Silicon Piezoresistive Six-Degree of Freedom Micro Force-Moment Sensor

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Abstract

In this paper, we describe the design, fabrication and calibration results of a 6-degree of freedom force-moment micro sensing chip utilizing the piezoresistance effect in silicon. The sensing chip is designed to be able to simultaneously detect three components of force and three components of moment in three orthogonal directions. Conventional p-type and four-terminal p-type piezoresistors have been combined in this single sensing chip in the (111) plane of silicon. The total number of piezoresistors is 18, much fewer than the previous art piezoresistance-based 6-component force moment sensors known to the authors. Calibration results show linear output responses (the maximum nonlinearity is 2% F.S.), and small crosstalk (the maximum crosstalk is less than 4%).

1. Introduction

Recently, the demands for micro force sensors in engineering applications are increasing. There have been substantial research and fabrication efforts for micro force sensors. Some examples of these are the three-component force sensors, (1,2) normal force sensor, (3) shear force sensor, (4) and three-dimensional tactile sensors. (5,6) While much work has dealt with three-component force sensors, studies on six force-moment components micro sensors are rare. The three-component sensors are adequate for the tasks involving feature identification, or determining object location. However, for certain applications, they are inadequate. (7)

Examples of such applications include measuring external forces on particles in liquid flows, and grasping and manipulation by robot hand. There have been several approaches to the design and fabrication of full six-component force sensors. Sinden and Boie (8) introduced some theoretical designs of a planar capacitive force sensor with six degrees of freedom (6-DOF). However, these designs are more complex than those of piezoresistance sensors and not economic to fabricate with MEMS in terms of fabrication accuracy, reproducibility, and sensor dimension. Some centimeter-scale conventional 6-DOF force sensors have also been presented, (9,10) in which the metallic strain gauges were fixed on a spatial structure. Kim et al. (11) designed and fabricated a six-component force moment sensor, which used a crossbeam combined with eight other surrounding beams for measuring $F_{x}, F_{y}, F_{z}, M_{x}$, $M_{y}$ and $M_{z}$. Twenty-four strain gages were bonded on the surface of the beams. These sensors are large and structurally complicated. Grahn (7) invented a triaxial normal and shear force sensor, which used ultrasonic technique as the detecting principle. Okada (12) also reported a planar six-axis force sensor based on the silicon piezoresistance effect. Forty-eight piezoresistors are formed at twenty-four places on the upper surface of beams. This structure, then, was bonded on the surface of a strain generative body. Large numbers of piezoresistors on beams make the electrical circuit complicated, and result in high power dissipation, wide beams, and consequently, high structural stiffness. Maximum crosstalk of about 24% was reported. Jin and Mote (13) developed a six-component silicon micro force sensor. Lorentz forces were used to calibrate the sensor. However, eight Wheatstone bridges were arranged on the four diaphragms increasing the size of the sensing area, or in other words, increasing the structural stiffness. Furthermore, the assembling of three components made the sensor sophisticated and larger in overall size. Crosstalk above 10% was reported.

In this research, a piezoresistance-based micro sensing chip with 6-DOF using only 16 conventional and 2 four-terminal piezoresistors is described. The sensing chip presented in this paper was designed for application to measurement of turbulent flow, and design ranges of force and moment were based on the estimated fluid forces. (14,15)

The structural analysis was carried out by FEM to optimize the dimensions and to locate the optimal positions for the piezoresistors. Then, the sensing chip was fabricated by micromachining processes. Finally, the sensing chip was calibrated using a computer-controlled ultra-small load indenter.

2. Design of Sensing Chip

The sensing chip is a single crystalline silicon crossbeam with two-terminal (conventional type) and four-terminal piezoresistors diffused on the surface of the four suspended-beams. Forces and moments applied to the sensing chip, shown in Fig. 1, deform the four suspended-beams and change the resistance of the piezoresistors, which leads to a change in output of corresponding measurement circuits. The beam’s size, piezoresistance coefficients and the positions of piezoresistors on the sensing chip are the main factors determining the sensitivity of the sensor. This section discusses how crystallographic orientations and piezoresistor arrangement were specified in order to obtain large sensitivity while satisfying the constraint that the sensor can detect six components of force and moment independently.

2.1 Piezoresistance effect - selection of crystallographic orientations

The piezoresistance effect is a phenomenon in which the electrical resistivity of a material changes due to applied stress. In semiconductors, strain-induced distortions of the energy band structure affect the mobility of the electrons and holes, and also redistribute the electron and hole concentrations. These changes in turn lead to the change of electrical resistivity $\rho$ of semiconductor. Substantial
calculated values of piezoresistance coefficients in single crystal silicon have been performed here recently, (18,19) valuable results have been obtained. In this research, forces and moments are measured by two-terminal and four-terminal piezoresistors.

As mentioned above, the piezoresistance coefficients can be expressed as,

$$\Delta R = \frac{\Delta R}{R} = \pi_{11} \sigma_1 + \pi_{12} \sigma_2 + \pi_{13} \sigma_3 + \pi_{14} \tau_1 + \pi_{15} \tau_2 + \pi_{16} \tau_3.$$  \hspace{1cm} (1)

where \(\Delta R/R\) is the relative change of resistance due to the normal stresses \(\sigma_i\) (i=1, 2, 3), and shear stresses \(\tau_j\) (j=4, 5, 6). The primed quantities \(\pi_{ij}^\prime\), \(k = 1, 2, 3, 4, 5, 6\), are the piezoresistance coefficients referred to arbitrarily oriented axes, or to a Cartesian system: 1’, 2’, and 3’. These coefficients \(\pi_{ij}^\prime\), being derived from a fourth-rank tensor, are defined here in terms of direction cosines or with respect to the principal crystallographic axes 1, 2 and 3, respectively. The piezoresistance coefficients of the diffused layer depend on impurity concentration and are much smaller than these bulk values.

### Fig. 1. FEM model of sensing chip, (unit: \(\mu m\))

The piezoresistance effect of conventional piezoresistors can be expressed as,\(^{20}\):

$$\pi_{ij} = \frac{\pi_{ij} - \pi_{i2} - \pi_{i4}}{\pi_{i2} - \pi_{i4}} [l_j (l_j^2 + m_j m_k + n_j n_k)] \hspace{1cm} (2)$$

$$\pi_{12} = \pi_{12} + (\pi_{11} - \pi_{12} - \pi_{44}) [l_j (l_j^2 + m_j m_k + n_j n_k)] \hspace{1cm} (3)$$

$$\pi_{13} = \pi_{13} + (\pi_{11} - \pi_{12} - \pi_{44}) [l_j (l_j^2 + m_j m_k + n_j n_k)] \hspace{1cm} (4)$$

$$\pi_{14} = 2(\pi_{14} - \pi_{44}) [l_j (l_j^2 + m_j m_k + n_j n_k)] \hspace{1cm} (5)$$

$$\pi_{15} = 2(\pi_{15} - \pi_{44}) [l_j (l_j^2 + m_j m_k + n_j n_k)] \hspace{1cm} (6)$$

$$\pi_{16} = 2(\pi_{16} - \pi_{44}) [l_j (l_j^2 + m_j m_k + n_j n_k)] \hspace{1cm} (7)$$

That is, the 1’-axis has the direction cosines \(l_1, m_1, n_1\), the 2’-axis has the direction cosines \(l_2, m_2, n_2\), and the 3’-axis has the direction cosines \(l_3, m_3, n_3\) with respect to the principal crystallographic axes 1, 2 and 3, respectively. These direction cosines can be calculated through Euler’s angles in the transformation of the coordinate system from principal crystallographic axes to the considered directions. For a bulk p-type piezoresistor with a resistivity of 7.8 Ωcm, these coefficients are \(\pi_{11} = 4.6 \times 10^{-11} \text{ Pa}^{-1}\), \(\pi_{12} = -1.1 \times 10^{-11} \text{ Pa}^{-1}\), and \(\pi_{44} = 138.1 \times 10^{-11} \text{ Pa}^{-1}\).\(^{22}\) In fact, the piezoresistance coefficients of the diffused layer depend on impurity concentration and are much smaller than these bulk values. With an impurity concentration of about \(5 \times 10^{19} \text{ cm}^{-3}\) (typical of our process), \(\pi_{11} = 1.5 \times 10^{-11} \text{ Pa}^{-1}, \) \(\pi_{12} = 85 \times 10^{-11} \text{ Pa}^{-1}\).\(^{23}\)

In a four-terminal piezoresistor, on the other hand, normal and shear stresses can produce an electrical field that is perpendicular to the direction of current flow.\(^{20,24}\) If one ignores extremely small effects of dimensional changes, the output transverse voltage between two voltage taps \(V_{out}\) of a four-terminal piezoresistor can be expressed as:

$$V_{out} = \frac{V_{in}}{V_{in}} = \pi_{i6} \sigma_1 + \pi_{i5} \sigma_2 + \pi_{i4} \sigma_3 + \pi_{i3} \tau_1 + \pi_{i2} \tau_2 + \pi_{i1} \tau_3.$$  \hspace{1cm} (8)

Here, \(V_{in}\) is the supply voltage, and the primed quantities \(\pi_{ij}^\prime\), \(i = 1, 2, 3, 4, 5, 6\), are the piezoresistance coefficients corresponding to normal and shear stresses of a four-terminal piezoresistor in arbitrary orientations. The coefficients \(\pi_{ij}\) are derived from a fourth-rank tensor by the transformation rule employed for \(\pi_{ij}^\prime\) mentioned above. The first subscript is 6 implying that the current density component and electrical field component are in perpendicular directions, i.e. 1’ and 2’. Similar to \(\pi_{ij}\), \(\pi_{ij}^\prime\) can be expressed in terms of direction cosines and fundamental piezoresistance coefficients \(\pi_{11}, \pi_{12}\) and \(\pi_{44}\).

The coefficients \(\pi_{ij}\), and \(\pi_{ij}^\prime\), \(i = 1, 2, 3, 4, 5, 6\), can be made large or small by selecting suitable orientations, e.g. changing the direction cosines \(l_1, m_1, n_1\), \(j = 1, 2, 3\) in eqs. (1) – (7). For convenience, we will assume that the X-axis, Y-axis, Z-axis are aligned with 1’, 2’ and 3’, respectively.

In our research, the piezoresistors are formed by the mask-diffusion method, so the piezoresistors lie on the surface of the sensing beams, and are very thin in comparison with the thickness of the beams. Stress analysis on the surface of the sensing structure, which will be presented in the section 2.2, shows that the components \(\pi_1\) (the tensile or compressive stress components parallel to direction 1’ (X-axis) or 2’ (Y-axis)) and \(\pi_6\) (the shear stress component in the plane containing axes 1’ and 2’, called “in-plane shear...
stress”) are found to be much larger than other components of stress, and become dominant for sensing purposes. For this reason, one of the criteria to select the crystallographic orientation is to make \( \eta_{11}' \) and \( \eta_{06}' \) as large as possible. Investigating various crystallographic orientations of single crystal silicon, the two crystallographic orientations \(<1\overline{1}0>\) and \(<1\overline{1}2>\) of silicon (111) were chosen to be the in-plane principal axes of the piezoresistors, since these orientations meet the selection criteria mentioned above, and the silicon (111) wafers are widely available on the market.

Substituting the direction cosines of these directions \(<1\overline{1}0>, <1\overline{1}2>\) and \(<11\overline{1}>\) into eqs. (1) – (7), we have:

\[
\eta_{11} = \frac{1}{2}(\eta_{11} + \eta_{12} + \eta_{44}), \quad \eta_{12} = \frac{1}{3}(\eta_{11} + \eta_{12} + \eta_{44}), \\
\eta_{13} = \frac{1}{3}(\eta_{11} + 2\eta_{12} - \eta_{44}), \quad \eta_{14} = \frac{\sqrt{2}}{3}(\eta_{11} - \eta_{12} - \eta_{44}), \quad \eta_{15} = \eta_{16} = 0, (9)
\]

Similarly,

\[
\eta_{41} = \eta_{42} = \eta_{43} = \eta_{44} = 0, \quad \eta_{45} = \frac{\sqrt{2}}{3}(\eta_{11} + \eta_{12} - \eta_{44}), \\
\eta_{46} = \frac{1}{3}(\eta_{11} - \eta_{12} + 2\eta_{44}). \quad (10)
\]

From eqs. (1) and (9) we can see that the two-terminal piezoresistors in these crystallographic orientations are not sensitive to in-plane shear stress \( \tau_6 \), while from eqs. (10) and (8) we can say that the four-terminal piezoresistors in these orientations are not sensitive to normal stress components \( \sigma_1 \), \( \sigma_2 \), \( \sigma_3 \). Hence, the four-terminal piezoresistor is named shear stress piezoresistor, or shear piezoresistor. The complementary properties of these two types of piezoresistors form the basis of our sensing principle for independently detecting in-plane shear stress and normal stress.

The selection of silicon (111) has turned out to have another advantage; \( \eta_{11}' \) and \( \eta_{06}' \) are constant in all directions in plane (111), so that the sensitivities to \( \sigma_1 \) and \( \tau_6 \) are constant along all orientations in the plane (111).

2.2 Structural analysis of the sensing chip and piezoresistor arrangement on the beams

The structural analysis of the sensing chip consists of two steps. The first step deals with qualitative analysis by classical elasticity theory. The dimensions of the sensing chip were tentatively specified based on the specified ranges of force and moment acting on a test particle (diameter of 10 mm) in water flow, \( <14,15> \) and the desired sensitivity, the piezoresistance effect of silicon, the non-buckling condition, and the necessary width of beam for wiring.

Next, this model was analyzed by a finite element method (FEM) to investigate more comprehensively the stress field in the structure, and to refine the specifications of the beam dimensions. Figure 1 shows the finite element model of the sensing chip for numerical analysis using MENTAT 3.1 software (MARC Research Corp.). The axes \( X \), \( Y \), \( Z \) are aligned with directions \(<1\overline{1}0>, <1\overline{1}2>\) and \(<11\overline{1}>\), respectively. The dimensions of each suspended-beam of the crossbeam: length x width x thickness are 500 x 120 x 40 \( \mu \)m. The anisotropic elasticity of silicon (111) is taken into account during FEM analysis to obtain more reliable simulation results.

Figures 2 - 5 show the distributions of stress components along the central axes on the surface of \( X \)-oriented and \( Y \)-oriented beams due to the application of each force or moment applied to the central point \( O \) of the chip. The point \( O \) coincides with center of central plate and lies on the neutral surface of the beams. Stresses in the central plate are not indicated since this area is not used for sensing purposes. The stress component \( \sigma_1 \) is the normal stress component parallel to the longitudinal axis of a beam and also to the direction of current density and electrical field of the conventional piezoresistors placed on that beam. Hence, it is called longitudinal stress \( \sigma_1 \). The component \( \sigma_2 \) is the normal stress component perpendicular to the longitudinal axis of a beam and of the conventional piezoresistors placed on that beam. It is called transverse stress; \( \sigma_3 \) is normal stress component perpendicular to \( \sigma_1 \) and \( \sigma_2 \); Component \( \tau_6 \) is an in-plane shear stress component (i.e., the shear stress component in the plane of the four-terminal piezoresistor, in this case it is the plane (XOY)), and \( \tau_4 \) and \( \tau_5 \) are out-of-plane shear stress components.

From classical elasticity and the FEM analysis, the stress statuses along the central axes on the surface of the beams were completely clarified. The piezoresistors’ positions on the beams were determined. Accordingly, sixteen p-type conventional piezoresistors, and two p-type shear piezoresistors were formed by using impurity diffusion along the central-longitudinal axes on the upper surface of an n-type silicon crossbeam. Figure 6 shows the layout of all eighteen piezoresistors on the surface of the crossbeam. The piezoresistors to measure one component of force or moment were arranged symmetrically through central point \( O \) on the two beams. All conventional piezoresistors were designed to be identical, as were the two shear piezoresistors.
The structural analysis results also show that, the out-of-plane shear stress components (i.e. \( \tau_4 \) and \( \tau_5 \)) on the beams' surface are so small that they can be ignored. The transverse stress components \( \sigma_2 \) and \( \sigma_3 \) are almost two-order smaller than \( \sigma_1 \), except in the area adjacent to the fixed ends of the beams, where \( \sigma_2 \) is same sign and about tens times smaller than \( \sigma_1 \). The appearance of this stress component in piezoresistors will slightly affect the sensitivity of the sensing chip, (see eq. 15 and note that \( \pi_{11}' \) and \( \pi_{12}' \) are in opposite sign). Hence, the piezoresistors have been arranged far enough from the fixed ends of beams (at least 10 \( \mu \)m or 2% of the beam length) to avoid this undesirable stress component.

Accordingly, eqs. (1) and (8) simplify to:

\[
\frac{\Delta R}{R} \approx \pi_{11}' \sigma_1, \quad \text{and} \quad \frac{V_{out}}{V_m} = \pi_{66}' \sigma_6. \tag{11}
\]

For p-type piezoresistors, \( \pi_{11} \) and \( \pi_{12} \) are sufficiently small in comparison with \( \pi_{44} \) so that they can be neglected. Equation (11) is thus approximated as:

\[
\frac{\Delta R}{R} = \frac{1}{2} \pi_{44} \sigma_4, \quad \text{and} \quad \frac{V_{out}}{V_m} = \frac{2}{3} \pi_{44} \tau_4 V_m \tag{12}
\]

\[
S_{\sigma} = \frac{1}{2} \pi_{44} \quad \text{and} \quad S_{\tau} = \frac{2}{3} \pi_{44}. \tag{13}
\]

where \( S_{\sigma} \) and \( S_{\tau} \) are the stress sensitivities of the conventional and shear piezoresistors, respectively.

Table 1 summarizes increases and decreases of resistance of the normal piezoresistors and output voltages of the four-terminal piezoresistors due to the applied loads. The ‘+’ and ‘-’ signs indicate, respectively, an increase and decrease, ‘0’ means unchanged and ‘-’ means a similar change in both sign and magnitude in piezoresistors of a corresponding bridge. Shaded regions indicate where the response of the corresponding bridge is non-zero.
Wheatstone bridge is a useful circuit to convert a change in components of force and moment independently. The 2.3 Electrical circuits and working principle

Based on the table 1, piezoresistors are connected to form the measurement circuits so as the sensor can detect six components of force and moment independently. The Wheatstone bridge is a useful circuit to convert a change in resistance to an output voltage. The general measurement circuit for measuring the five components, (Fx, Fy, Fz, Mx, and My), is created by connecting in parallel five independent detecting potentiometer circuits together and with a potentiometer circuit to form five Wheatstone bridges sharing a common half bridge, (Fig. 7 (a)).

Table 1. Resistance changes of normal piezoresistors and output voltages of shear piezoresistors.

<table>
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<tr>
<th></th>
<th>Fx-Bridge</th>
<th>Fy-Bridge</th>
<th>Fz-Bridge</th>
<th>My-Bridge</th>
<th>Mx-Bridge</th>
<th>Mz-Circuit</th>
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<tbody>
<tr>
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<tr>
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<td>0</td>
<td>0</td>
<td>+</td>
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<tr>
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<td>0</td>
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<td>0</td>
<td>+</td>
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<tr>
<td>Mz</td>
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</tbody>
</table>

V_{outFx} = \frac{1}{4} \left( \frac{\Delta R_{Fx1}}{R_{Fx1}} + \frac{\Delta R_{Fx2}}{R_{Fx2}} \right) V_{in} , \quad (17)

V_{outFy} = \frac{1}{4} \left( \frac{\Delta R_{Fy1}}{R_{Fy1}} + \frac{\Delta R_{Fy2}}{R_{Fy2}} \right) V_{in} , \quad (18)

where V_{in} is the input voltage. Note that all conventional piezoresistors mentioned here are identical.

Two four-terminal piezoresistors for measuring the moment around the Z-axis can give the output voltage directly without any additional converting circuits, (eq. 12). These piezoresistors are connected together via a standard operational amplifier to form a summing circuit, (25) which performs the algebraic addition operation between the voltages V_{outM1} and V_{outM2} of the two piezoresistors R_{M1} and R_{M2}, respectively, (see Fig. 7 (b)).

V_{outM} = V_{outM1} + V_{outM2} , \quad (19)

where V_{outM1} and V_{outM2} are calculated from Eq. (12).

The next sub-sections will describe the working principle of the sensing chip.

2.3.1 Detection of tangential forces Fx and Fy

When a tangential force Fx in the X-direction is applied to the sensing chip, the beam ⊙ with piezoresistor R_{Fx} will be subjected to a tensile stress, (Fig. 3), while the opposite beam (⊙), on which piezoresistor R_{Fy} is located, will undergo a corresponding compression, hence ΔR_{Fx} = -ΔR_{Fy}. As a result, the output voltage of the Fx-bridge is nonzero, (see eq. (17)):

V_{outFx} = \frac{1}{2} \frac{\Delta R_{Fy}}{R_{Fy}} V_{in} = \frac{1}{4} \frac{\Delta R_{Fx}}{R_{Fx}} V_{in} , \quad (20)

where S_{cxy} is defined as the circuit sensitivity of the Fx-bridge. By contrast, R_{Fx} and R_{Fy} in the Y-oriented beam exhibit no change in resistance because the longitudinal stresses in them are nearly equal to zero. Therefore, the Fy-bridge is still balanced, i.e., there is no response in this bridge. Similarly, the Mx-bridge has no response. In the case of the Fz-bridge, as the stresses at R_{Fx} and R_{Fy} have the same absolute magnitude, but are of opposite sign, so ΔR_{Fx} = -ΔR_{Fy}. Analogously, ΔR_{Fy} = -ΔR_{Fx}. Therefore V_{outFx} = 0,
so the $F_z$-bridge has no sensitivity to the force $F_x$. Similarly, the $M_y$-bridge has no response. In the $Y$-oriented beam, shearing stresses with the same magnitude but opposite in sign will exist in four-terminal piezoresistors $R_{M1}$ and $R_{M2}$, so the total output voltage of the $M_z$-circuit is still zero. Note that four-terminal piezoresistors with crystal directions mentioned above are not sensitive to longitudinal stress, (see eq. (12)).

The detection of tangential force $F_y$ is similar $F_x$.

### 2.3.2 Detection of vertical force $F_z$

When a vertical force $F_z$ is applied to the sensing chip, from the FEM result, (Fig. 4), the longitudinal stresses in the four piezoresistors of the $F_z$-bridge can be written as below:

$$\sigma_{F_z} = \sigma_{F_y} = -\sigma_{F_y} = -\sigma_{F_z}$$

where $\sigma_{F_z}$ is the longitudinal stress at piezoresistor $R_{F_z}$, $i=\frac{1}{4}$. Therefore, $\Delta R_{F_z} = \Delta R_{F_y} = -\Delta R_{F_y} = -\Delta R_{F_z}$.

Consequently, the $F_z$-bridge is unbalanced, and the output response is different from zero, (see eq. (14)):

$$V_{outF_z} = \frac{1}{2} \sigma_{F_z} \frac{1}{2} R_{F_z} + \frac{1}{4} \sigma_{F_y} \frac{1}{2} R_{F_y} + \frac{1}{4} \sigma_{F_y} \frac{1}{2} R_{F_y} + \frac{1}{4} \sigma_{F_z} \frac{1}{2} R_{F_z} = \frac{V_c}{2} \Delta R_{F_z}$$

where $S_{F_z}$ is defined as the circuit sensitivity of the $F_z$-bridge. Due to the symmetry of the arrangement of piezoresistors and the structure of the sensing chip, the longitudinal stresses at $F_{R1}$ and $R_{F2}$ are equal, (Fig. 4), hence their resistance changes are equal: $\Delta R_{F1} = \Delta R_{F2}$, so the output voltage of the $F_x$-bridge is equal to zero, (see eq. (17)). Similarly, no response will occur in the $F_y$-bridge. Likewise, in the case of the $M_x$-bridge, the total resistance change of the upper arm ($\Delta R_{M_x}$) is equal to that of the lower arm ($\Delta R_{M_y} = \Delta R_{M_y}$), (Fig. 7 (a)); therefore the $M_y$-bridge is still balanced. Similarly, the response of the $M_z$-bridge is zero. The in-plane shear stress component is equal to zero at $R_{M1}$ and $R_{M2}$, so the output of the $M_z$-circuit is equal to zero.

### 2.3.3 Detection of moments $M_x$ and $M_y$

When a moment $M_y$ around the $Y$-axis is applied to the sensing chip, as can be seen from the FEM result, (see Fig. 2), the longitudinal stresses in the four piezoresistors of the $M_y$-bridge can be written as $\sigma_{F_0} = -\sigma_{F_2} = -\sigma_{F_2} = \sigma_{F_0}$, where $\alpha$ is a constant depending upon the width and length of the beam; in this study, $\alpha \approx 0.75$. Therefore, the resistance change in the $M_y$-bridge can be written by $\Delta R_{M_y} = -\Delta R_{M_2} = -\alpha \Delta R_{M_2} = \alpha \Delta R_{M_2}$. Substituting this relation into eq. (16), the output voltage and circuit sensitivity of the $M_y$-bridge are expressed by:

$$V_{outM_y} = \frac{1}{4} \sigma_{F_2} \frac{1}{2} R_{F_2} + \frac{1}{4} \sigma_{F_2} \frac{1}{2} R_{F_2} + \frac{1}{4} \sigma_{F_2} \frac{1}{2} R_{F_2} + \frac{1}{4} \sigma_{F_2} \frac{1}{2} R_{F_2} = \frac{V_c}{2} \Delta R_{M_y}$$

$$S_{M_y} = \frac{1}{4} \sigma_{F_2} \frac{1}{2} R_{F_2}$$

However, for the piezoresistors of the $F_z$-bridge, $\Delta R_{F_z} = \Delta R_{F_4} = -\Delta R_{F_4}$. Therefore, the output voltage of the $F_z$-bridge is zero. $R_{F_{41}}$ and $R_{F_{42}}$ are intentionally located at the positions where the longitudinal stress, induced by the concentrated moment $M_y$, is equal to zero, as mentioned in the section 2.2. As a result, the $F_x$-bridge has no response either. The FEM analysis result has shown that these positions are unchanged when the beam thickness and/or the moment $M_y$ are changed. In the $Y$-oriented beam, the longitudinal stress is equal to zero along the central longitudinal axis (or at the piezoresistors), so the $F_y$-bridge and $M_x$-bridge have no response. Shearing stresses of identical magnitude but opposite sign exist along the $Y$-oriented beams, therefore they also exist in the four-terminal piezoresistors $R_{M1}$ and $R_{M2}$, so the total output voltage of the $M_z$-circuit is still zero, (eq. (19)).

The detection of tangential force $F_x$ is similar to $M_y$.

### 2.3.4 Detection of moment $M_z$

When a moment around the $Z$-axis $M_z$ is applied to the sensing chip, only shearing stresses ($\tau_y$) are large enough to consider, (Fig. 5). These stresses are equal in magnitude and sign at $R_{M1}$ and $R_{M2}$, so the total output voltage in the $M_z$-circuit is nonzero:

$$V_{outM_z} = \frac{2}{3} \pi_3 \pi_6 \tau_y V_c = \frac{2}{3} \pi_3 \pi_6 \tau_y S_{M_z}$$

where $S_{M_z} = 2V_{in}$ is the circuit sensitivity of the $M_z$-bridge. The other bridges have no response to these shearing stresses.

### 3. Fabrication Process

The sensing chip (Fig. 8) was fabricated by micromachining processes described briefly by the following steps:

**Step 1:** The starting material was a 4-inch n-type (111) silicon wafer with a thickness of 400 μm.

**Step 2:** A 0.3μm-thick SiO₂ insulator layer was formed by a thermal oxidation process.

**Step 3:** Piezoresistors were patterned so that their principal axes align with the crystal directions $<1\overline{1}0>$ and $<1\overline{1}2>$, Boron ions were diffused to form p-type piezoresistors by using a spin-on diffusion source (PBF, Tokyo Ohka Kogyo Co., Ltd). Pre-deposition process was performed in $N_2$ at 1000°C for 60 min. Then, a drive-in process was carried out in dry $O_2$ at 1100°C for 30 min to activate boron ions in the Si. In order to reduce the temperature sensitivity of piezoresistors, the surface impurity concentration was controlled at about $5 \times 10^{19}$ cm$^{-3}$.

**Step 4:** Contact holes were opened by wet etching in buffered HF solution.

**Step 5:** 0.6-μm-thick aluminum wires and bonding pads were formed by vacuum evaporation, photolithography, and etching processes. Next, a sintering process was performed in $N_2$ at 400°C for 30 min to form an Ohmic contact between electrodes and piezoresistors.
Step 6: A crossbeam pattern was defined by photolithography using a double-sided mask aligner. Then, a front side surface deep reactive ion etching (D-RIE) process was performed to a depth of 40 μm. Finally, the cavity and overload-stopper were formed by D-RIE from the back surface. A thick photoresist was adopted as a passivation layer during the D-RIE process.

The sensitivities of each components are: $S_{F_x} = 1.32$ mV/mN, $S_{F_y} = 0.12$ mV/mN, $S_{F_z} = 0.107$ mV/mN, $S_{M_x} = 4$ mV/mNμm, $S_{M_y} = 3.88 \times 10^{-3}$ mV/mNμm, and $S_{M_z} = 4.6 \times 10^{-4}$ mV/mNμm. The crosstalk was small. Maximum crosstalk of 4% was measured. The maximum nonlinearity ($NL$) of each components are $NL_{F_x} = NL_{F_y} = 1.02$ % F.S., $NL_{F_z} = 0.53$ % F.S., $NL_{M_x} = NL_{M_y} = 2.51$ % F.S., and $NL_{M_z} = 1.62$ % F.S. The relation of the output voltages of measurement circuits and the applied force and moment components can be summarized as below:

$$V = \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} 0.121 & 0.0035 & 0.007 & 0.042 & 0.009 & 0.008 \\ 0.0041 & 0.107 & 0.003 & 0.024 & 0.025 & 0.002 \\ 0.0022 & 0.0035 & 1.32 & 0.031 & 0.024 & -0.002 \\ 0.0021 & 0.0040 & 0.022 & 4.00 & 0.029 & 0.007 \\ 0.0025 & 0.0042 & 0.01 & 0.039 & 3.88 & 0.011 \\ 0.0023 & 0.0032 & 0.008 & 0.005 & 0.036 & 0.461 \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix}$$

where the unit of force is mN, of moment is Nμm and the output voltage is mV. Range of forces $F_x$ and $F_y$ is 1000 mN, of force $F_z$ is 100 mN, of moments $M_x$ and $M_y$ is 30 Nμm, and of moment $M_z$ is 300 Nμm. The off-diagonal components, which represent for the crosstalks, were not zero. The crosstalks occurred due to some defects in fabrication process, such as misalignments of piezoresistors on the beams. As described in the section 2.2, the piezoresistors to measure one specific component of force or moment are laid out symmetrically through the central point $O$. The misalignment could break this symmetric feature, and causes undesirable unbalances in the Wheatstone bridges. Consequently, slight crosstalks can be occurred. A well-controlled fabrication process can improve this situation.

5. Conclusions

The theoretical investigation, design, fabrication, and calibration of a 6-DOF force-moment sensing chip have been presented. By combining conventional and four-terminal piezoresistors in Si (111), and arranging and connecting them appropriately, their number was considerably reduced in comparison with the prior 6-DOF piezoresistive force sensors known to the authors; consequently, the sensing chip is smaller, more sensitive, and consumes less power. Calibration for six components of force versus output voltages has been completed. The sensitivities are high, linear, and close to the design values. The crosstalks are smaller than that of previously reported 6-DOF micro force moment sensors.

The design of the sensing chip presented above can be applied to different integrated force-based micro devices, such as tactile sensors, and micro multi-axis accelerometers.

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