Experimental and Finite-Element Study of Convective Accelerometer on CMOS

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EXPERIMENTAL AND FINITE-ELEMENT STUDY OF CONVECTIVE ACCELEROMETER ON CMOS

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Abstract: This paper addresses the design of CMOS thermal accelerometers. A test-chip including the sensor and a signal conditioning circuit has been designed, fabricated and characterized. The obtained sensitivity is 375mV/g while resolution is estimated at 30mg. This test-chip is used to improve the modelling of heat transfer phenomenon in theses devices. FEM is successfully used as a first modelling approach.

Keywords: CMOS, MEMS, Thermal, Accelerometer.

INTRODUCTION

The front-side bulk micromachining technique (FSBM) allows the cheap manufacturing of suspended structures (basically cantilevers or bridges) on CMOS dies. Typical applications are mechanical or thermal sensors. Although the intrinsic characteristics of so-obtained sensors are usually modest (due to the non-optimized properties of CMOS back-end layers), the system performance can be raised by on-chip circuitry (amplification and filtering). As a result, it has been demonstrated in a previous study that a simple cantilever based FSBM device can perform z-axis (out of plane) acceleration measurements with acceptable performances [1]. For in-plane measurement (x,y), an interesting approach is to use convection heat transfer principles [2]. Thermal accelerometers have already been reported and even commercialized. However, few information regarding behavioural modelling, optimization issues, and their integration on CMOS technology is available.

The purpose of this study is to provide information concerning the integration of convection heat transfer accelerometers on CMOS. A test-chip has been designed and characterized. Based on experimental results, FEM testbenches and simulations are validated.

TEST-CHIP DESIGN AND MANUFACTURING

The designed sensor is based on three polysilicon resistors, each being embedded in a multilayer CMOS bridge: a heating resistor flanked by two temperature detectors as shown in figure 1. With acceleration in the chip plane, the temperature profile created by the heater becomes asymmetric and the temperature gradient is converted into a resistance variation in the detectors.

The sensor has been fabricated in an AMS 0.8µm CMOS technology. The detectors are arranged in a Wheatstone bridge and connected to an on-chip instrument amplifier of programmable gain (20\100\1000). In fig. 1, the dimensions of the heating bridge are 40×1040µm and the dimensions of the detectors are 30×700µm. The distance between the heater and the sensors is 200µm. An aluminum pad is designed in the middle of the heater to make the temperature uniform along the bridge. A smaller device (about 30%) has also been designed to enable a parametric study.

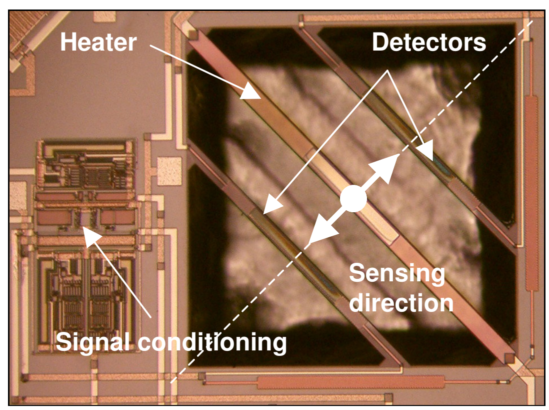


Fig. 1. Picture of the sensor.

EXPERIMENTAL RESULTS

Fig. 2 shows the sensitivity of the sensor to inclination (±1g). This characteristic is obtained using a supply power of 35mW in the heater. In this condition, the heater temperature reaches 438°C (deduced from the polysilicon temperature coefficient of resistance (TCR)). The temperature difference across the detectors is calculated from the output voltage (taking into account the Wheatstone bridge and the amplifier gain). We obtain about 1.53°C/g. Finally an angular resolution of about 1.7° (around 90°) is observed (SNR=1), corresponding to a resolution of 30mg.

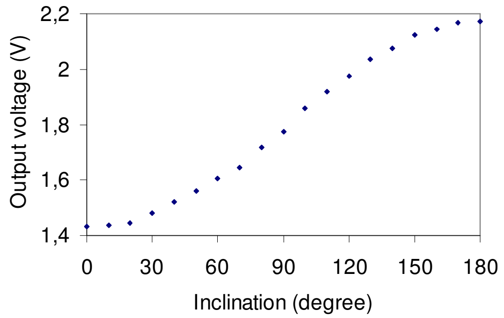


Fig. 2. Sensor output under inclination (Gain=1000).

To study the sensor response to both shocks and vibrations, the packaged test chip has been attached to a one-axis shaker which can apply sine-wave vibrations with magnitudes ranging from 0.1g up to 20g at various frequencies up to 200Hz. The experimental setup is shown in figure 3.

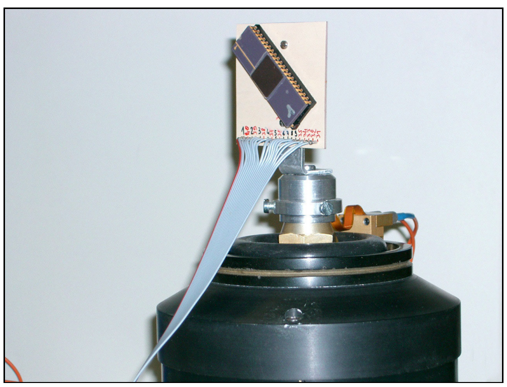


Fig. 3. Picture of the test chip attached to the shaker.

The sensor output signal amplitude under a sinusoidal acceleration of 40Hz is presented in Fig. 4. The measured sensitivity is 375mV/g. The sensor exhibits a good linearity up to 10g. The linearity error as a percentage of full scale is smaller than 2%. Non linearity is expected for elevated accelerations because the temperature difference across the detectors can not exceed T_{heater}-T_{room}. Experimentally, non-linearity appears much before this physical limit.

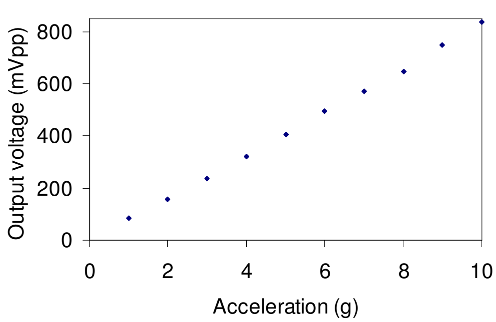


Fig. 4. Sensor output under sinusoidal acceleration (Gain=100).

MODELLING AND THERMAL SIMULATIONS

We have simulated the convection heat transfer in the sensor with the FEM simulator ANSYS®. Results obtained with a 2D approach, representing the sensor cross-section (accordingly to the dashed line in fig.1) are presented. The solver is FLOTRAN CFD and meshing makes use of the FLUID 141 element. The velocities are obtained from the principle of momentum conservation, the pressure comes from the mass conservation and the temperature is deduced from the energy conservation. Geometrical parameters are consistent with the test-chip sensor depicted in Fig. 1. The cavity depth is 300 µm.

Fig. 5 illustrates the temperature distribution due to an acceleration of 200g towards the left. With this model we find a difference of temperature on the detectors of 1.37°C for 1g acceleration and a heater temperature of 438°C. This result is in good accordance with the characterized temperature difference mentioned above (1.53°C/g). For the same model and load, Fig. 6 displays the air velocity vector (convection) in the device cavity.

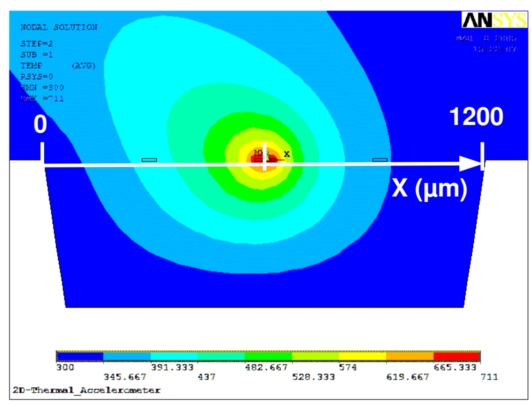


Fig. 5. Temperature distribution for an acceleration of 200g towards the left.

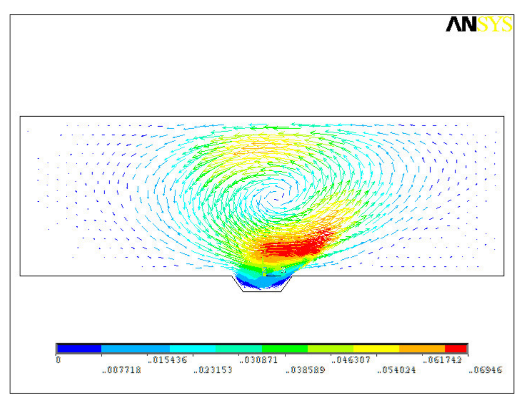


Fig. 6. Fluid velocity vectors in the cavity

Heater and detector optimization

The graph of Fig. 7 is obtained by substracting the temperature profile along the X-axis (see Fig. 5) obtained under 1g acceleration from the same temperature diagram obtained without any acceleration. The temperature is raising, due to the acceleration, in the left part of the cavity, while the right part gets colder. The center part of the graph where the difference of temperature is zero, corresponds to the heater position. This analysis helps us to determine the optimum position of the detectors since they have to be located where the difference of temperature is maximum. It has been found that the optimum position of the detectors is approximately half–way between the heater and the cavity limit (280µm from the cavity limit in our case). At this location, the temperature difference of the detectors is about 1.58°C.

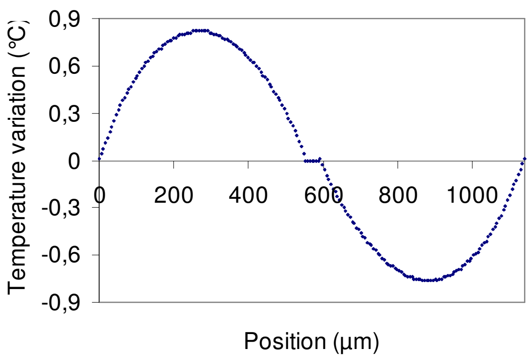


Fig. 7. Temperature difference along x-axis for an acceleration of 1g towards the left.

Obviously, the sensitivity of the sensor also depends on the heater temperature. Fig. 8 plots the sensor output signal as a function of the heater temperature (at a constant room temperature). The sensitivity is only limited by the electrical power allowed in the suspended heater structure.

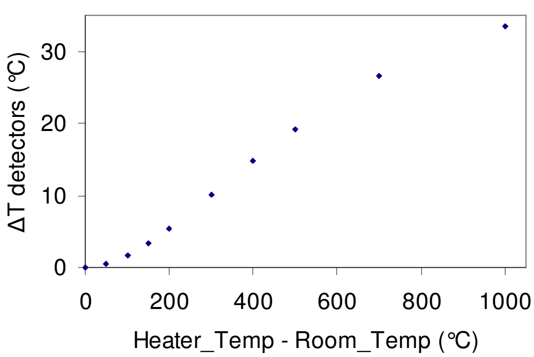
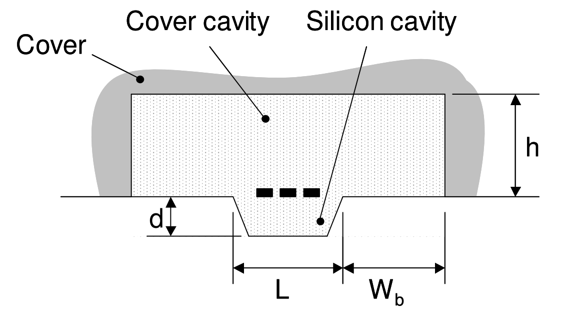


Fig. 8. Sensor output signal versus heater temperature for a 10g acceleration.

Effect of the package

As shown in Fig. 6, the maximum heat exchange occurs in the top part of the device. Consequently, the volume of the package plays an essential role.

First order results (Fig. 9) demonstrate that heat exchange increases with the cavity volume. However, this phenomenon reaches a limit for big cavities. From the simulations, a cavity cross section $A = h(L + 2W_b)$ of 200mm², would give the same performance as an open (unsealed) package.



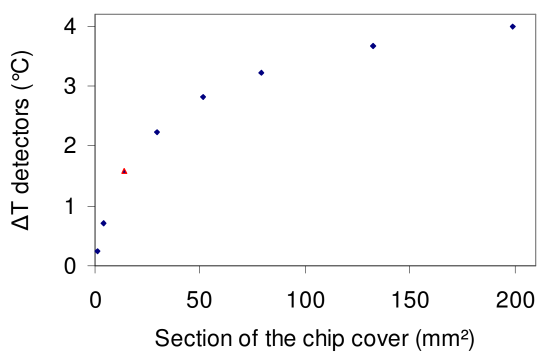


Fig. 9. Effect of the cover cavity section area
$A = h(L + 2W_b)$
(under 1g acceleration)

In Fig. 8, the velocity vector plot shows that the convection phenomenon produces a rotational movement of the fluid in the cavity. The radius of this convection movement is basically limited by the closer cavity boundary (the ceiling in our case). The aspect ratio of the cavity h/W_b has therefore been studied.

In Fig. 10, the sensor output is plotted as a function of the cavity width (W_b) for three different heights (h). For a given height, it is not necessary to increase the width of the package behind a given limit. We have established that the optimum shape is ruled by :

$$h = W_b + \frac{L}{2}.$$

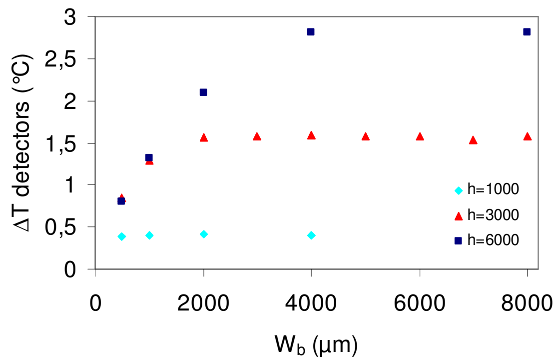


Fig. 10. Effect of the cover aspect ratio

Effect of the silicon cavity

As it was described in [3], the silicon cavity limits the thermal boundary layer and the convection phenomena in the bottom region of the fluid. Therefore the volume of the packaging influences the convection in the top region and has a large consequence on the sensor sensitivity. This sensitivity would be improved by the design of a larger cavity (using back-side etching for instance). Doing-so, the horizontal plane of maximum temperature difference would be lower and closer to the plane of the detectors (horizontal symmetry around detector plane would be ideal).

CONCLUSION

This study investigates the integration of thermal accelerometers on CMOS. Convection heat sensing provides a solution for in-plane acceleration measurement. As a complement of a piezoresisitive seismic mass, it enables low-cost 3D sensing system.

The paper presents both characterization and simulation results. The fabricated prototype exhibits a sensitivity of 375mV/g with a resolution of 30mg. With the support of experimental results, Finite-Elements Models have been developed and validated.

Simulations are used to study the effects of geometrical parameters on both sensor and package. Design rules for the location of the detectors and for the package dimensioning are then sketched.

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