no difference will be detected during a single period (one up and down sequence) of measurement. A difference of 1 pulse is expected to be accumulated every 4 periods (precisely 3.74). Assuming a measurement window of 1 second, the digital result should be around:

$$Data\_out = \frac{8600 \times 1s}{3.74} \approx 2300$$

It finally comes that the sensor resolution is theoretically:

$$B_{\min} = \frac{1mT}{2300} \approx 0.4 \mu T$$

Since earth natural magnetic field is about 20µT in amplitude, the performance of the proposed sensor is suitable for a micro-compass application. The resolution can be improved by using a greater measurement time, or a higher oscillator frequency.

The maximum detectable magnetic field depends on the size of the counter. With a 16 bits counter, we have:

$$B_{\max} = 0.4 \cdot 10^{-6} \times 2^{16} = 26.2 mT$$

SYSTEM INTEGRATION & SIMULATION

The digital processor has been described in VHDL and synthesized for an ASIC target using a 0.8µm CMOS technology from AMS, which is available for MEMS fabrication. After placing and routing the cells, the surface of the IP block is about $0.12 mm^2$. This is an interesting result since a surface of $0.48 mm^2$ is required by the 10 bits ADC available in the foundry library of analog cells.

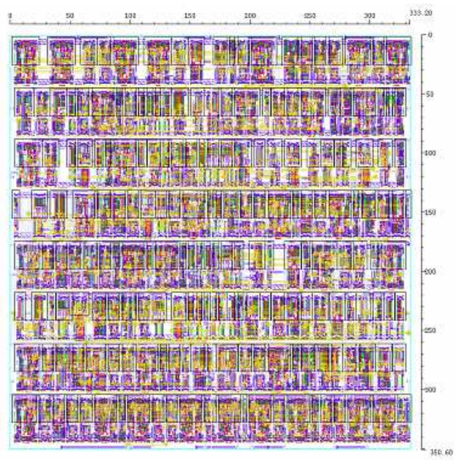


Figure 13: Layout of the IP block

VHDL simulations have been performed after the back-annotation in order to take account for parasitic delays. The digital processor has been validated with clock frequencies up to 30MHz.

Table 1 summarizes obtained results, that match the previously presented evaluation. A 16 bits counter and two measurement windows of 1s and 2s have been considered.

Table 1: Simulation results

	Time = 1s		Time = 2s	
Oscillator frequency MHz	B_{max} (mT)	Resolution (µT)	B_{max} (mT)	Resolution (µT)
10	33	0.5	16	0.25
20	22	0.33	11	0.17
30	10	0.16	5	0.08

CONCLUSIONS

In this paper, an original readout circuitry has been proposed for MEMS resonant sensors. This circuit is based on the conversion of the gauge resistor value to a frequency modulated signal. A simple counter is then used to translate this frequency into a digital result. The originality of the method relies on a up and down counting mechanism, which is synchronized with the frequency modulation envelope. An averaging operation cancels random signals (noise, jitter…) and enables an interesting sensor resolution such as 80nT at the price of a limited sensor bandwidth. In a first approach, the proposed method can be compared with the Sigma-Delta conversion principle.

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