Analysis of Thermal Drift of A Constant Temperature Control Type Three-Axis Accelerometer for High Temperatures

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In this paper, a suppression method of generated distortion on the beam structures due to thermal stress is investigated for reduction of remainder thermal drift in three-axis accelerometer for high temperatures. An arrangement of piezoresistors for acceleration detection is presented to further reduction of thermal drift. Thermal drift analysis and design of advanced three-axis accelerometer for high temperatures without temperature dependence has been carried out with the finite element method (FEM) program, ANSYS. Experimental results agreed well with these theoretical results. Design considerations that enable the three-axis accelerometer to have stable sensitivity and offset are described with the simulated results.

Keywords : FEM, High temperature environment, Constant temperature control, Accelerometer, SOI, Micro-heaters

1. Introduction

Recently, many kinds of silicon micromachined sensors for high temperature environments have been widely used in various industrial application fields, such as the automobile industry, the geothermal energy development, the nuclear power generation, and the aerospace industry. Various types of sensor for high temperatures using micro electro mechanical systems (MEMS) technology and silicon on insulator (SOI) technology are realized, and the operating characteristics under high temperature environment (300°C or more) are reported[(1)~(3)]. Applying SOI technology to a working sensor under high temperature environments is one of means to raise environment-proof of the sensors[(4)]. However, the performances of silicon micromachined sensors are degraded under high temperature environments, and it is difficult to have a stable characteristic over wide temperature range. In order to stabilize temperature characteristics, a three-axis accelerometer for high temperatures with integrated temperature sensor and micro-heaters using SOI has been fabricated and evaluated over a wide temperature range. The fabricated devices operated up to 300°C with very small temperature dependence of sensitivity when SOI piezoresistors temperature was controlled. The temperature coefficient of sensitivity (TCS) of fabricated devices is much reduced for variation of atmospheric temperature. On the other hand, when the temperature control of the device is performed, temperature coefficient of offset (TCO) of fabricated devices increased.

In order to solve the problems of remainder sensitivity drift and increased offset voltage, the device structure is redesigned and optimized by finite element method (FEM). In this paper, design considerations that enable the three-axis accelerometer to have desirable characteristics are described with the results of FEM simulation.

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2. Analysis of Thermal Drift of Temperature Controlled Three-Axis Accelerometer for High Temperatures

The three-axis accelerometer for high temperatures has been reported as shown in Fig.1[(5)]. It has a center support and surrounding mass structure[(6)~(8)]. Four folded beams are formed between the center support and the surrounding mass to achieve high sensitivity for three-axis detection[(9)]. The die size of the accelerometer is 6.5mm×6.5mm. The length of each beam structure is 2mm, the width is 50μm, and the thickness is 15μm.

The SOI piezoresistors to detect acceleration (deflection of beams) is formed at the edges and center connection points of the beams. The four piezoresistors on one folded beam are connected to form a wheatstone bridge. The piezoresistors are enclosed with the integrated micro-heaters. The whole resistance of four wheatstone bridges is used as the temperature sensor, because it is insensitive to acceleration input while it is proportional to temperature. The circuit configuration of the accelerometer

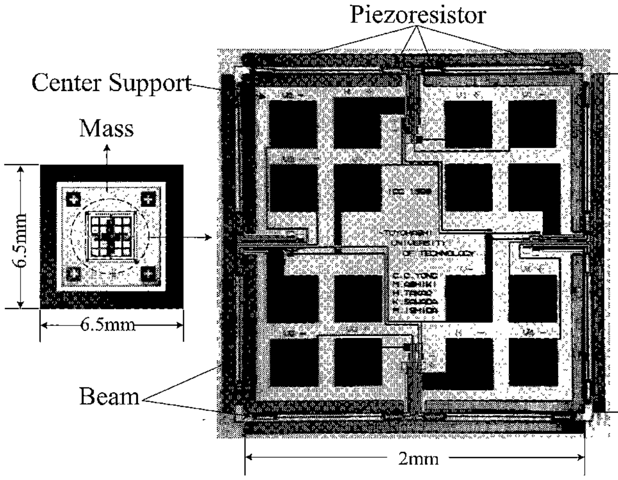
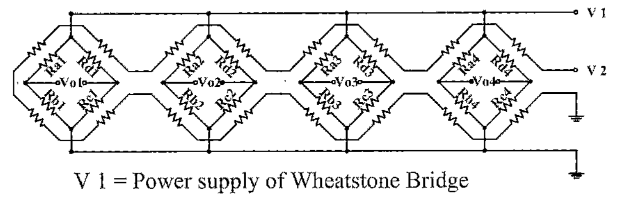
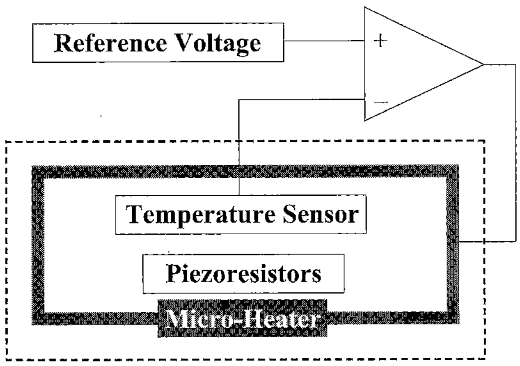


Fig. 1. Photograph of the fabricated three-axis accelerometer for high temperature environments with temperature control elements[(5)].



V 1 = Power supply of Wheatstone Bridge
V 2 = Power supply of Integrated Microheaters

Fig. 2. Circuit configuration of the fabricated three-axis accelerometer.



Temperature Sensor, Piezoresistors and Micro-Heater are integrated in the three-axis accelerometer

Fig. 3. Schematic diagram of constant temperature control system.

including wheatstone bridges and integrated micro-heaters is shown in Fig. 2. X, Y and Z-axis acceleration can be detected by calculating the output voltages of wheatstone bridges (Vo1, Vo2, Vo3 and Vo4) with the equations (1)-(3).

$$Vout\_x = (Vo2 + Vo3) - (Vo1 + Vo4) \quad \cdots\cdots (1)$$
$$Vout\_y = (Vo3 + Vo4) - (Vo1 + Vo2) \quad \cdots\cdots (2)$$
$$Vout\_z = (Vo1 + Vo2 + Vo3 + Vo4) \quad \cdots\cdots (3)$$

Fig. 3 shows the schematic diagram of constant temperature control system applied to the three-axis accelerometer. Temperature sensor, piezoresistors, and micro-heaters are integrated in the same chip(5)(10). In order to stabilize the characteristics of the three-axis accelerometer over a wide temperature range, the constant temperature control was performed to SOI piezoresistors on the accelerometer using integrated the micro-heaters and the temperature sensor. TCS of fabricated device is much reduced from original TCS of 1051ppm/°C to 298ppm/°C for variation of atmospheric temperature. On the other hand, when the temperature control of the device is performed, the offset voltage increased 14 times as compared to the offset voltage of the device without temperature control. This is due to large thermal stress generated by temperature distribution on the beam structures. In order to solve the problems of remainder sensitivity drift and increased offset voltage, the device structure is redesigned and optimized using finite element method (FEM).

2.1 Consideration of FEM Model for Thermal Drift Analysis The thermal drift analysis of the three-axis accelerometer is performed for reduction of the remainder sensitivity drift and increased offset voltage. Bottom views of FEM model for thermal drift analysis is shown in Fig.4(a), and the close-up of beam structure is shown in Fig.4(b). The FEM model

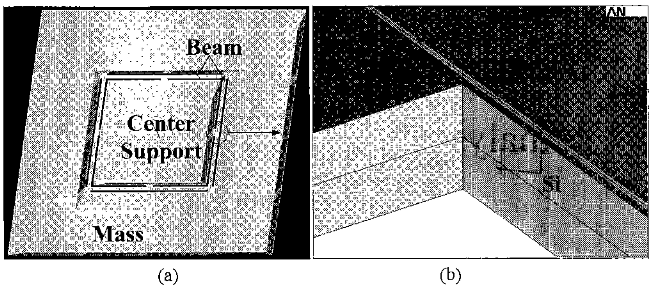


Fig. 4. Shapes of three-axis accelerometer for FEM simulation (Five layer structure): (a) bottom view, (b) close-up of beam structure.

Table 1. Properties of materials in FEM model.

Properties	Aluminum	Silicon	SiO_2
Young's modulus (GPa)	69	162	70
Poisson's ratio	0.29	0.29	0.29
Density (kg/m^3)	2692	2660	2328
Thermal Expansion Coefficient (ppm /°C)	25	2.6	0.4
Thermal Conductivity (w/m·°C)	237	149	1.4

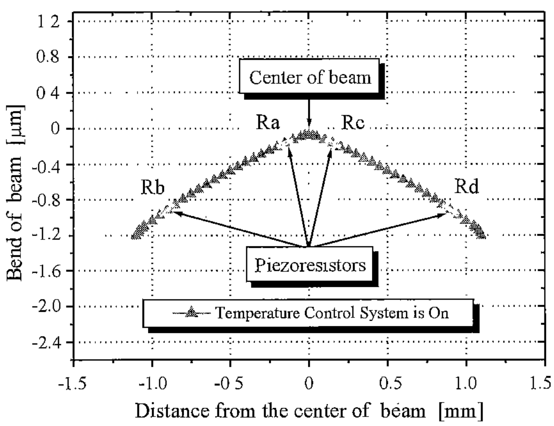


Fig. 5. Simulated result of bend of beam by FEM simulation.

has five layer (Aluminum/SiO_2/Silicon/SiO_2/Silicon) structure so that it may become the same structure with the actual accelerometer device. Properties of these materials are shown in Table 1.

The validity of FEM analysis is confirmed by comparison between estimated bend of beam by FEM and measured bend of beam by laser microscope. Fig. 5 shows the simulated bend of beam at 300°C with the results of FEM simulation. Triangle markers show the bend of beam at 300°C with constant temperature control. When the constant temperature control of the device is performed, the value of simulated bend is about 1.2μm as shown in Fig. 5. Fig. 6 shows the measured bend of beam at 300°C by laser microscope. The value of measured bend is about 1.14μm. This value agrees well with the estimated value by FEM simulation. It is demonstrated that the FEM model expresses temperature characteristic of actual accelerometer well.

2.2 Results of Thermal Drift Analysis About Sensitivity and Offset Voltage Fig.7 shows the measured and simulated results of sensitivity dependence on atmospheric temperature of the accelerometer. Circle markers show the measured temperature characteristic of sensitivity with constant temperature control at 300°C, and triangle markers show the simulated result. As shown

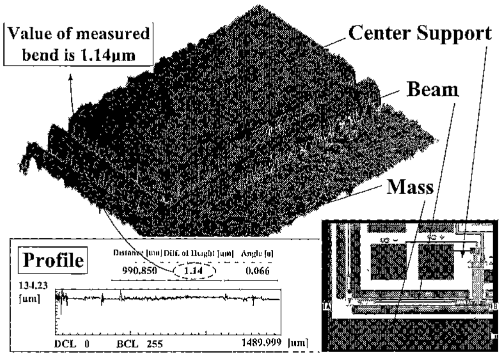


Fig. 6. Measured result of bend of beam by laser microscope.

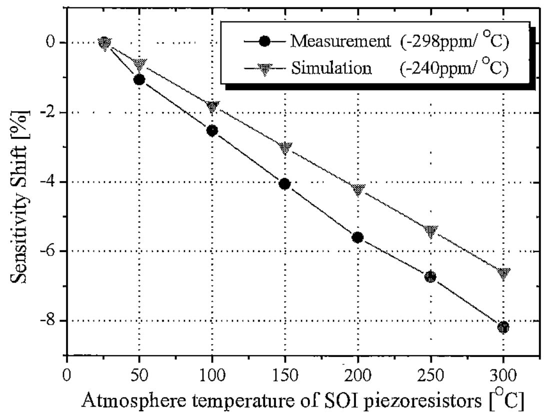


Fig. 7. Sensitivity shift in the temperature range from 26°C to 300°C.

the Fig.7, the measured sensitivity shift in the temperature range from 26°C to 300°C is -8.1%, and the simulated sensitivity shift is -6.6%. It is considered that the sensitivity depends on a change of apparent rigidity of beam caused by shape deformation of beam cross section. If constant temperature control is performed, the shape of beam cross section changes with atmospheric temperature. This is due to the difference of thermal expansion coefficient of the materials formed on the beam structure. In this case, apparent rigidity of the beam structure is increased in proportion to thermal in the atmospheric temperature range from 26°C to 300°C. As a result, sensitivity of the accelerometer has negative temperature coefficient. If the beam layout of device is modified so that the thermal strain is suppressed, it is considered that the remainder sensitivity shift will be reduced.

The variation of resistance can be expressed as

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \approx \frac{1}{2}\pi_{44}\left(\sigma_l - \sigma_t\right) \cdots\cdots (4)$$

where R is initial resistance, ΔR represents the resistance change, π_l and σ_l represent the longitudinal piezoresistive coefficient and stress, π_t and σ_t represent the transverse piezoresistive coefficient and stress, π_{44} represents the piezoresistive coefficient of p-type silicon. Offset voltage of the wheatstone bridges is proportional to the difference of stress (σ_l - σ_t), and it is calculated with equation (4). Fig.8 shows comparison of measured and simulated offset voltage drift of the accelerometer for atmospheric temperature change. Circle markers show the measured offset voltage drift when constant temperature control is performed, and triangle markers show the results of FEM simulation. As shown the Fig.8,

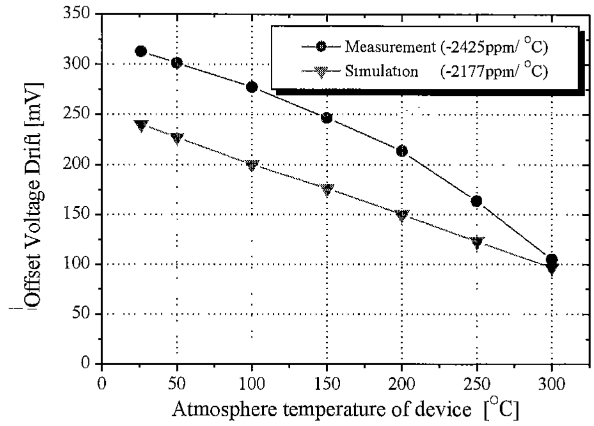


Fig. 8. Offset voltage drift in the temperature range 26°C to 300°C.

the measured TCO in the temperature range from 26°C to 300°C is -2425ppm/°C, and the simulated TCO is -2177ppm/°C. It is considered that offset voltage of the accelerometer increase with thermal deformation of beam, since stress balance in wheatstone bridge is increased. Precipitous thermal gradient is shown on the beam structure when the piezoresistor temperature is controlled to 300°C. From a result of FEM simulation, the thermal deformation becomes in maximum when atmospheric temperature is 26°C. If thermal isolation of the accelerometer from atmosphere is further improved, precipitous thermal gradient on beams will be eased, and thermal offset drift of the device will be reduced. Analysis of the thermal drift and improvement of design have been performed with the FEM model in this study. Improved characteristics of devices using the thermal drift analysis results are discussed in the next section.

3. Improvement of Device Structure

In this section, in order to solve the problems mentioned above, the device structure is redesigned and optimized using FEM. A suppression method of generated distortion on the beam structures due to thermal stress is investigated for reduction of remainder thermal drift in the accelerometer. Moreover, an arrangement of piezoresistors for acceleration detection is presented to reduce thermal drift more.

3.1 Consideration of Device Structure with Minimum Thermal Drift Fig.9 shows the structure of previous device (hereinafter, "Type I") and improved device (hereinafter, "Type II"). Four folded beams of Type I and Type II are formed between center support and surrounding mass[6] to achieve high sensitivity for three-axis detection. In the case of Type I, the center portion of the beams is fixed to center support, and the end portion of the beams is connected with the mass. Since the thermal expansion coefficients of material on the beam are different, distortion of the beams is generated largely. In order to suppress the distortion on the beam structure, the center portion of the beams is fixed to mass, and the end portion of the beams is connected with the center support as shown in Fig.9. Type II can suppress the thermally generated distortion on the beam structures by the redesigned beam structures and controlling the length of "C". Fig.10 shows the simulated bend of beam for various lengths of "C". The role of "C" is cancellation of the thermally generated compressive strain on the beam with the tensile strain on the portion of "C" as shown in Fig.10. The optimized length of "C" is

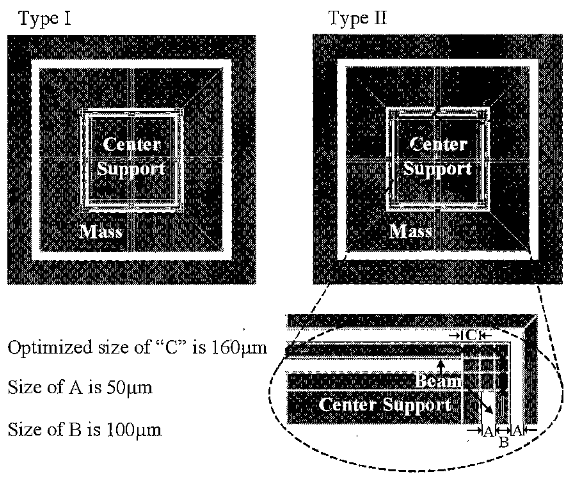


Fig. 9. Schematics of Type I and Type II device, and close-up of beam.

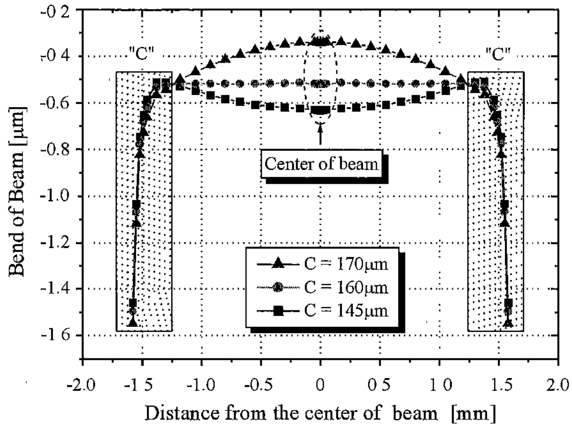
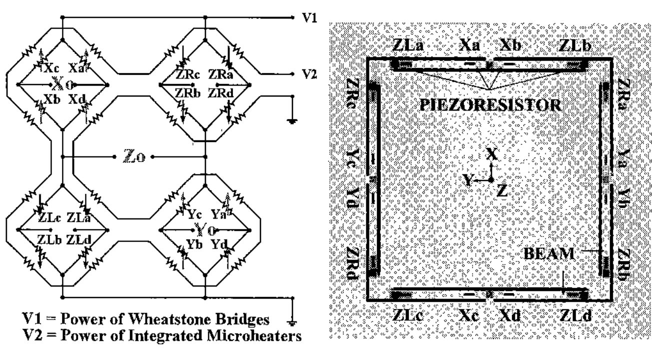


Fig. 10. Simulated results of bend of beam for the variation of length of "C".

160μm in this case. If the compressive strain and tensile strain are balanced, it is considered that the distortion of beam which is cause of offset voltage drift can be reduced. The remainder TCS and the increased TCO of previous devices will be much reduced by optimizing the length of "C" for cancellation of thermal distortion on the beams during constant temperature controlling.

3.2 Further Reduction of Thermal Drift by Configuration Change of Wheatstone Dridges In Type I device, four piezoresistors on one beam was composed as one wheatstone bridge. When distortion of a beam is caused by thermal stress, an offset voltage is generated since two piezoresistors (Ra, Rc) and two piezoresistors (Rb, Rd) have a different stress distribution. Fig. 11(a) shows the arrangement of the wheatstone bridge newly configured in this study (arrows mean stress increase and decrease when acceleration is applied to the Z-axis). In the configuration, the stress variation of two piezoresistors Xa, Xb are the same as shown in Fig. 11(b), and these are composed as one wheatstone bridge. Moreover, two piezoresistors ZLa, ZLb formed at the edge is composed to form the detection element of other wheatstone bridge. It is possible to cancel the occurred offset voltage due to the thermal stress difference which exists between four piezoresistors on one beam by newly designed arrangement. Fig.12 shows the sensitivity shift for variation of atmospheric temperature in Type I and Type II. The simulated TCS of Type II is reduced from -240ppm/°C (TCS of Type I) to -72ppm/°C.



(a) (b)

Fig. 11. (a) New circuit configuration and (b) New arrangement of SOI piezoresistors of optimized device and stress distribution of z-axis by FEM.

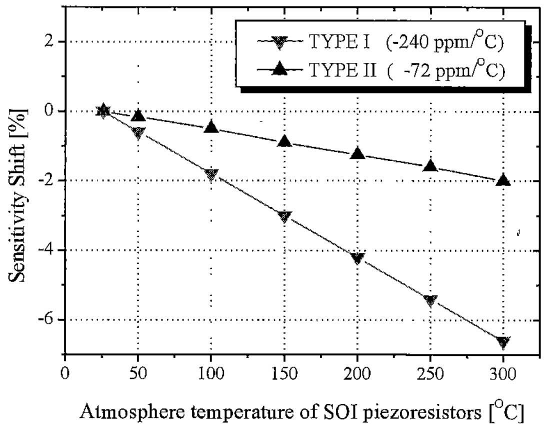


Fig. 12. Sensitivity shift of the Type I and Type II for variation of atmospheric temperature in the constant temperature control.

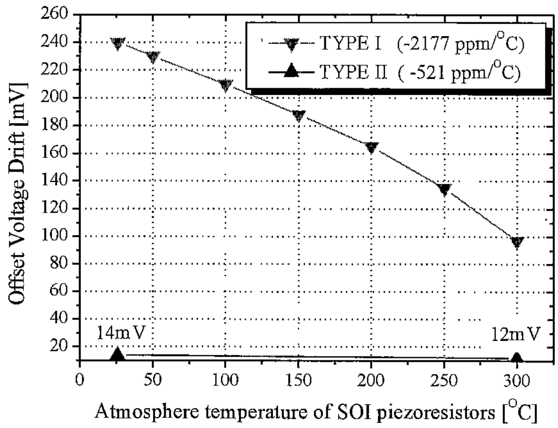


Fig. 13. Offset voltage drift of the Type I and Type II for variation of atmospheric temperature in the constant temperature control.

Fig.13 shows the offset voltage drift for variation of atmospheric temperature. The simulated TCO of Type II is much reduced from -2177ppm/°C (TCO of Type I) to -521ppm/°C. TCS of the optimized device will be reduced to 30% of Type I, and TCO will be reduced to 23.9% of Type I. The thermal drift characteristics of the device with a constant temperature control are improved by redesign of device and new arrangement of piezoresistors.

4. Conclusions

In this paper, the thermal drift characteristics of the constant temperature control type three axis accelerometer for high temperature are analyzed to reduce thermal drift with FEM simulation. The influence of generated distortion on the beam structure due to the thermal stress is investigated, and the suppression method of generated distortion is presented to reduce thermal drift. Thermal analysis, and design optimization to minimize the drift of sensitivity and offset voltage have been performed with ANSYS in this study. Temperature coefficient of sensitivity (TCS) and temperature coefficient of offset (TCO) are reduced to 30% and 23.9% of the previous devices, respectively. It is possible to reduce the generated distortion on the beam structures due to thermal stress if the proposed methods based upon thermal drift analysis are used.

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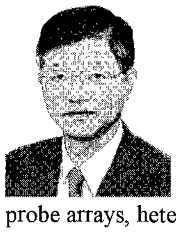

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