Advances in Natural Sciences, Vol. 10, No.2 (2009) (187-192)

Nanosciences and Nanotechnology

FULL ANALYSIS AND FABRICATION OF A PIEZORESISTIVE THREE DEGREE OF FREEDOM ACCELEROMETER

Tran Duc Tan, Nguyen Thang Long, and Nguyen Phu Thuy
Faculty of Electronics and Telecommunication,
College of Technology, Vietnam National University,
144 Xuan Thuy Road, Hanoi, Vietnam
Dao Viet Dung and Bui Thanh Tung
Research Organization for Science and Engineering,
Ritsumeikan University, Shiga, Japan

Received January 26, 2009

Abstract. In this paper, a miniaturized piezoresistive three-degree of freedom accelerometer has been developed and fabricated 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 1.5×1.5×0.5 mm^3 (L×W×T) and the beam size is 950×80×10 μm^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. This sensor is designed to have the bandwidth of 200 Hz with a cross-axis sensitivity drops to below 3%. A completed simulation and analysis were performed in which the real conditions in fabrication are considered. The full analysis proposed in this paper is capable to eliminate the discrepancy between simulation results and experimental data. The measured sensitivity is 0.2 mV/G (V_{in} = 3 V). Experimental results show that the sensor is suitable for applications in sign language or patient monitoring with a high accuracy.

Keywords: MEMS, piezoresistive effect, design
PACS number: 85.85.+j

1. INTRODUCTION

During last decades, MEMS technology has been rapidly developed with the success in fabricating miniaturized mechanical structures and integrating them with microelectronic components. In order to commercialize MEMS products effectively, one of the key factors is to optimize the design process. In this paper, we focused on the design aspects of a typical MEMS device: a piezoresistive accelerometer.

Although piezoresistive accelerometers suffer from the dependence of temperature, they have DC response, simple readout circuits, ability to meet the requirement of high sensitivity, high reliability and low cost in addition to the potential for mass production.

The full simulation and analysis proposed in this paper can give the results which are very close to experimental data.

2. WORKING PRINCIPLE

The three-degree of freedom 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 designs.

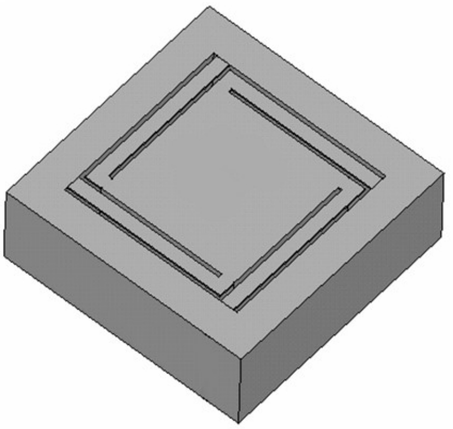

Fig. 1. The 3-DOF Piezoresistive accelerometer.

The operation of the device is based on Newton's second law of motion. An external acceleration results in a force being exerted on the mass. This force results in a deflection of the proof mass. When a vertical acceleration (A_z), i.e. Z component, applies to the sensor, the mass will move vertically up and down. Similarly, when the X or Y component of transversal acceleration acting on the sensor, the mass will move laterally. The deflection of the proof mass causes stresses in four beams, resulting in resistance variation of the piezoresistor doped on the surface of the beam structure [1]. This variation was converted into electrical signals by using three imbalance Wheatstone bridge circuits. These Wheatstone bridge circuits were built by interconnecting twelve p-type piezoresistors. These p-type piezoresistors were chosen to diffuse on the surface of these four beams because they can provide the maximal resistance variations. These piezoresistors were aligned with the crystal directions <110> and <1$\bar{1}$0> of n-type silicon (100). These piezoresistors were designed to be identical and fabricated by diffusion method.

The phenomenon that resistance of crystal material is varied when subjected to mechanical stresses is called piezoresistance effect. It caused by the anisotropic characteristics of the energy resolution in crystal space. In silicon material, there are only three independent coefficients π_{11}, π_{12} and π_{44}. The longitudinal piezoresistance coefficient π_l is defined in the case when 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 when 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), we can find these two coefficients from to three independent coefficients π_{11}, π_{12} and π_{44} by using relations:

$$\begin{aligned}\pi_l &= \frac{1}{2}\left(\pi_{11}+\pi_{12}+\pi_{44}\right),\\ \pi_t &= \frac{1}{2}\left(\pi_{11}+\pi_{12}-\pi_{44}\right).\end{aligned} \tag{1}$$

From simulation results in Fig. 3 (section 3), we found that two normal stresses σ_2 and σ_3 are rather smaller when comparing to σ_1. This phenomenon will affect the sensitivity of the sensor. To eliminate this effect, we should avoid placing piezoresistors near the fixed end and the start of the beam. Thus, we can calculate the relative change of resistance due to the normal stress as follows:

$$\frac{\Delta R}{R} = \pi_l\sigma_l + \pi_t\sigma_t. \tag{2}$$

3. DESIGN AND ANALYSIS BY USING ANSYS

At first, the structural analysis of the sensing chip was done by modified nodal analysis (MNA) method for a quick estimation of sensor dimensions based on the required ranges of acceleration and the dimensions of the beam. Then, 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.

Figure 2 shows the mesh generation for analysis, and the stress distribution on the beam is shown in Fig. 3. Figure 4 shows the stress distribution in the X-oriented, Y-oriented and Z oriented of the first beam caused by the acceleration A_z. Clearly, the stress distribution in the direction along the beam is much larger than the others'.

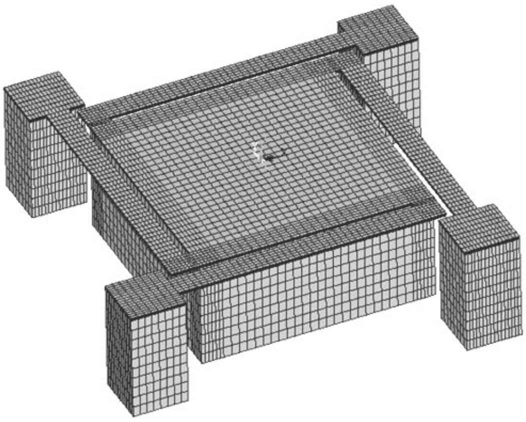

Fig. 2. The dense mesh generation of the FEM model.

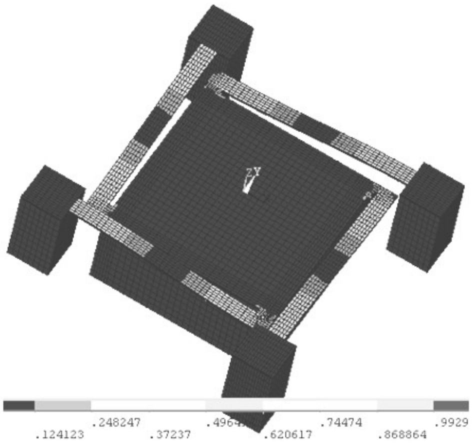

Fig. 3. The stress distribution on the beams caused by the acceleration A_z.

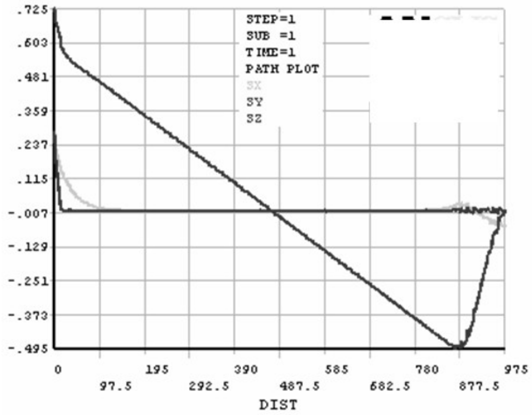

Fig. 4. The stress distribution on the first beam.

Based on the stress distribution in the flexure beams, twelve piezoresistors are placed to maximize the sensitivities to three components of acceleration and eliminate the cross-sensitivity. The sensing principle of the sensor is based on the characteristic of the p-type piezoresistor. These identical piezoresistors are diffused on the surface of the beams to form three Wheatstone bridges [2].

4. SENSITIVE ERROR ANALYSIS

In the previous section, we have performed design and simulation on the sensor with idealization constraints. The full analysis in this section is capable to eliminate the discrepancy between simulation results and experimental data. The mechanical sensitivities of each components of acceleration can be respectively expressed as:

$$S^i_{stress} = \frac{\sigma^i}{a_i},\ i = 1,\ 2,\ 3, \tag{3}$$

where S^i_{stress} and σ^i are mechanical sensitivity to the acceleration i^{th} component a_i and longitudinal stress, induced by the application of this acceleration, respectively. The electronic 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 Eq. (3) obtained from the stress analysis by utilizing ANSYS software. This value is the stress at the center point of the piezoresistor and on the surface of the beam. We have to recalculate it by the stress analysis along the length, width and thickness of the piezoresistor. Figure 4 represents the stress distribution when the A_z is applied to the sensor. The A_z piezoresistors are placed onto this transverse beam in order to sense this acceleration component. We can see that the stress is not the same along length of the piezoresistor. The stress analysis along the width and thickness can give the similar results. We now can define α_l, α_w, and α_t as the stress factors in length, width, and thickness of the piezoresistor, respectively. These values can be evaluated as follows:

$$\alpha_l = \left(L\sigma_l^i\right)^{-1}\int\limits_0^L \sigma^i\left(l\right)dl, \quad \alpha_w = \left(W\sigma_l^i\right)^{-1}\int\limits_0^W \sigma^i\left(w\right)dw, \quad \alpha_t = \left(T\sigma_l^i\right)^{-1}\int\limits_0^T \sigma^i\left(t\right)dt, \tag{5}$$

where $\sigma^i(l)$, $\sigma^i(w)$ and $\sigma^i(t)$ are the stress along the length, width, and thickness (L, W and T) of the piezoresistor caused by the i^{th} acceleration a_i. They can be obtained by ANSYS stress analysis technique. Finally, the value of the longitude stress can be corrected by using following formula

$$\widehat{\sigma}^i = \alpha_l \alpha_w \alpha_t \sigma^i \tag{6}$$

After stress correction processes, we derived $\widehat{\sigma}^1 = 0.73\sigma^1$, $\widehat{\sigma}^2 = 0.73\sigma^2$, and $\widehat{\sigma}^3 = 0.75\sigma^3$.

Recalculation of (4) can give us the more correct analysis. This correction is a very important step because this stress error is a major error compared to fabrication or readout circuit ones.

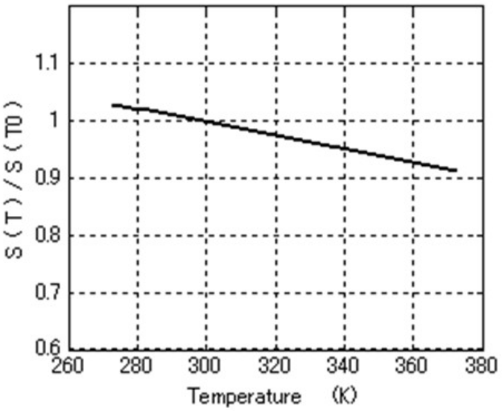

Fig. 5. The ratio $S^i\left(T\right)/S^i\left(T_0\right)$ at the impurity concentration of 5.1019 atoms/cm^3.

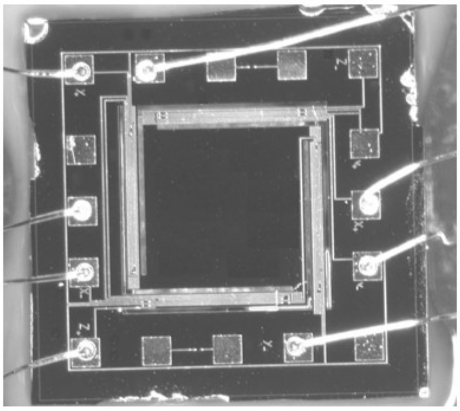

Fig. 6. Microphotograph of fabricated accelerometer.

In order to differentiate between the temperature sensitivity of the piezoresistors and the piezoresistive coefficient π_1, the impurity concentration was controlled at about 5.1019 atoms cm^{-3} to get $\pi_1 = 35.10^{-5}$ MPa [3]. However, we will investigate the sensitivity error that this choice still brings about. Temperature affects the piezoresistive coefficient through a change in the mobility and carrier concentration (N) in the respective bands [4]. The dependence of the piezoresistive coefficient on the impurity concentration at a given temperature (T) can be obtained by multiplying the piezoresistive factor $P(N,T)$ by the PR coefficient at room temperature (T_0) as follows:

$$\pi\left(T\right) = \pi\left(T_0\right)P\left(N,T\right), \tag{7}$$

$$P\left(N,T\right) = \frac{300}{T}\frac{F'_{s+0.5}\left(E_F/kT\right)}{F_{s+0.5}\left(E_F/kT\right)}, \tag{8}$$

where k is Boltzmann constant and T is temperature. The Fermi integral is the function of temperature and the Fermi energy E_F [5]. We observe that the ratio between the sensitivity at environment temperature to the sensitivity at the room temperature $S^i\left(T\right)/S^i\left(T_0\right)$ by substituting Eq. (7) into Eq. (4) (see Fig. 5).

The big gap between simulation and experimentation can be reduced effectively by these full analyses. The measured sensitivity is 67 μV/V/G while the theoretical sensitivity is 82 μV/V/G. Experimentation results show that the sensor (Fig. 6) is suitable for applications in sign language or patient monitoring.

5. CONCLUSION

This paper presents a full design and analysis for a specific MEMS accelerometer. The piezoresistive effect was used as the sensing principle of the sensor. The design results can be closest to fabrication condition by sensitivity error analysis.

ACKNOWLEDGMENTS

This work is supported by the Ministry of Science and Technology, project No. 410506.

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Corresponding author: *Tran Duc Tan, Faculty of Electronics and Telecommunication, College of Technology, Vietnam National University, 144 Xuan Thuy Road, Hanoi, Vietnam. E-mail: tantd@vnu.edu.vn*