Design of a Dual Axis Thermal Accelerometer using Single Axis Structure

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Abstract— **In this paper, we are reporting a dual axis thermal accelerometer using a single axis structure. The structure of the device is very simple and can be easily realized. The device contains a bridge shaped heater with four temperature sensors to detect x and y axis acceleration. The device is designed in 3D and simulated using FEM simulator. In this accelerometer, when acceleration is applied along x-axis its sensitivity is 1.07 K/g and along y-axis 0.23 K/g when the heater temperature is 610K. However, this difference in sensitivity between two axes can be improved through on-chip amplifiers. Thus, we believe that this work may lead to a simpler high sensitive dual axis thermal accelerometer.**

Keywords—thermal accelerometer; heater; sensitivity

Introduction

The accelerometers are used to detect acceleration or tilt of a device. The acceleration is detected by deformation or displacement of solid proof mass. According to different working principle, there are different types of accelerometers, e.g. capacitive [1], piezo-electric [2], piezo-resistive [3] to name a few. Such accelerometers require solid proof mass to detect acceleration. This solid proof mass creates mechanical instability and reduces shock survival rating. These accelerometers are compact if developed in Micro Electro Mechanical Systems (MEMS) - Complementary Metal Oxide Semiconductor (CMOS) platform. However, it is costly to integrate such devices because of the presence of their solid proof mass.

There is another type of accelerometer, known as thermal accelerometer [4], which does not contain any solid proof mass. Here, a heated gas bubble is used as the proof mass of the accelerometer. Thus, it is easier to integrate with CMOS substrate. Such sensors can have interface electronics on the same silicon die, which reduces the fabrication cost and system complexity.

Despite the above advantage, the thermal accelerometers have some disadvantages; e.g., the sensitivity of this type of accelerometer is poor especially for dual and triple axis accelerometers. In literature, it is found that the sensitivity of the single axis accelerometers is higher compared to dual axis accelerometers [10][11]. This paper presents a dual axis thermal accelerometer whose structure is close to that of a single axis accelerometer. The higher sensitivity of the single axis accelerometer is utilized in this device. The heater and sensors structures are very simple and can be easily implemented in CMOS-MEMS process. The device is designed in 3D and simulated in FEM simulator COMSOL Multiphysics. The simulated results are discussed in detailed and also compared with other thermal accelerometers in the following sections.

Operating Principle

A dual axis thermal accelerometer consists of a heater and four temperature sensors. They are placed within an etched cavity of silicon substrate. The cavity is generated by front side bulk micromachining. The cavity provides thermal insulation for both heater and temperature sensors. Otherwise, the heat is conducted from heater to the sensors. The heater is placed symmetrically at the center of the cavity. The temperature sensors are also placed symmetrically at the opposite sides of the heater. The heater is heated to higher temperature compared to ambient temperature. Thus, the surrounding fluid is also heated up. The temperature profile of thermal accelerometer generated by heater is shown in Fig. 1. At zero acceleration, there is no temperature difference between the temperature sensors as they are equally spaced from the heater. When an acceleration is applied, the temperature contour is deformed and a differential temperature ΔT is detected by the sensors. This temperature difference is proportional to the applied acceleration. This differential voltage (corresponding to temperature difference) is detected by an instrumentation amplifier and processed using signal conditioning circuit.

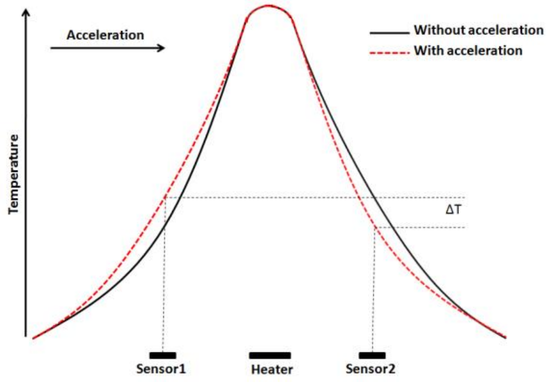


Figure 1. Thermal accelerometer temperature profile.

Device Sensitivity

The working principle of thermal accelerometer is based on the natural convection of fluid. The sensitivity of the thermal accelerometer is proportional to the Rayleigh number[12].

The sensitivity S of the device can be expressed as:

$$S \propto Ra\, f(R) \Delta T \qquad (1)$$

where Ra is the Rayleigh number, $f(R)$ is a function of device geometry and ΔT is the temperature difference between heater and the bulk silicon temperature.

Rayleigh number is defined as the product of Grashof number(Gr) and Prandtl number(Pr).

$$Ra = Gr.Pr \qquad (2)$$

Fluid flow of the natural convection is governed by Grashof number which is the ratio of the buoyancy force to the viscous force. Prandtl number is the ratio of momentum diffusivity to thermal diffusivity which determines whether the heat transfer is dominated by conduction or convection. *Ra*, *Gr* and *Pr* are all dimensionless numbers.

Device Design

A 3D view of our device is shown in Fig. 2. A heater of bridge shaped has been suspended in the cavity along the corners. The length and width of the heater are 1414 µm and 42 µm, respectively. Four temperature sensors are suspended in parallel with the heater. The sensors are placed 235 µm away from the heater where the maximum sensitivity can be achieved. The sensor length and width are 350 µm and 10 µm, respectively. The thickness of the heater and sensor layers have been considered as 2 µm. The polysilicon layer is used for heater and temperature sensors. The fluid has been considered as air. For simulation, the x-axis is set perpendicular to the heater bridge and y-axis along the heater length.

Generally, the cavity of the thermal accelerometer is realized using anisotropic wet etching. Here, the area of the cavity at heater surface was taken as 1000 µm × 1000 µm and the lower plane of the cavity is considered as 800 µm × 800 µm. An air cover of dimension 2mm × 2mm × 2mm has been placed above the accelerometer as shown in Fig. 2. The air cover protects the air of the chamber from unwanted flow.

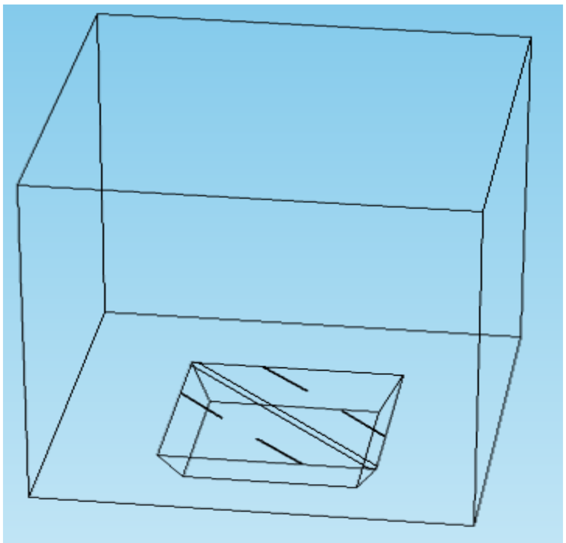


Figure 2. 3D view of the thermal accelerometer.

FEM Simulation

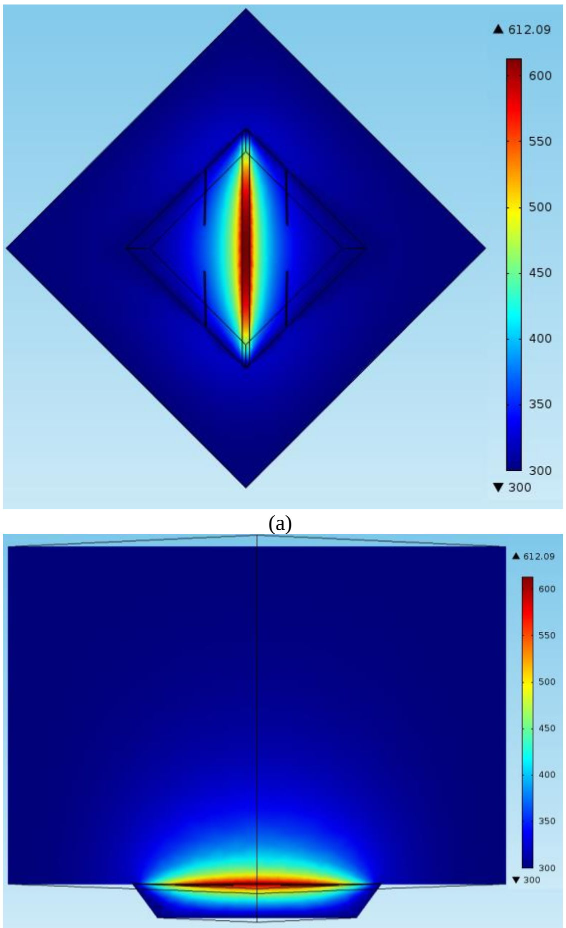
The analytical model used for thermal accelerometer is very simple. Complex structures cannot be solved using analytical model. So, a 3D model has been designed and simulated using standard FEM (Finite Element Method) simulator, COMSOL Multiphysics [13]. This FEM model allows optimizing heater structure and sensor positions. The thermal effect was simulated using *joule heating* physics and the acceleration effect on the device was simulated using *laminar flow* physics.

The properties of the materials (e.g. thermal conductivity, density, heat capacity) were considered as temperature dependent and varies with temperature. A constant current was supplied to the heater to generate heat.

The temperature of the cavity walls and outer walls of air cover were set as 300 K. The acceleration was applied along x and y axes using *volume force* of *laminar flow* physics. The mesh elements were generated in *tetrahedral* mode. Higher numbers of mesh elements were generated in the critical regions (heater and sensors regions) to get more accurate results. The results were studied on *stationary* mode i.e. steady state condition.

Result and Discussion

Fig. 3 and Fig. 4 shows the temperature contours when 10g and 30g acceleration were applied along positive x and y axes, respectively. As the sensitivity of the y-axis is lower compared to x-axis, temperature contour with higher acceleration along y-axis is shown, so that the deformation of thermal bubble due to acceleration can be seen in the figure. The heater was supplied with constant current and due to joule heating effect, the polysilicon heater resistor temperature increases. The highest temperature occurs at the middle of the heater and decreases towards cavity in parabolic fashion. In both the cases, the heater temperature is kept almost equal around 615 K. It can be seen in top view of Fig. 5(a) that the temperature contour is slightly shifted to the left side of the cavity.

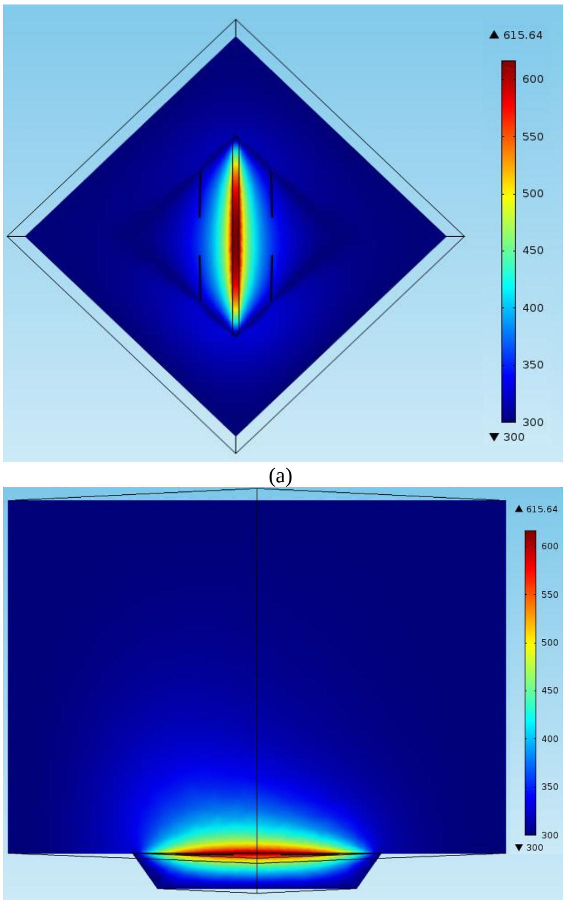


(a)

(b)

Figure 3. Temperature contour with 10g acceleration along x-axis (a) top view (b) side view.

In Fig. 4, it can be seen that the temperature contours are shifted towards left in side view. The sensitivity of the x-axis was much higher than the y-axis. Along x-axis, the air directly flows from heater to the sensor. So, the temperature gradient is much higher. On the other hand, along y-axis sensors the temperature difference occurs due to the air flow parallel to the heater. The temperature decreases rapidly from heater to the sensors and for that reason, the sensitivity was much lower in y-axis compared to the x-axis.



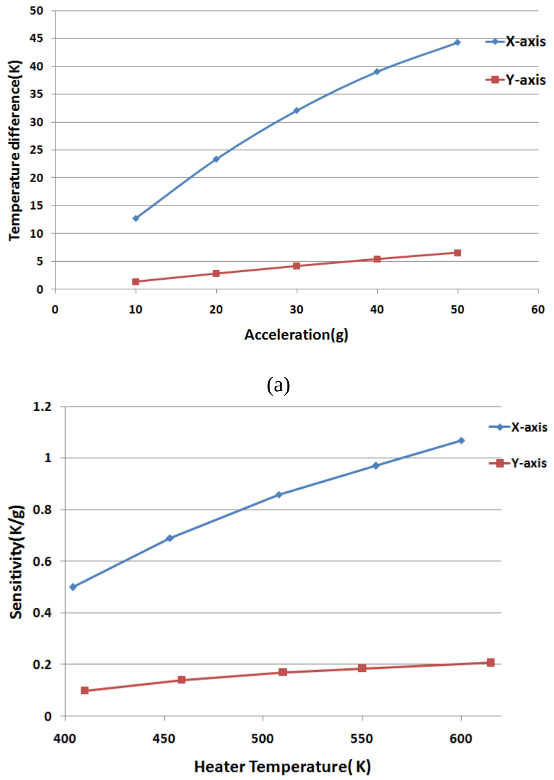
(a)

(b)

Figure 4. Temperature contour with 30g acceleration along y-axis (a) top view (b) side view.

The temperature difference with acceleration is plotted in Fig. 5(a). The temperature difference is directly proportional to the applied acceleration. From the figure, it can be observed that the temperature difference in x-axis is much higher than y-axis.

Heater temperature is another influencing factor for sensitivity. When the heater temperature is increased, the sensitivity also increases proportionally as shown in Fig. 5(b). When the heater temperature is around 615K the x-axis sensitivity is 1.07 K/g and y-axis sensitivity is 0.23 K/g.



(a)

(b)

Figure 5. (a)Temperature difference Vs. accelerarion, (b) Sensitivity Vs. heater temperature.

In our device, the sensitivity along x-axis. comparable to single axis accelerometer and y-axis sensitivity is close to dual axis accelerometer. Thus, we can conclude that our reported structure can be used as dual axis thermal accelerometer although the structure is similar to single axis accelerometer and much simpler than dual axis.

Conclusion

This paper presents a dual axis thermal accelerometer whose structure is close to that of single axis structure. The higher sensitivity concept of the single axis accelerometer has been utilized to design this accelerometer, although two additional temperature sensors were included so that dual axis acceleration can be detected. The accelerometer is designed in 3D and simulated in commercial FEM simulator. The x and y axis sensitivity are found to be 1.07 K/g and 0.23 K/g, respectively when the heater temperature is 610K. Hence, we believe such accelerometer structure will be useful in future to develop highly sensitive, simpler dual axis and triple axis thermal convective accelerometer.

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