Piezoresistive Force Sensor Utilizing Combination of Three-Axis Stress Components

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Summary

A high sensitive miniature piezoresistive force sensor utilizing combination of three-axis stress components has been developed. This work aims to develop a force sensor which acts as a sensing unit assembled in a new miniature high pressure sensor. By using a force transmission rod, forces are applied to piezoresistors on a Si diaphragm of the sensor. Resistance changes of the piezoresistors depend on combination of stress components generated by the applying forces. FEM stress analysis was carried out, in order to investigate dependence of stress components on dimensions and Young's modulus of the rod, and diaphragm thickness. A sensor structure to obtain large resistance changes of the piezoresistors was found by utilizing valid combination of three-axis stress components according to the analysis. As an experimental result, an output voltage more than 140 mV / 5 V at 150 N was obtained.

Keywords : force sensor, pressure sensor, piezoresistive effect, Si diaphragm, FEM analysis

1 INTRODUCTION

Piezoresistive semiconductor pressure sensors have been widely used in the fields of industrial measurement, automobiles, medicine and so on, since they are miniature, light and highly reliable [1-5]. Conventionally, as a typical structure of the piezoresistive Si pressure sensor, a thin diaphragm is formed on a Si substrate and piezoresistors are arranged on the diaphragm [6]. However, the thin diaphragm pressure sensor is not suitable for measuring high pressure because of the strength restriction of the diaphragm. Several high pressure sensors have been developed. Generally, oil-sealing type pressure sensors or sensors with piezoresistors bonded on a metal diaphragm are used for measuring high pressure [7]. The oil-sealing type pressure sensors are difficult to compensate temperature characteristic due to thermal expansion of sealed oil. Fabrication process of oil-sealing type sensors are complex and cost are relatively high by introducing oil sealing technology. The sensors with piezoresistors bonded on the metal diaphragm are affected by creep due to bonding portion. It is difficult to bond the small piezoresistors on the metal diaphragm and connect piezoresistors by wires. The structure and fabrication process of the sensors with piezoresistors bonded on a metal diaphragm have been also complex, and it has been difficult to reduce cost and size of the sensors.

It is expected to develop low cost, miniature and

Fig. 1 Schematic structure of the pressure sensor.

Fig. 2 Schematic of the sensor chip.

simple structure high pressure sensors in order to measure internal high pressure distribution such as in injection molding machines. For this purpose a force sensor which acts as a sensing unit assembled in a metal diaphragm type high pressure sensor has been developed. The force sensor can measure various range of pressure by changing metal diaphragm thickness of the pressure sensor. Figure 1 shows a schematic structure of the pressure sensor. A pressure applied to a metal diaphragm is transmitted to a sensor chip by using a force transmission rod. Diffused piezoresistors are used as force detecting elements. In this paper, high sensitivity of the force sensor was achieved by utilizing a combination of three-axis stress components on the diaphragm which influence the resistance changes of the piezoresistors. The relation between parameters of the force sensor structure and the output characteristics was investigated by FEM stress analysis. The output characteristics of a prototyped force sensor were reported.

2 PRINCIPLE

2.1 Sensor Structure and Resistance Changes

A sensor chip as shown in Fig. 2 was adopted as a detecting element of the force sensor. A substrate of the sensor chip was n-type (110) Si. A rectangular diaphragm of $2080 \times 750 \mu\text{m}^2$ was formed by using anisotropic etching. Four p-type piezoresistors were formed by impurity diffusion of boron on the surface of diaphragm. A shape and dimension of the piezoresistor is shown in Fig. 3. A structure of the force sensor is shown in Fig. 4. The force sensor was composed of a hemispheric head, a force transmission rod, a sensor chip and a metal plate. The principle of detection is as follows. An elastic deformation of the force transmission rod due to an external applied force is acted on the diaphragm. The resistance changes of the piezoresistors are induced by the stresses of the diaphragm surface. When the stress is applied to the piezoresistors, a resistance change ratio $\Delta R/R$ is expressed by using the piezoresistive effect as follows [8-10].

$$\Delta R/R = \pi'_{11}\sigma_1 + \pi'_{12}\sigma_2 + \pi'_{13}\sigma_3 + \pi'_{14}\sigma_4 + \pi'_{15}\sigma_5 + \pi'_{16}\sigma_6 \quad \dots\dots\dots(1)$$

Where, σ_1 , σ_2 and σ_3 are the normal stress components. σ_4 , σ_5 and σ_6 are the shearing stress components. π'_{11} , $\dots, \pi'_{16}$ are the piezoresistive coefficients with respect to arbitrary directions. $\pi'_{11}, \dots, \pi'_{16}$ are able to express in terms of fundamental piezoresistive coefficients π_{11} , π_{12} and π_{44} . For the p-type piezoresistors, the absolute value of π_{44} is much larger than that of π_{11} and π_{12} [9]. Therefore, Eq. (1) is able to be approximated in

Fig. 3 Dimension of the piezoresistors (μm).

Fig. 4 Structure of the force sensor.

Fig. 5 Full-bridge circuit.

Fig. 6 Analytical model.

terms of π_{44} alone. When $\langle 111 \rangle$ is selected for longitudinal direction (X) and $\langle 211 \rangle$ is selected for transverse direction (Y) as shown in Fig. 2, each piezoresistive coefficients in Eq. (1) are expressed as follows.

$$\left. \begin{aligned} \pi'_{11} &\approx \frac{2}{3} \pi_{44} \\ \pi'_{12} &\approx -\frac{1}{3} \pi_{44} \\ \pi'_{13} &\approx -\frac{1}{3} \pi_{44} \\ \pi'_{14} &\approx \pi'_{15} \approx \pi'_{16} \approx 0 \end{aligned} \right\} \dots\dots\dots (2)$$

The relation between the stresses and the resistance changes of piezoresistors can be approximately expressed as Eq. (3).

$$\begin{aligned} \frac{\Delta R}{R} &\approx \frac{2}{3} \pi_{44} \sigma_1 - \frac{1}{3} \pi_{44} \sigma_2 - \frac{1}{3} \pi_{44} \sigma_3 \\ &\approx \frac{1}{3} \pi_{44} (2\sigma_1 - \sigma_2 - \sigma_3) \end{aligned} \dots\dots\dots (3)$$

Each piezoresistors are arranged into a full-bridge circuit as shown in Fig. 5. According to the circuit, the resistance changes of piezoresistors are transformed into the voltage changes as Eq. (4).

$$V_{out} = \frac{1}{2} \left(\frac{\Delta R_p}{R_p} - \frac{\Delta R_c}{R_c} \right) V_{in} \dots\dots\dots (4)$$

Where, V_{out} is the output voltage, V_{in} is the input voltage, R_c is the resistance for the central piezoresistors on the diaphragm (R_1 and R_4) and R_s is the resistance for the perimeter piezoresistors on the diaphragm (R_2 and R_3).

2.2 Combination of Stress Components

In the case of the ordinary diaphragm pressure sensor, when the pressure is applied on the surface of the sensor chip, stress components generated on the diaphragm can be estimated only σ_1 and σ_2 , because the other stress components are almost negligibly small. In this case, σ_1 and σ_2 on the center of the diaphragm are negative values (compressive stress), σ_1 and σ_2 on the perimeter of the diaphragm are positive values (tensile stress). σ_1 and σ_2 of both the center and the perimeter have the same signs. Therefore, the resistance changes of the central and the perimeter piezoresistors are proportional to $|2\sigma_1 - \sigma_2|$ according to Eq. (3). When the sign of σ_1 is opposite to that of σ_2 and σ_3 , larger resistance changes of the piezoresistors is obtained, because the stress term in Eq. (3) becomes summational as $|2\sigma_1| + |\sigma_2| + |\sigma_3|$. The sensor

structure which satisfies the above mentioned combination of stress components is investigated in the following chapter.

3 FEM ANALYSIS

3.1 Analytical Model

In order to estimate the output characteristics and obtain the most suitable structural parameters of the force sensor, FEM analysis was carried out. An analytical model was generated by MENTAT II, and MARC was used for the analysis [11]. This FEM analysis was three dimensional linear elastic analysis. The analytical conditions were as follows.

· Analytical model

The analytical model was composed of the sensor chip and the force transmission rod. The meshes of the piezoresistor portions having 150 μm length were divided with 50 μm step in order to obtain more than three nodes on the piezoresistors. The average values of stress of each nodes were used as stresses applied to the piezoresistors. The analysis was carried out by using one fourth part of the model, because of its symmetry. The analytical model is shown in Fig. 6.

· Boundary conditions

All nodes on the bottom of the sensor chip were restricted in X , Y and Z directions, respectively. Since the model was one fourth, the nodes on X -axis were restricted in Y direction and the nodes on Y -axis were restricted in X direction.

· Load condition

37.5 N (one fourth of 150 N which corresponds to 150 MPa) was applied to the center of the top of the rod.

· Material properties

In order to simplify the analysis, Si was assumed to be isotropic material. Young's modulus of Si was 170 GPa and Poisson's ratio was 0.25 [12].

The factors which influence on the output characteristics of the force sensor were considered as follows.

- (1) Young's modulus of the rod (E)
- (2) Height of the rod (h)
- (3) Diameter of the rod (d)
- (4) Thickness of the diaphragm (t)

As a result of the analysis and the investigation, a basic model was designed as follows: $E = 70 \text{ GPa}$, $h = 2.0 \text{ mm}$, $d = 1.5 \text{ mm}$, $t = 200 \mu\text{m}$. The variation of stress distributions on the piezoresistors were investigated by changing each factors in (1)-(4) from those of the basic model.

3.2 Analytical Results

As examples of analytical results, the distributions

of each stress components on X -axis with the variation of Young's modulus are shown in Fig. 7. As shown in Fig. 7, stress concentration is occurred at 750 μm from center due to notch effect of edge of the rod. The impurity concentration was approximately $2 \times 10^{20} \text{ cm}^{-3}$. The value of $\pi_{44} = 100 \times 10^{-12} \text{ cm}^2/\text{dyn}$ was used for calculation [13]. A dependence of the resistance changes on the Young's modulus is shown in Fig. 8. A dependence of the resistance changes on the height of the rod is shown in Fig. 9. A dependence of the resistance changes on the diameter of the rod is shown in Fig. 10. A dependence of the resistance changes on the thickness of the diaphragm is shown in Fig. 11.

3.3 Discussion

(1) Young's modulus of the rod (E)

The sensor is more and more sensitive as E is smaller as shown in Fig. 8. For the central piezoresistors, the dependence of σ_1 on E was larger than that of σ_2 and σ_3 as shown in Fig. 7. Therefore, σ_1 was most influential for the resistance changes. Duralumin was selected for the rod, because duralumin has smaller E comparing with Si, it is excellent as an elastic material, and it is stable and easy to fabricate.

(2) Height of the rod (h)

If h is more than 1.8 mm, the resistance changes were saturated as shown in Fig. 9. Therefore more than 1.8 mm was desirable to obtain the stable output. $h = 2.0 \text{ mm}$ was selected as the height of the rod.

(3) Diameter of the rod (d)

The sensor is more and more sensitive as d is smaller as shown in Fig. 10. With decreasing d , the location of peak stress at the rod edge became close to the location of the perimeter piezoresistors and the stress gradients of the perimeter piezoresistors became larger. Therefore, the scatter of output characteristic due to alignment errors might occur. $d = 1.5 \text{ mm}$ was selected from the view point of endurance load of sensor chip. When 150 N as full scale load is applied to the rod having $d = 1.5 \text{ mm}$, the maximum compressive stress of the sensor chip becomes less than half of the compressive fracture stress of Si.

(4) Thickness of the diaphragm (t)

In case of less than $t = 100 \mu\text{m}$, σ_1 , σ_2 and σ_3 were approached to zero as shown in Fig. 11. Thus, the resistance changes were also approached to zero. For the perimeter piezoresistors, the resistance changes of $t = 150 \mu\text{m}$ was little larger than that of $t = 200 \mu\text{m}$ and the largest value was obtained in case of $t = 100 \mu\text{m}$. As a result, resistance changes of the piezoresistors were almost same values in the range between $t = 150 \mu\text{m}$ and $t = 200 \mu\text{m}$. $t = 200$

μm has shortest etching time and highest sensor chip strength against compressive load among this range. Therefore, $t = 200 \mu\text{m}$ was selected.

• Thickness of the Si substrate

The dependence of resistance change on thickness of Si substrate was confirmed by FEM analysis. A Si substrate of 300 μm thickness is defined as standard thickness. When the Si substrate thickness changed $\pm 50 \mu\text{m}$ from 300 μm of standard thickness, the value of $|\sigma_3|$ on the perimeter piezoresistor changed $\pm 3 \%$. As the result, the sensor output changed $\pm 3 \%$.

4 CHARACTERISTICS

4.1 Prototyped Force Sensor

The thickness of the diaphragm was 200 μm . The parameters of the force transmission rod were as follows: $E = 70 \text{ GPa}$, $h = 2.0 \text{ mm}$, $d = 1.5 \text{ mm}$. The materials of the rod and the metal plate were duralumin and stainless steel, respectively. An epoxy bonding agent was used to bond each part. The above force sensor was fabricated and measured its characteristics.

4.2 Experimental Results

The compressive loads to 150 N were applied to the force transmission rod with Instron (the universal testing instrument). Then the output characteristic of the full-bridge circuit at the input voltage of 5 V was measured. The typical results are shown in Fig. 12 and Fig. 13.

4.3 Discussion

The measured resistance changes of the piezoresistors were negative values at the center (R_1 , R_4) and positive values at the perimeter (R_2 , R_3). At 150 N, $\Delta R/R$ of the center was -2.41 % and that of the perimeter was 2.36 %. The correlation between the experimental values and the analytical values were obtained as follows: $\Delta R/R$ of the center was 111 % and that of the perimeter was 91 % comparing with the analytical values. Experimental results were in good agreement with analytical values. As shown in Fig. 12, differences between each pairs of $\Delta R/R$ were due to alignment error of the rod and non-uniform stress distribution which depends on degree of parallel and surface roughness on contact area between the rod and the sensor chip. In fabrication of the prototyped force sensor, alignment error was within $\pm 20 \mu\text{m}$. FEM analysis revealed that when alignment error is within $\pm 20 \mu\text{m}$, change of $\Delta R/R$ on central piezoresistor is from -19.0 % to +8.2 %, and that of on perimeter

 Fig.7 Dependence of stress distribution on Young's modulus (E).

 Fig. 8 Dependence of resistance changes on Young's modulus (E).

 Fig. 9 Dependence of resistance changes on height of rod (h).

 Fig. 10 Dependence of resistance changes on diameter of rod (d).

 Fig. 11 Dependence of resistance changes on thickness of diaphragm (t).

piezoresistor is from -20.0 % to +16.0 %. The non-linearity of 5.1 % (F.S.) wasn't too much. This is due to unstable contact between the head, the rod and the sensor chip in lower applied load region, i.e., up to 30 N. As to the improvement, the nonlinearity can be approximately within 1 % by applying of more than 30 N preload. As to the improvement, the nonlinearity can be approximately within 1 % by applying of more than 30 N preload.

5 CONCLUSIONS

A structure of a piezoresistive force sensor unit which will be assembled into a miniature high pressure sensor with high sensitivity was investigated. In order to obtain relations between parameters of the force sensor structure and output characteristics, FEM analysis was carried out. The sensor structure to obtain large resistance changes of the piezoresistors was found by utilizing valid combination of three-axis stress components. According to FEM analytical results, duralumin of Young's modulus $E = 70$ GPa was selected as a material of the force transmission rod ($h = 2.0$ mm, $d = 1.5$ mm). As an experimental result, the output voltage more than 140 mV / 5 V at 150 N was obtained. In the future work, we will improve the precision of fabrication and develop the high pressure sensor assembled from the force sensor.

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Fig. 12 Resistance changes of piezoresistors versus applied load.

Fig. 13 Output characteristics of the force sensor.

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