Study on stress isolation structure of piezoresistive high-g accelerometer

Yongle Lu*, Zhen Qu, Jiawei Hui, Wenxin Wang and Yu Liu

Chongqing engineering research center of intelligent sensing technology and microsystem, Chongqing University of Posts and Telecommunications, Chongqing, China

*Corresponding author e-mail: luyl@cqupt.edu.cn

Abstract. We put forward a novel thermal stress isolation structure with five anchors, which greatly suppresses the zero offset of piezoresistive high-g accelerometer. In this paper, the parameters of the thermal stress isolation structure are optimized by finite element simulation to ensure that the sensor has lower zero offset and a good natural frequency. A high natural frequency can prevent the sensor from being damaged due to resonance when it is subjected to shock. Finally, the zero offset of the sensor with thermal stress isolation is reduced to 10% of that without thermal stress isolation. Natural frequency of the sensor is 264.18 kHz. Its sensitivity is 1.1μV/G/5V according to shock simulation of 100,000 g.

Keywords: thermal stress isolation; zero offset; piezoresistive; high-g accelerometer.

1. Introduction

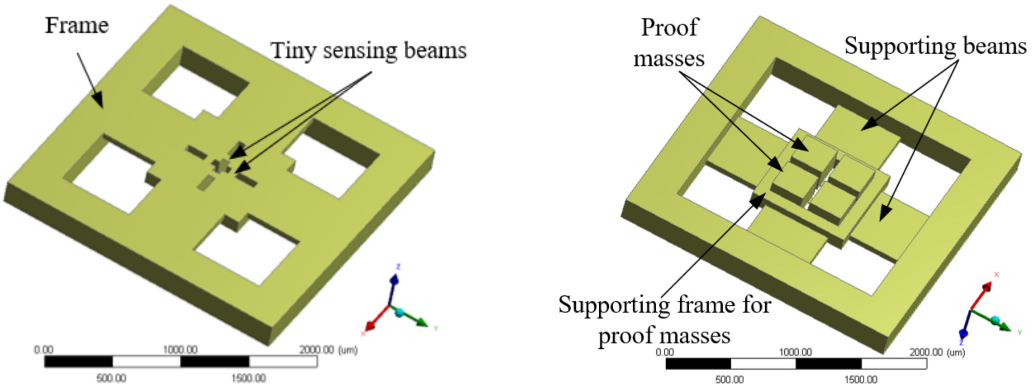
High-g accelerometers have the characteristics of high measuring range and impact resistance, which are widely used in many fields such as weapon systems, collision test and aerospace [1]. However, accelerometer can cause unwanted displacements and deformations in the sensing structure when subjected to temperature changes, which particularly has effects on piezoresistive accelerometer, which are based on stress changes on beams.

Although piezoresistive high-g accelerometers usually have a high natural frequency above 200 kHz, and the high measuring range above 100,000 g, the application of high temperature applications such as blast may lead to the temperature characteristic drifts, which skews the measuring results. At present, researchers have optimized the structure design, chip packaging, control circuit of the accelerometer to reduce the interference thermal stress [2]. Atsushi Kazama et al. [3] designed an annular stress relaxation structure, which can effectively improve the bending of beams caused by residual stress. Bowen Xing et al. [4] designed a stress isolation layer suitable for microelectromechanical systems (MEMS) devices, which relieves packaging stress by matching the coefficients of thermal expansion (CTEs) of materials [5]. However, in the current research, there are few studies on thermal stress isolation of piezoresistive high-g accelerometers. It is of great significance to study the thermal stress isolation structure to improve the temperature characteristics of piezoresistive high-g accelerometers.

In this study, a novel five-anchors thermal stress isolation structure is proposed to optimize the zero offset of a piezoresistive high-g accelerometer. Ansys Workbench is used to simulate the sensor's performance under different parameters of the thermal stress isolation structure to determine the optimal structural parameters. The modal simulation and thermal simulation results show that the natural frequency of the sensor is 264.18 kHz and the zero offset of the sensor is reduced to 10% of that without thermal stress isolation. The shock simulation results show that the sensor has a good performance under the shock of 100,000 g, and its sensitivity is 1.1 μV/G/5V.

2. Sensing structure of sensor

The research object of this paper is a Z-axis piezoresistive high-g accelerometer sensing structure with tiny sensing beams, as shown in Figure 1. The sensing structure is mass-spring system which consists of four supporting beams, four proof masses, four tiny sensing beams, and one supporting frame for proof masses. The accelerometer uses a Wheatstone bridge circuit as the detection circuit. The Wheatstone bridge circuit consists of four resistors along the Y-axis ([110] crystal direction of silicon), which are located on four tiny sensing beams, respectively.



(a) (b)

Figure 1. The diagram of the sensing structure of the piezoresistive high-g accelerometer
(a) Front of sensing structure (b) Backside of sensing structure.

2.1 Theoretical analysis of sensing structural characteristics

According to the mechanical properties, the maximum deformation of the sensing structure is obtained as:

$$w_{\max} = \frac{2(m_2+m_3)a_Z}{E_{Si}c_1h_3^3}\cdot\left(l_3+\frac{(c_1-c_2)}{2}\right)^3+\frac{(2m_1+m_2+m_3)a_Z}{E_{Si}b_1h_1^3}l_1^3 \tag{1}$$

Where, E_{Si} is the Young's modulus of silicon, a_Z is the acceleration, l_1, b_1, h_1, m_1 is respectively the length, width, thickness and mass of the supporting beam, l_3, h_3, m_2 is the length, thickness and mass of the proof mass, c_1 and c_2 is respectively the outer and inner side length of the supporting frame for proof mass, m_3 is the mass of the supporting frame for proof masses.

According to the Rayleigh Method, the natural frequency f_A of the sensing structure is calculated as:

$$f_A = \pi\sqrt{\frac{E_{Si}b_1h_1^3}{3(2l_1+c_1)^3M_A}} \tag{2}$$

Where, M_A is the total mass of the sensing structure.

M_A it is mainly related to the sizes of the supporting beam according to Equation (2) when the sizes of the masses system are constant so the natural frequency of the sensing structure mainly depends on the sizes of the supporting beam.

According to the theoretical analysis, Table 1 gives a set of structural parameters.

Table 1. Structural parameters of the accelerometer sensing structure.

Geometry structure	Parameter	Value(μm)
Supporting beam	length×width×thickness	455×550×50
Tiny sensing beam	length×width×thickness	60×60×6.5
Proof mass	Side length×thickness	270×200
Supporting frame for proof masses	Outer side length×inner side length×thickness	800×600×50

2.2 Natural frequency analysis of packaged sensors

The natural frequency f_B of the packaged sensor can be expressed as:

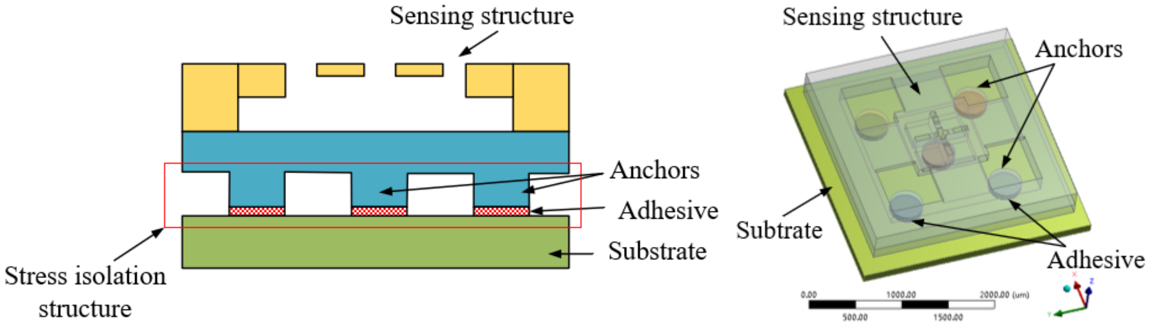
$$f_B = \frac{1}{2\pi}\sqrt{\frac{E_{ad}S}{HM_B}} \tag{3}$$

Where, E_{ad} is the Young's modulus of the adhesive, S is the contact area between the adhesive and the sensor, H is the thickness of the adhesive, and M_B is the total mass of the sensor.

Equation (3) show that the parameters of the adhesive have a great influence on the natural frequency of the packaged sensor. The larger the bonding area and the thinner the adhesive, the higher the natural frequency of the packaged sensor.

3. Design and simulation of stress isolation structure

The traditional piezoresistive sensor package is to bond the sensing structure to the glass, and then fix it on the substrate of the shell through adhesive [6]. The proposed novel thermal stress isolation structure is shown in Figure 2. The accelerometer sensing structure is bonded to the thermal stress isolation structure. Then it is bonded to the substrate through five anchors.



(a) (b)

Figure 2. Thermal stress isolation structure (a) Diagram (b) Model.

3.1 Simulation of thermal stress isolation structure

The finite element simulation software ANSYS workbench is used for modeling. The properties of materials are shown in Table 2. The initial temperature is set as 22°C and -45°C to 65°C is the sensor operating temperature.

Table 2. Properties of materials.

Material	Density (kg/m3)	Young's modulus (GPa)	Thermal expansion coefficient (ppm/°C)
Silicon	2330	170	2.5
Glass	2230	63	3.25
Adhesive	980	2.7	60
Substrate	3200	360	6.5

In order to analyze the influence of the distribution of anchors on the performance of the sensor, it is assumed that the distance between the four surrounding anchors and the central anchors is L. The simulation results of the zero offset of the sensor with different L under -45°C to 65°C are shown in Figure 3.

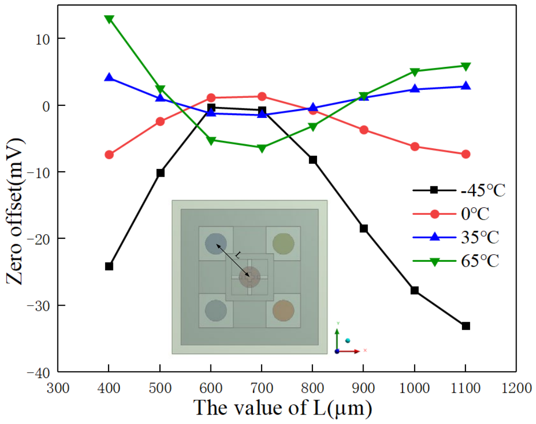
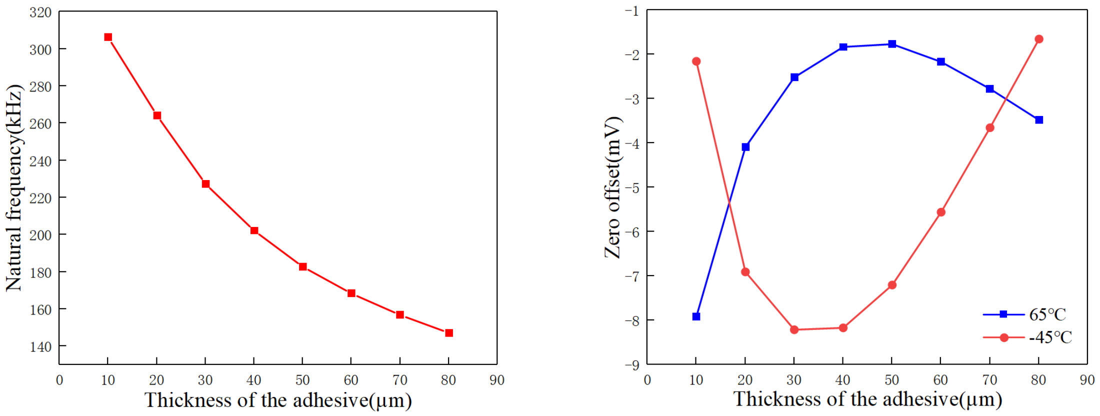


Figure 3. Zero offset with different L.

The results show that the distribution of the anchors has a great influence on the performance of the sensor. In the actual production process, the position of glue dispensing is too close to cause adhesion, so the L is to be 800 μm.

According to Equation (3), the thickness of the adhesive will affect natural frequency of the sensor, and the parameters of adhesive are also the main factors affecting the zero offset. Different thicknesses of the adhesive are set to conduct thermal simulation. The relationship between the thickness of the adhesive and the zero offset of the sensor is shown in Figure 4.



(a) (b)

Figure 4. Optimization of the thickness of adhesive (a) Influence of thickness of adhesive on natural frequency (b) Influence of thickness of adhesive on zero offset

It can be seen from Figure 4(a) that with the increase of the thickness of the adhesive, the natural frequency of the sensor gradually decreases. 22°C is the initial temperature of the sensor so the zero offset at -45°C is maximum within the operating temperature of the sensor. Natural frequency and zero offset are both considered, the thickness of the adhesive is set as 20 μm and now its Natural frequency is 264.18 kHz.

4. Simulation analysis of sensor performance

The zero offset of the sensor with and without thermal stress isolation structure is shown in Figure 5 when the temperature is from -40°C to 65°C, which shows that the zero offset of the sensor is reduced to 10% of that without thermal stress isolation.

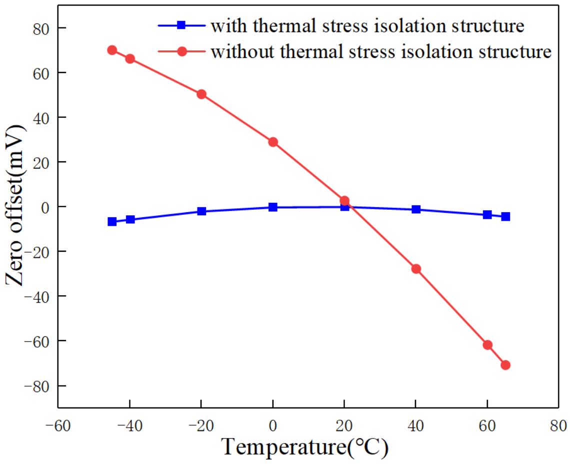


Figure 5. Zero offset of the sensor with or without thermal stress isolation structure.

Ls-DYNA is used to simulate the shock of the sensor. The 100,000 g shock waveform is a half sinusoidal with a width of 20 ms. The output of the sensor during the observation period of 40 ms is shown in Figure 6, which shows that the maximum output is 106.7 mV, so the sensitivity of the sensor is 1.1 μV/G/5V.

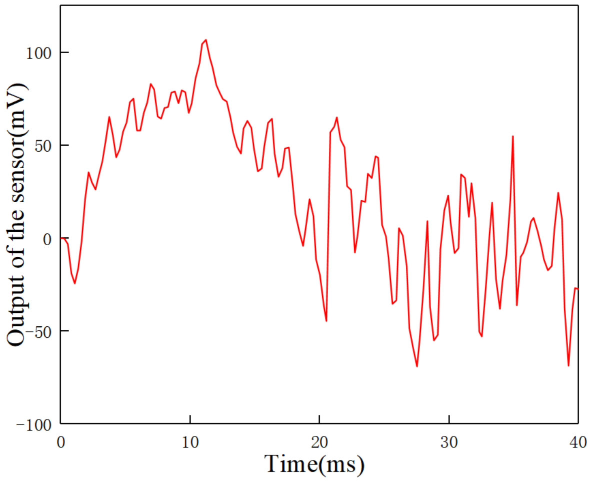


Figure 6. Shock simulation results.

5. Conclusion

In this paper, the thermal stress isolation structure of piezoresistive high-g accelerometer was simulated and optimized by the finite element simulation. The results show that the thermal stress isolation can effectively suppress the zero offset of the sensor. The sensor with the thermal stress isolation also has good performance in natural frequency and shock.

Acknowledgments

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References

[1] J. Chen, H. Li, Structural analysis of performance optimization of high g accelerometer chip, Mater. Sci. Eng. 793(1) (2020).

[2] J. Cui, H. Yang, D. Li, et al, A Silicon Resonant Accelerometer Embedded in An Isolation Frame with Stress Relief Anchor, Micromachines(Basel) 10(9) (2019).

[3] Y. Lu, B. Xie, Q. Wei, et al, A Resonant Pressure Microsensor With a Stress Isolation Layer, IEEE Sens. J. 19(18) (2019) 7875-7883.

[4] A. Kazama, T. Aono, R. Okada, High Shock-Resistant Design for Wafer-Level-Packaged Three-Axis Accelero-meter With Ring-Shaped Beam, J. Microelectromech. Syst. 27(2) (2018) 355-364.

[5] B. Xing, B. Zhou, J. Wang, et al, A Novel Packaging Stress Isolation Chip for MEMS Devices, 2019 IEEE SENSORS. IEEE (2020).

[6] H. S. Hsieh, H. C. Chang, C. F. Hu, et al, A novel stress isolation guard ring design for the improvement of three-axis piezoresistive accelerometer, J. Micromech. Microeng. 21(10) (2011).