# FEM Study of a 3-axis Thermal Accelerometer Based on Free Convection in a Microcavity

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## ABSTRACT

Thermal convective accelerometers are based on heat transfer in a fluid-filled cavity. The principle is well known and the first MEMS implementations were reported in the late 90's. Since that time, many single-axis or dual-axis sensors were reported. The device presented in this paper is the first reported 3-axis sensor manufactured in a standard CMOS technology. Therefore, the goal of this study is to demonstrate the feasibility of a third sensitive axis on a single device and to provide MEMS designers with a compact model and the main parameters that govern the sensitivity.

***Keywords***: MEMS, convective accelerometer, thermal sensor, FEM simulation

## 1 INTRODUCTION

Thermal convective accelerometers are based on heat transfer and fluid motion induced by free convection in a sealed cavity filled with a gaz. A heater is located at the center of a cavity and two thermal sensors are placed symmetrically on both sides to define a sensitive axis. Without acceleration, the temperature profile is symmetric along this axis and the two detectors measure the same temperature. When an acceleration is applied on this axis, free convection and fluid motion deform the thermal profile and temperature sensors measure a differential temperature. This principle is known for many years, since it was patented in the 40's [1], but the first MEMS implementations, obtained with bulk micromachining of the silicon substrate, were reported in 1997-98 [2, 3]. These early implementations were single-axis accelerometers and many other implementations were reported in the literature the years after [4-7]. A picture of a two-axis sensor was also presented in [2] but without experimental measurements. Experimental results obtained on a two-axis sensor are reported in [8-9] and a product is commercialized by MEMSIC[@] since 2002 [10].

For all these sensors, standard microelectronics technologies are used. Since these technologies are commonly planar (or 2D), heater and temperature detectors are then in the same plane and composed of thin film layers deposited on the silicon substrate. Due to this constraint, only in-plane accelerations may be measured and a third sensitive axis seems difficult to obtain as it is impossible to measure a differential temperature induced by a perpendicular out-of-plane acceleration. Then, the only reported 3-axis convective accelerometers [11-12] have been manufactured in a non-conventional technology: surface-micromachined polymer structures are fabricated on top of a CMOS die and then assembled out-of-plane using the tip of a wire-bonder. Finally, a 3-axis sensor is commercialized by MEMSIC but few information can be found about its working principle. Therefore, the goal of this paper is to demonstrate the feasibility of a simple out-of-plane sensitive axis using a standard CMOS technology.

In section 2, device under study and three-axis working principle are presented. Then, settings of FEM simulations are presented. In the last section, simulation results are presented and key parameters that govern the sensitivity are given.

## 2 DEVICE UNDER STUDY

Figure 1 presents the device under study. Its topology is similar to the one of a dual-axis accelerometer. The silicon cavity is easily obtained from the front side bulk micromachining of a CMOS die. The bottom part of the fluid-filled cavity consists of an etched silicon cavity and the top part is the die package.

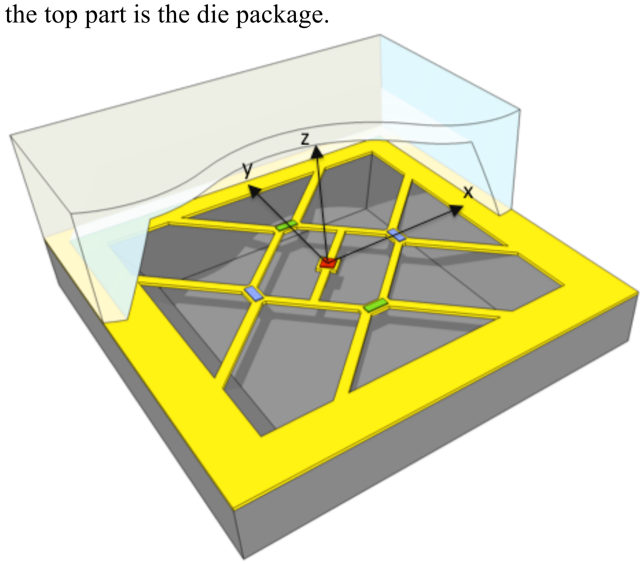


Figure 1: 3D sensor representation.

Suspended elements are composed of the back-end layers of the CMOS process and are all in the same plane. The heater is located at the cavity center and thermal sensors are placed symmetrically on both sides to define two sensitive axis ($x$ and $y$) in the wafer plane. Without acceleration, the temperature profile is symmetric along $x$ (or $y$) axis; $x$ and $y$ detectors measure the same temperature, called common mode temperature ($T_{CM}$). When an acceleration is applied on $x$ (or $y$) axis, the sensors measure a differential temperature. Since, it is impossible to add two detectors out-of-plane with this technology, we suggest measuring the common mode temperature of $x$ and $y$ detectors to deduce the out-of-plane acceleration.

Table 1: Parameters' nominal values used for all simulations

| Parameter | Symbol | Value |
|---|---|---|
| Ambient temperature | $T_0$ | 300K |
| Heater temperature | $T_H$ | 600K |
| Heater width | $w_H$ | 40μm |
| Silicon cavity width | $w_{Si}$ | 1mm |
| Silicon cavity depth | $h_1$ | 300μm |
| Package height | $h_2$ | 1mm |

## 3 FINITE ELEMENT MODELING

A behavioral model of the sensor sensitivity was proposed in [2]. For in-plane acceleration, sensitivity (or differential temperature measured by a detectors' pair) is assumed to be proportional to the Grashoff number:

$$\Delta T_{det} \quad \propto \quad a\,\frac{\rho^2\,\beta\;\Delta T_H\;l^3}{\mu^2} \tag{1}$$

with $a$, the acceleration along a sensitive axis, $\rho$, the gas density, $\beta$, the gas coefficient of expansion, $\Delta T_H$, the heater temperature (referenced to ambiant), $\mu$, the gas viscosity and $l$, a characteristic dimension of the sensor.

This model represents the overall behavior of the sensor but finite element modeling is essential to refine the behavioral model of in-plane sensing. Therefore, an ANSYS model of the sensor was implemented [7,13] and validated through experimental results obtained with a single-axis prototype. To reduce simulation time, 2D model is used by meshing the sensor cross section ($xOz$ or $yOz$ plane) with FLUID 141 elements of ANSYS library. The meshing size is adjusted to improve the elements density near the critical region (around the heater and detectors) and solver is FLOTRAN CFD. Fluid is assumed to be compressible but not turbulent and its thermophysical properties are assumed temperature-dependent. The equation of state is the ideal gas law while radiation is neglected. The boundary conditions are isothermal smooth walls at $T_{heater}$ for the heater and $T_0$ for the silicon cavity and package. Velocities, pressure and temperature are obtained respectively from the conservation principles of momentum, mass and energy. The nominal values of parameters used for all simulations are summarized in table 1.

## 4 FEM SIMULATION RESULTS

Before studying the third sensitive axis of the device, the temperature distribution without acceleration is simulated for an air-filled cavity at atmospheric pressure and nominal parameters of table 1. Simulation results are presented in figure 2. First, the ANSYS picture shows that the hot bubble created by the microheater does not extend far from the silicon cavity. In fact, package width was chosen high enough to ensure that the simulation result is independent of this parameter. As for in-plane acceleration [7], a width equal to $w_{Si}$ + 2 $h_2$ was found to be sufficient. Second, the curve in figure 2 shows the temperature profile along the x (or y) axis or the common mode temperature according to the detector distance.

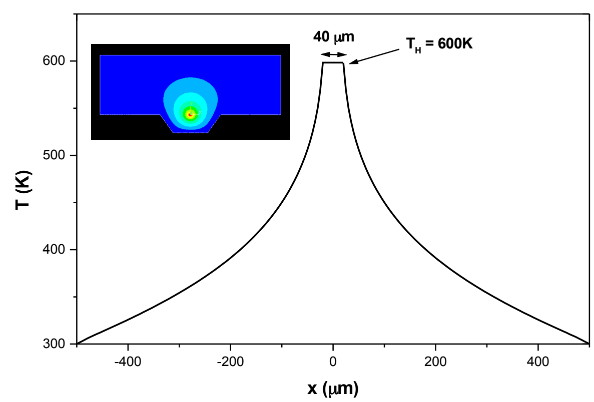


Figure 2: Temperature profile along x (or y) axis without acceleration (obtained with nominal parameters of table 1)

$X$-axis sensitivity for a positive acceleration of 1g along the $x$ axis is presented in figure 3 as a function of the detectors distance from the cavity center. Note that the result is the same for $y$-axis sensitivity for symmetry reason. This result shows that the sensitivity is equal to 0 at the silicon cavity center and boundary due to the isothermal FEM boundary conditions. The optimum distance for the detectors location $d_{xy}$ is about 230-235μm and the corresponding simulated sensitivity is equal to 255mK/g. Using resistive sensors having a temperature coefficient of resistance of $10^{-3}$/K, arranged in a full Wheatstone bridge configuration, the output voltage would be 841μV/g for a supply voltage of 3.3V.

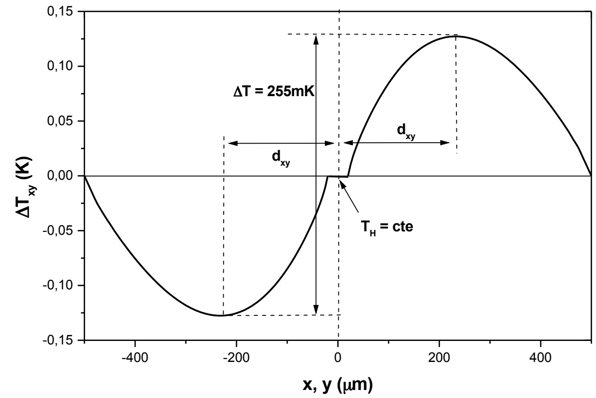


Figure 3: In-plane sensitivity or temperature variation along x (or y) axis with a positive acceleration of 1g according to the x axis (or y axis respectively), $d_{xy}$=230-235µm

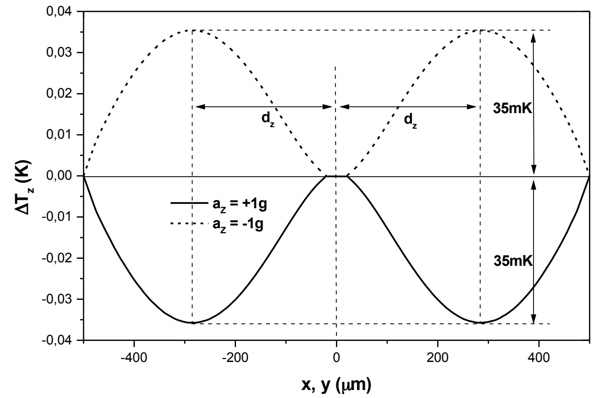


Figure 4: Out-of-plane sensitivity or temperature variation along x and y axis with accelerations of +1g (solid line) and -1g (dashed line) according to the z axis, $d_z$=280-290µm

For out-of-plane acceleration, the variation of the temperature of *x* and *y* detectors according to their distance from the cavity center is plotted in figure 4. As previously, sensitivity is equal to 0 at the silicon cavity center and boundary. However, temperature variations are now symmetric for positive and negative coordinates. Therefore, it is as expected a variation of the common mode temperature that is observed. Moreover, the sign of this variation is well correlated to the acceleration direction. This change of sign is due to the asymmetry of top (i.e. package) and bottom (i.e. silicon) parts of the cavity. This is illustrated in figure 5 where the phenomenon is exaggerated for a better comprehension. If the two cavity volumes are identical, the hot bubble (represented in light grey) is symmetric across the *xOy* plane without acceleration. Then, if a positive or negative z-acceleration is applied, the bubble is stretched in the corresponding z direction but its cross section is identical in the sensing plane *xOy* for both acceleration directions. Therefore, a decrease of the common mode temperature is observed in both case ; out-of-plane acceleration is well detected but its sign is unknown. Phenomenon is different if the cavity is asymmetric. In this case, the initial shape of the hot bubble is not symmetric across the sensing plane. Therefore, a positive acceleration stretches the hot bubble in the z direction and a temperature decrease is observed in the sensing plane. On the other side, a negative acceleration tends to flatten the hot bubble leading to a temperature increase of the detectors. Finally, figure 4 shows an optimum distance $d_z$ of *x* and *y* detectors slightly higher for the measurement of out-of-plane accelerations than for in-plane; about 280-290 µm instead of 230-235µm. The corresponding simulated sensitivity is equal to 35mK/g.

For the parameters nominal values and the optimal distance $d_z$, sensor response (i.e. common mode temperature variations of *x* and *y* detectors) is plotted according to out-of-plane acceleration in figure 6. A good linearity is observed up to 5g.

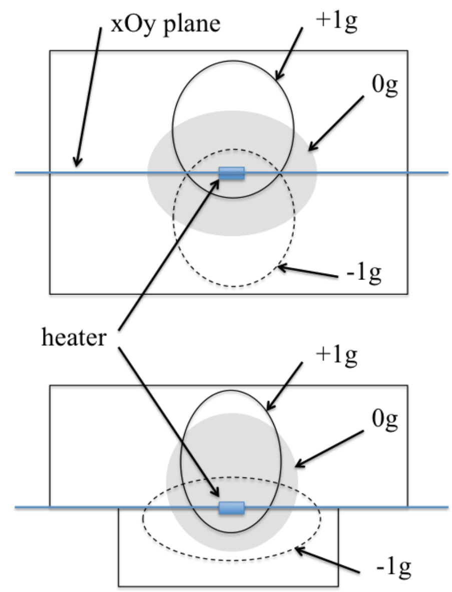


Figure 5: Illustration of the effect of the cavity asymmetry on the initial shape and deformation of the hot bubble.

As for in-plane acceleration [7,13], simulation results have shown that the out-of-plane sensitivity $S_z$ is related to heater temperature, cavity depth, cavity width or package heigh. Since the sensor working principle is closely linked to the cavity asymmetry, figure 7 presents the out-of-plane sensitivity at the optimal distance $d_z$ as a function of the package height $h_2$. It shows that sensitivity may vary of two orders of magnitude when the package height varies from 300 to 5000µm. For higher values, it seems that sensitivity saturates because the micro-heater is too small to disturb the fluid at a very large distance. For a package height equal to the silicon cavity depth, $S_z$ is close to zero. As a matter of fact, it was observed in previous study on in-plane sensitivity, that the cavity size is too small to allow the hot bubble to deform. Therefore, the velocities of fluid motion are small and the shape of hot bubble is only governed by heat conduction.

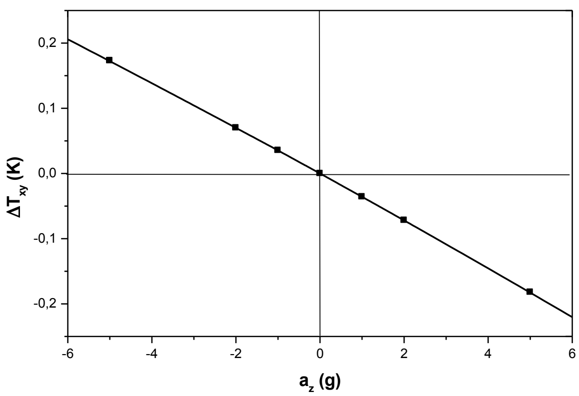


Figure 6: Out-of-plane response at the optimal distance $d_z$

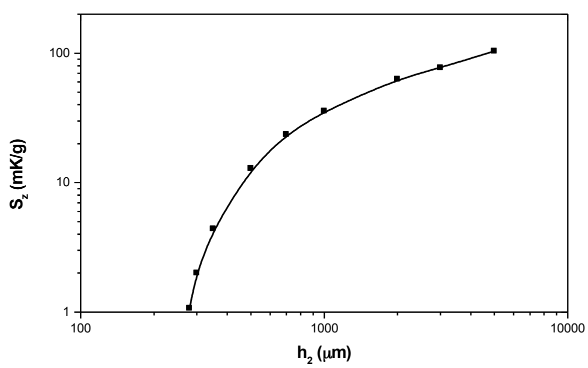


Figure 7: Out-of-plane sensitivity at the optimal distance $d_z$ according to the package height $h_2$

## 5 CONCLUSION

This paper has shown that a 3-axis accelerometer may be obtained with a standard technology. Cavity asymmetry was found to be a critical parameter for final sensitivity in the out-of-plane direction. This study allows us to design a 3-axis thermal convective accelerometer with its conditioning electronics using a standard CMOS technology (figure 8). This prototype is under manufacturing and first experimental results should be presented soon.

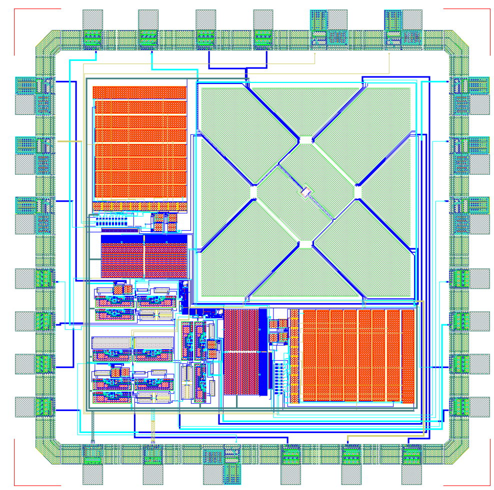

Figure 8: Layout of the silicon prototype (CMOS 0.35μm)

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