Three-axis piezoresistive accelerometer with uniform axial sensitivities

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***Abstract*—A three-axis piezoresistive accelerometer which has uniform sensitivities to three axes was developed using MicroElectroMechanical Systems (MEMS) technology. This sensor which is made of a heavy proof mass and four long beams allow us to obtain high sensitivities by reducing the resonant frequencies. Uniform axial sensitivities with small cross axis sensitivity could be obtained by a three-dimensional sensor structure.**

Keywords-MEMS, accelerometer, piezoresistance, simulation

I. INTRODUCTION

Micro-machined inertial sensors that consist of accelerometers and gyroscopes have a significant percentage of silicon based sensors. The accelerometer has got the second largest sales volume after pressure sensor [1]. Accelerometer can be found mainly in automotive industry, biomedical application, household electronics, robotics, vibration analysis, navigation system, and so on. Various kinds of accelerometer have increased based on different principles such as capacitive, piezoresistive, piezoelectric, and other sensing ones. The concept of accelerometer is not new but the demand from commerce has motivated continuous researches in this kind of sensor in order to minimize the size and improve its performance.

As we know, the realistic applications create a huge motivation for the widely research of MEMS based sensors, especially accelerometer. In this modern world, applications require new sensors with smaller size and higher performance. In practice, there are rare researches which can bring out an efficient and comprehensive methodology for accelerometer designs.

II. LITERATURE SURVEY AND LIMITATIONS OF EXISTING METHODS

T. Mineta et al. [2] presents design, fabrication, and calibration of a 3-DOF capacitive acceleration which has uniform sensitivities to three axes. However, this sensor is more complex than piezoresistive one and is not economical to fabricate with MEMS technology.

In 2004, Dzung Viet Dao et al. [3] presented the characterization of nanowire p-type Si piezoresistor, as well as the design of an ultra small 3-DOF accelerometer utilizing the nanowire Si piezoresistor. Silicon nanowire piezoresistor could increase the longitudinal piezoresistance coefficient π_l [011] of the Si nanowire piezoresistor up to 60% with a decrease in the cross sectional area, while transverse piezoresistance coefficient π_t [011] decreased with an increase in the aspect ratio of the cross section. Thus, the sensitivity of the sensor would be enhanced.

In 1996, Shin-ogi et al. [4] presented an acceleration sensor fabricated on a piezoresistive element with other necessary circuits and run parallel to the direction of acceleration. The accelerometer utilizes lateral detection to obtain good sensitivity and small size. The built-in amplifier has been formed with a narrow width, and confirmed operation.

In 1998, Kruglick E.J.J et al [5] presented a design, fabrication, and testing of multi-axis CMOS piezoresistive accelerometers. The operation principle is based on the piezoresistive behavior of the gate polysilicon in standard CMOS. Built-in amplifiers were designed and built on chip and have been characterized.

In 2006, Dzung Viet Dao et al [6] presented the development of a dual axis convective accelerometer. The working principle of this sensor is based on the convective heat transfer and thermo-resistive effect of lightly-doped silicon. This accelerometer utilizes novel structures of the sensing element which can reduce 93% of thermal-induced stress. Instead of the seismic mass, the operation of the accelerometer is based on the movement of a hot tiny fluid bubble from a heater in a hermetic chamber. Thus, it can overcome the disadvantages of the ordinary "mechanical" accelerometers such as low shock resistance and complex fabrication process.

In this paper, a miniaturized piezoresistive three-degree of freedom accelerometer with uniform axial sensitivities has been developed using MEMS (Micro electromechanical systems) technology. We proposed a flexure configuration in order to meet requirements of small cross-axial acceleration, high and linear sensitivity. The overall chip dimension is $1.5 \times 1.5 \times 0.5$ mm^3 (L×W×T). Twelve piezoresistors are diffused on the surface of beam structure. Three simple Wheatstone bridges are formed directly on this sensor by interconnecting these piezoresistors to sense three components of acceleration independently. A completed simulation and analysis were performed by utilizing ANSYS software. The obtained uniform sensitivity is 0.15 mV/V/g.

III. THE PROPOSED 3-DOF ACCELEROMETERS

The 3-DOF accelerometer always requires small cross-axial acceleration, high and linear sensitivity. We proposed a flexure configuration that is shown in Fig. 1 in order to meet these critical characteristics [11].

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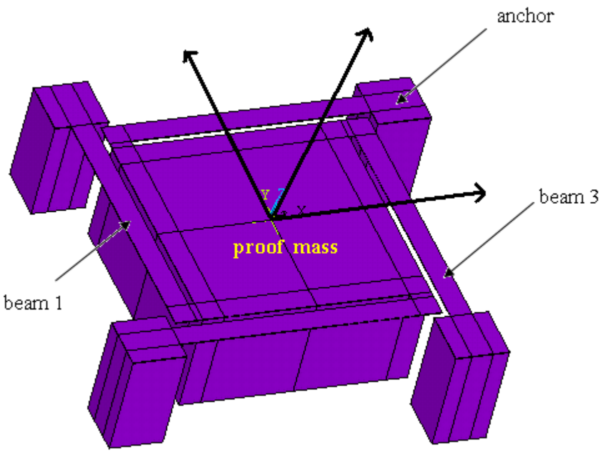


Figure 1. 3D model of the 3-DOF piezoresistive accelerometer

When an external acceleration is applied to the sensor, the proof mass is deflected. The vertical acceleration component (*AZ*) causes the mass to move up and down. The second type of motion is caused by the transversal accelerations (*AX* and *AY*). The deflection of the proof mass causes stress variations on the four beam surfaces. This can be measured by the Wheatstone circuit formed by diffused piezoresistors. Four Wheatstone bridge circuits were built by interconnecting twelve p-type piezoresistors [7, 8].

These piezoresistors were aligned with the crystal directions <110> and <1 $\bar{1}$ 0> of n-type silicon (100). In the silicon material, there are only three independent piezoresistive coefficients π_{11}, π_{12} and π_{44}. The longitudinal piezoresistance coefficient π_l is defined in the case the stress parallels with the direction of the electric filed and current density. Similarly, the transverse piezoresistance coefficient π_t is defined in the case the stress is perpendicular with the direction of the electric filed and current density. In directions <110> and <1 $\bar{1}$ 0> of n-type silicon (100), these coefficients can be expressed as:

$$\pi_l = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44}) \quad \pi_t = \frac{1}{2}(\pi_{11} + \pi_{12} - \pi_{44}) \tag{1}$$

From simulation results in section 3, we would found that two normal stresses are rather smaller when comparing to the longitudinal stress σ_l. The total resistance change is given by the following equation:

$$\frac{\Delta R}{R} \approx \pi_l \sigma_l \tag{2}$$

The mechanical sensitivities of each components of acceleration can be respectively expressed:

$$S^i_{stress} = \frac{\sigma^i}{a_i} \qquad i = X, Y, Z \tag{3}$$

Where S^i_{stress} is the mechanical sensitivity and σ^i is longitudinal stress induced by the acceleration i^{th} component a_i.

The electronics sensitivity can be given by:

$$S_i = \frac{V_{out}}{a_i} = \frac{\Delta R}{R} V_{in} = \pi_l S^i_{stress} V_{in} \tag{4}$$

Where S_i and V_{out} are the sensitivity to the i^{th} acceleration component and output voltage, respectively. The longitudinal stress σ^i in Equ. (3) obtained from the stress analysis by utilizing ANSYS software. This value is stress at the center point of piezoresistors and on the surface of the beam.

From Equ. (4), it is obvious that the sensitivities in three axes can be uniform if the twelve piezoresistors are diffused at specific locations that can lead to the uniform longitudinal stresses σ^i.

IV. Design and Simulation Using ANSYS

The finite element method (FEM) is applied to perform analyses of the stress distribution in the flexure beams. Based on the stress distribution, piezoresistors are placed to eliminate the cross-axis sensitivities and to maximize the sensitivities to three components of acceleration. The finite element model of the sensing chip was analyzed by using ANSYS software. The boundary condition with the fixed beams (i.e. anchor) is applied.

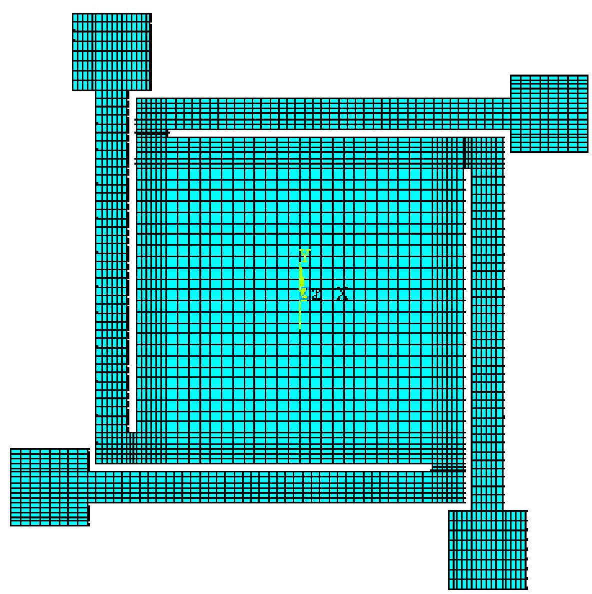


Figure 2. The dense mesh generation of the FEM model.

Fig. 2 shows the mesh generation for FEM analysis and Fig. 3 shows the Von Mise stress causef by the AZ acceleration. Simulated results show that the stress distribution in the direction along the beam (the longitudinal stress) is much larger than that of the transverse one.

The parameter of the structure brought to the FEM process is shown in Table 1.

TABLE I. SENSOR PARAMETERS AFTER MANUAL TUNING AND SYNTHESIS BLOCK

	Size
Mass	845×845×400 μm^3
Beam	975×80×10 μm^3
Die size	1.5×1.5×0.5 mm^3
Outer frame width	200 μm

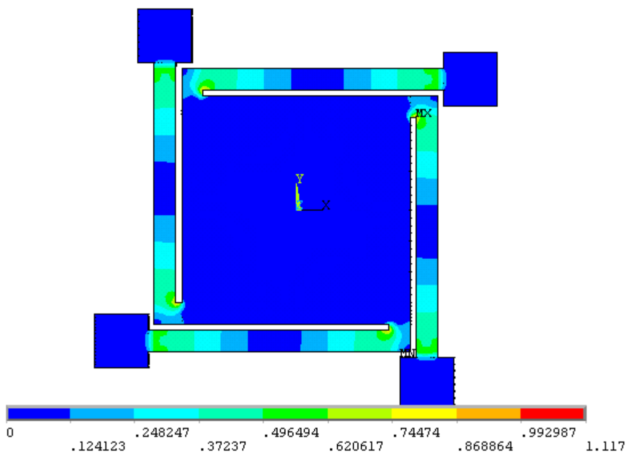
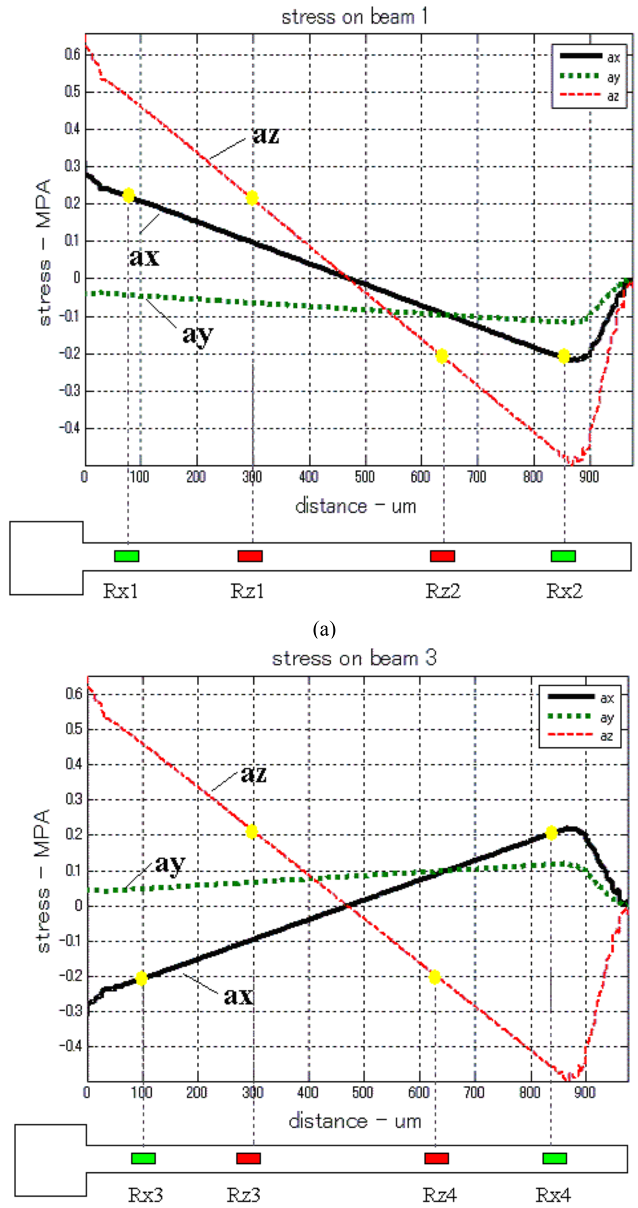


Figure 3. The stress distribution on the beams caused by the acceleration Az.

The most important aspect of our design process which requires FEA is the analysis of the stress distribution in the flexure beams. Based on this distribution, piezoresistors are placed to eliminate the cross-axis sensitivities and to maximize the sensitivities to the three acceleration components. The Von Mises stress distribution on the surface of beam structure caused by AZ acceleration component is shown in Fig.3. The sensing principle of the sensor is based on the characteristic of the p-type piezoresistor [7]. The resistance decreases when the sensor is exerted by a compressive stress and increases when it is exerted by a tensile stress.

Fig. 4 shows the stress analysis results along the 1st and the 3rd beams when the sensor is forced by acceleration in three directions (X, Y and Z). From this figure, we can find the optimal locations for the piezoresistors in order to sense accelerations *AX* and *AZ* without cross-talk. To get the uniform stress corresponding to three cases of applying acceleration, the locations of piezoresistors are also illustrated in this figure. By the same method, *AY* acceleration can be sensed via four piezoresistors on the 2nd and the 4th beams.



(a)

(b)

Figure 4. Longitudinal stresses on the surface of the 1st (4.a) and the 3rd (4.b) beams due to the 1*g* acceleration

Table 2 summarizes the increase (+), decrease (-), or invariance (0) in resistance of piezoresistors due to application of accelerations AX, AY, and AZ. These identical piezoresistors are diffused on the surface of the beams to form three Wheatstone bridges [3].

TABLE II. RESISTANCE VALUES CHANGES WITH THREE COMPONENTS OF ACCELERATION

	Rz_1	Rz_2	Rz_3	Rz_4	Ry_1	Ry_2	Ry_3	Ry_4	Rx_1	Rx_2	Rx_3	Rx_4
Az	+	-	+	-	-	-	-	-	-	-	-	-
Ay	-	0	+	0	-	+	-	+	0	+	+	0
Ax	-	-	+	+	0	+	+	0	-	+	-	+

Resolution is defined as the noise divided by the sensitivity. It is observed that optimization of the resolution has been achieved by increasing the sensitivity and reducing the noise. There are two typical noise sources existing in all piezoresistive sensors, including the Johnson noise and flicker noise [9, 10]. The noises depend on the bandwidth of sensor, the temperature, the geometry of piezoresistor, the doping concentration and also the thickness of the beam.

Johnson noise (thermal noise) is the electronic noise generated by the thermal agitation of the charge carriers inside an electrical conductor when applying an arbitrary voltage. The power spectral density (PSD) of thermal noise is nearly constant throughout the frequency spectrum. It means that Johnson noise can be assumed to be White noise.

In fact, it is hardly to observe this noise in a realistic accelerometer because electrical noise in the measurement circuit is often larger. The *root mean square* voltage of equivalent acceleration noise in each piezoresistor is:

$$V_i^{Johnson} = \sqrt{4k_B T B_i R} \quad i = X, Y, Z \qquad (5)$$

where k_B= 1.38 x 10^{-23} J/K is Boltzmann's constant, T is temperature in resistors, R is resistance value of the piezoresistor, and B is measured bandwidth. The bandwidth can be determined by many parameters such as the sampling frequency, analogue filtering, the resonant frequency of the mechanical structure, or losses in the wires, etc.

Resolution is defined as the noise divided by the sensitivity:

$$R_i = \frac{V_i^{noise}}{S_i} \qquad i = X, Y, Z \qquad (6)$$

The performance of the sensor can be summarized in Table 3.

TABLE III. PERFORMANCE PARAMETERS OF THE SENSOR

	Sensitivity (mV/V/g)	**Johnson noise per 1 piezoresistor (μV)**	**Resolution (mg)**
Az	0.15	0.42	1.09
Ax, Ay	0.15	0.51	1.37

The MEMS fabrication process requires precise photo masks to accurately create micro-scale patterns and structures. In this work, the sensor is fabricated with six photo masks for photolithography steps in piezoresistor patterning, contact hole opening, interconnection wiring, crossbeam forming, and deep reactive ion etching from backside. The mask layout design was drawn using L-EDIT software (Fig. 5).

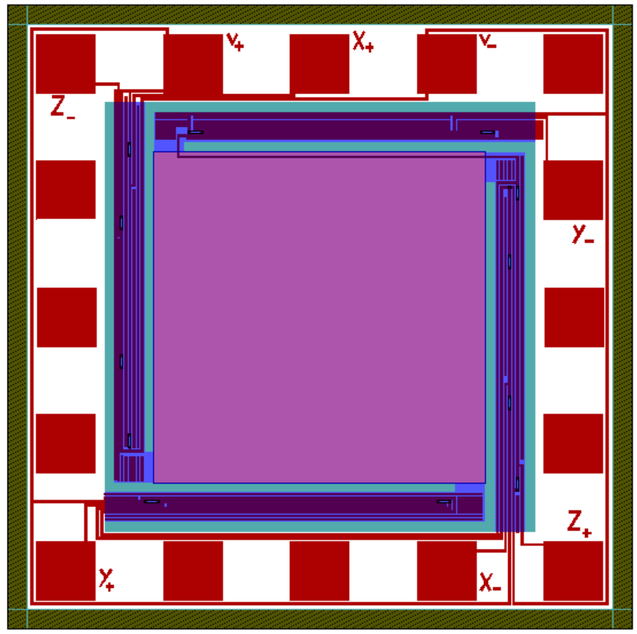


Figure 5. Overlapped mask layout of the 3-DOF sensor

V. CONCLUSION

This paper presents a design and simulation of 3-DOF MEMS based accelerometer with uniform sensitivity. The piezoresistive effect was used as sensing principle of the sensor. The most important aspect of Finite Element Analysis in our design process is the analysis of the stress distribution in the four flexure beams. The stress analysis was performed in order to determine the positions of the doped piezoresistors on these beams. The miniature 3-DOF accelerometer with uniform sensitivity is expected to be applied in some biomedical applications such as sign language recognition or patient monitoring system.

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