논문 2002-11-4-01

Design and Fabrication of Six-Degree of Freedom Piezoresistive Turbulent Water Flow Sensor

Dzung Viet Dao*, **Toshiyuki Toriyama****,

John Wells* and **Susumu Sugiyama***

Abstract

This paper presents the design concept, theoretical investigation, and fabrication of a six-degree of freedom (6-DOF) turbulent flow micro sensor utilizing the piezoresistive effect in silicon. Unlike other flow sensors, which typically measure just one component of wall shear stress [1,2], the proposed sensor can independently detect six components of force and moment on a test particle in a turbulent flow. By combining conventional and four-terminal piezoresistors in Si (111), and arranging them suitably on the sensing area, the total number of piezoresistors used in this sensing chip is only eighteen, much fewer than the forty eight piezoresistors of the prior art piezoresistive 6-DOF force sensor [3].

Keywords: *piezoresistive effects, micro force-moment sensor, flow sensor.*

INTRODUCTION

One of the holy grails in geophysical research is reliable simulation technology for the micromechanics of sediment particle, erosion and transport, which are the fundamental processes shaping the land and major factors in flooding phenomena. In the previous work here[4], temporally resolved, high-resolution Particle Image Velocimetry (PIV) has provided the first experimental confirmation of the staggered arrangement of streamwise vortices previously predicted by numerical simulations to occur near the wall of turbulent channel flow. Figure 1 shows a perspective view of coherent vortices over the wall of a turbulent channel flow, measured by stereographic PIV in a cross-stream laser sheet, near the lower wall of a water channel. Isosurfaces of streamwise vorticity are shown in dark and light gray, while low speed fluid is indicated by wire frame. Prominent Reynolds-stress producing events are indicated by black spheres (ejections) and transparent gray spheres (sweeps.)

Fig. 1. Perspective view of coherent vortices over the wall of a turbulent channel flow.

In order to investigate the spatio-temporal re-

---

* Graduate School of Science and Engineering, Ritsumeikan University, Japan.
** New Energy and Industrial Technology Development Organization, Japan.
<접수일자 : 2002년 5월 24일>

lationship between near-wall vortices and particles, it is necessary to have micro force sensors with Six Degrees of Freedom (6-DOF) to measure the fluctuating components of force and moment on a particle at the bed of a turbulent channel flow. Such data will be invaluable in verifying simulations of sediment transport.

There have been several approaches to design and fabricate full six-component force-moment sensors. Sinden and Boie [5] introduced some theoretical designs of a planar capacitive force sensor with 6-DOF. However, these designs are more complex than piezoresistive sensors and not advantageous 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 [6,7], in which the metallic strain gauges were fixed on spatial structure. These sensors are very complicated structurally and have low sensitivity. Grahn [8] invented a triaxial normal and shear force sensor, which used ultrasonic technique as the detecting principle. Okada [3] also reported a planar six-axis force sensor based, on the silicon piezoresistive effect. Forty-eight piezoresistors are formed at twenty-four places on the upper surface of beams. Large numbers of piezoresistors on beams make the electrical circuit complicated, and result in high power dissipation, wide beams, and consequently, high structural stiffness.

In this paper, a piezoresistive-based micro sensing chip with 6-DOF using only sixteen conventional and two four-terminal piezoresistors is described. The configuration of a specific sensor to measure forces and moments acting on particles in turbulent liquid flows is also briefly presented. One can use this design of sensing chip to fabricate other micro integrated force-based devices, such as tactile sensors, and micro accelerometers.

CONFIGURATION OF SENSOR

The sensor configuration is shown in Fig. 2. The sensing chip has a Si crossbeam with normal and shear piezoresistors on the upper surface of the beams. Connections are wired to off-chip circuits by flexible cables sealed onto 4 walls of a base pillar. As mentioned above, the first planned application of this sensor is to measure the forces and moments acting on a particle placed at the boundary wall of a turbulent flow of water. The test particle has a diameter of about 8 mm and is made of polyethylene, of which the specific gravity is 0.965, nearly equal to that of water. By this selection of material, the vertical force component induced by gravity of particle is almost eliminated during working. The centroid of particle will coincide with the center of the surface of the sensing chip. The sensing chip is completely overlThe sensor are waterproofed by a silicone rubber layer. oad-protected by a protection base located under it. All electrical elements of the sensor are waterproofed by a silicone rubber layer.

Forces and/or moments from liquid flow acting on the test particle will be transmitted to the sensing chip via a force transmission pillar placed at the center of the sensing chip; consequently, the crossbeam will deform and the resistance of the piezoresistors will change, thus changing the output of the corresponding bridge circuits.

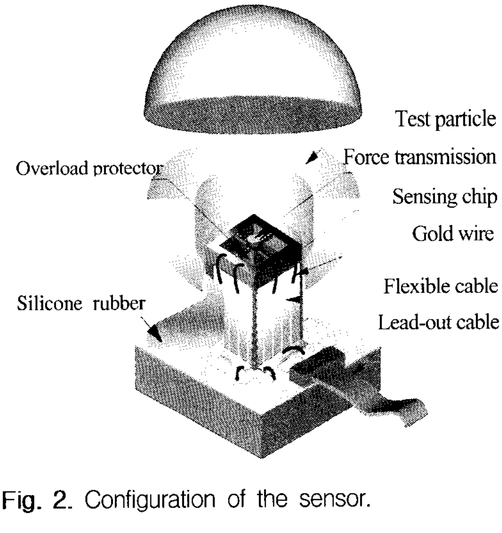


Fig. 2. Configuration of the sensor.

DESIGN OF SENSING CHIP

Structural Analysis

The dimensions of the sensing chip were tentatively specified based on the expected ranges of force and moment acting (horizontal forces *Fx*, *Fy* of about 1 N, and moments around *X* or *Y* axes of about 10 Nm, Fig. 3) and the desired sensitivity, the piezoresistive effect of silicon, the non-buckling condition, and the necessary width of beam for wiring. This model was then analyzed by FEM to investigate more fully the stress field in the structure, and to optimize the specifications of the beam dimensions. Figure 3 shows the finite element model of the sensing chip for numerically analyzing in MENTAT 3.1 software (MARC Research Corp.). The modal analyses were also performed to ensure the sensor work well in turbulent liquid flow. The dimensions of each arm of the crossbeam: length x width x thickness are 500 x 120 x 40 μm^3. The overall sizes of the chip are 3000 x 3000 x 400 μm^3. Two lateral faces of the four pedestals at the outer ends of beams are fixed as a boundary condition. For all directions in the plane (111) of Si, Young's modulus E = 169 GPa and Poisson's ratio ν = 0.358, [9]. External forces and moments are applied on the central plate. Figure 4 shows the distributions of longitudinal stress components in *X*-axial beams due to the action of forces Fz = 0.04N, Fx = 0.7N and moment My = 12Nμm, applied consecutively. Figure 5 shows the shear stress distributions in the Y-axial beams, induced by moments Mz = 88 Nμm, My =12 Nμm and force Fx = 0.7 N also applied in turn. Stresses in the central plate are not indicated since this area is not used for sensing purposes. The structural sensitivity S_{stL}(or structural flexibility) to an applied load L is defined as below:

$$S_{stL} = \frac{\sigma_{\max}}{L} \tag{1}$$

where $\sigma_{\max}$ is the maximum absolute stress among the stresses occurring at the various piezoresistors used in measuring that load.

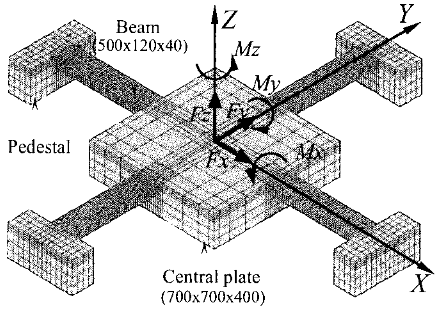


Fig. 3. FEM model of sensing chip.

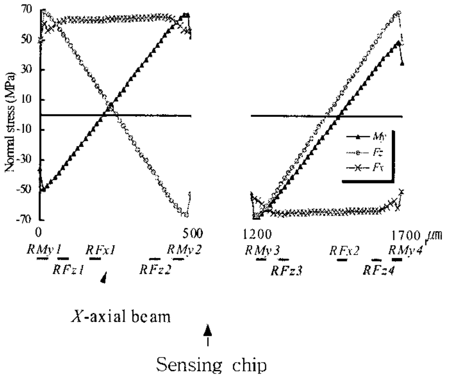


Fig. 4. Longitudinal stress distributions in X-axial beams.

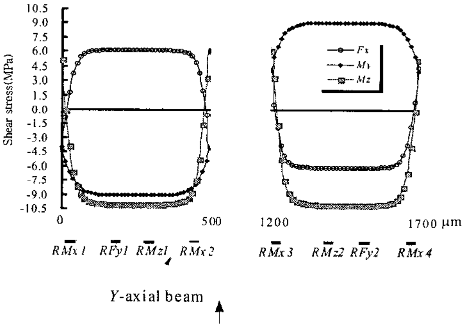


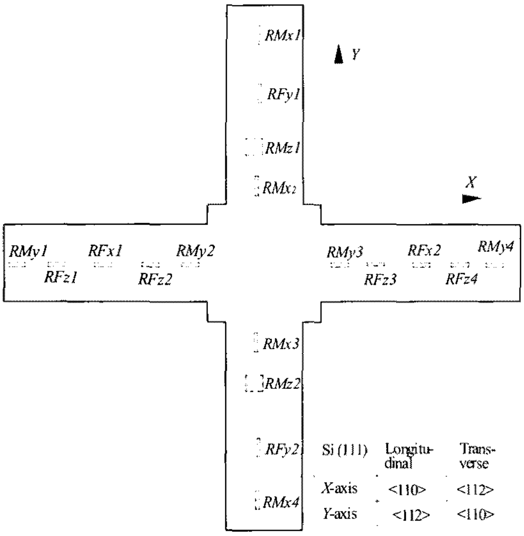
Fig. 5. Shear stress distributions in Y-axial beams.

Arrangement of Piezoresistors

Based on the stress distribution in the crossbeam derived from FEM analysis, piezoresistors were placed to eliminate the cross-axis sensitivities, and to maximize the sensitivities to various components of force and moment as shown in Figs. 4, 5 and 6. Sixteen p-type conventional piezoresistors, (4-R_{Fz}, 2-R_{Fx}, 2-R_{Fy}, 4-R_{Mx}, and 4-R_{My} to detect Fz, Fx, Fy, Mx, and My, respectively), and two p-type four -terminal piezoresistors (R_{Mz1} and R_{Mz2} to measure the moment Mz), are diffused along the central- longitudinal axes on the upper surface of an n-type silicon crossbeam, (Fig. 6). The in-plane principal axes of the piezoresistors are aligned with the crystal directions $<1\bar{1}0>$ and $<11\bar{2}>$ of silicon (111). All conventional piezoresistors are designed to be identical, as are the two shear piezoresistors. The piezoresistive effect of conventional single- crystalline piezoresistors can be expressed as below, [10]:

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

where $\frac{\Delta R}{R}$ is the relative change of resistance in a conventional piezoresistor due to the longitudinal stress σ_l (*i.e.* the component parallel to the current flow and electrical field) and transverse stress σ_t . π_l and π_t are the corresponding piezoresistance coefficients.



Si (111)	Longitudinal	Transverse
X-axis	<110>	<112>
Y-axis	<112>	<110>

Fig. 6. Arrangement of piezoresistors on the crossbeam.

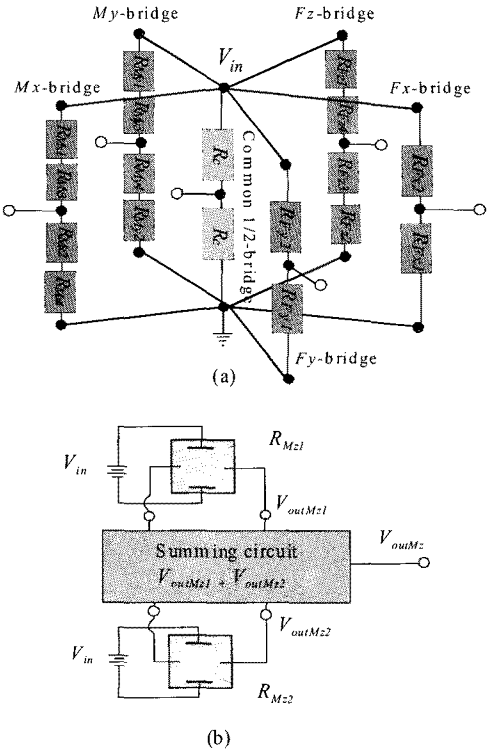


Fig. 7. Measurement circuits.

Piezoresistors are arranged far enough from the fixed beam-ends to avoid unexpected stress components, so that the stress status at each conventional piezoresistor is uniaxial, and as a result, $\sigma_t \approx 0$. Thus, Eq. (2) can be rewritten by:

$$\frac{\Delta R}{R} = \pi_l \sigma_l \tag{3}$$

The piezoresistive effect of a four-terminal piezoresistor can be expressed as below, [11]:

$$V_{out} = \pi_s \tau_s V_{in} \tag{4}$$

where V_{out} is the output voltage of the four-terminal piezoresistor in response to an in-plane shear stress τ_s (or τ_{xy}), V_{in} is the supply voltage, and π_s is the shear piezoresistance coefficient. Ignoring extremely small dimensional changes of the piezoresistors, π_l and π_s are constant and their values in the two crystal directions $<1\bar{1}0>$ and $<11\bar{2}>$ can be expressed respectively by Eqs. (4) and (5) below, [12]:

$$\pi_{l<1\bar{1}0>} = \pi_{l<11\bar{2}>} = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44}) \tag{5a}$$

$$\pi_{s<1\bar{1}0>} = \pi_{s<11\bar{2}>} = \frac{1}{3}(\pi_{11} - \pi_{12} + 2\pi_{44}) \tag{5b}$$

With an impurity concentration of about 5×10^{19} cm^{-3} (typical of our process), $\pi_{44} = 85\times10^{-11}$ Pa-1, [13]. For p-type piezoresistors, π_{11} and π_{12} are sufficiently small in comparison with π_{44}, that they can be neglected. Equation (5a) and Eq. (5b) are thus approximated by:

$$\pi_{l<1\bar{1}0>} \approx \frac{1}{2}\pi_{44}; \pi_{s<1\bar{1}0>} \approx \frac{2}{3}\pi_{44} \tag{6}$$

Define $S_{gn} = \frac{1}{2}\pi_{44}$ and $S_{gs} = \frac{2}{3}\pi_{44}$ (7)

where S_{gn} and S_{gs} are the stress sensitivities of the normal and shear piezoresistors, respectively.

Table 1 summarizes the resistance changes for the conventional piezoresistors and output voltages for 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. Gray-colored regions indicate where the response of the corresponding bridge is non-zero

Measurement Circuits

The measurement circuit for measuring the five components, (*Fx*, *Fy*, *Fz*, *Mx*, and *My*), is created by connecting five parallel detecting potentiometer circuits with a common potentiometer circuit to form Wheatstone bridges sharing a common half-bridge, (Fig. 7 (a)). The common half-bridge resistors are identical and placed side by side on an unstressed region of the chip. The output voltage of each bridge can be measured between the output point of each sensing potentiometer and the output point of the common one (Wheatstone-bridge rule) to find the corresponding applied load.

To measure the moment around the Z-axis Mz, the voltages V_{outMz1} and V_{outMz2} of the two four-terminal piezoresistors R_{Mz1} and R_{Mz2} are summed by a summing circuit, (Fig. 7 (b)).

$$V_{outMz} = V_{outMz1} + V_{outMz2} \tag{8}$$

where V_{outMz1} and V_{outMz2} are calculated from Eq. (4).

Detection of *Fx* and *Fy*

When a tangential force *Fx* in *X*-direction is applied to the sensing chip, the beam with piezoresistor R_{Fx1} will be subjected to a tensile stress, (Fig. 4), while the opposite beam, on which piezoresistor R_{Fx2} is located, will undergo a corresponding compression, hence $\Delta R_{Fx1} = -\Delta R_{Fx2}$. As a result, the output voltage of the *Fx*-bridge is different from zero:

$$V_{outFx} = \frac{\Delta R_{Fx1}}{2R_{Fx1}} V_{in}, \text{ and } S_{CFx} = \frac{V_{outFx}}{\frac{\Delta R_{Fx1}}{R_{Fx1}}} = \frac{V_{in}}{2} \tag{9}$$

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

	***Fx*-bridge**		***Fy*-bridge**		***Fz*-bridge**				***My*-bridge**				***Mx*-bridge**				***Mz*-circuit**	
	R_{Fx1}	R_{Fx2}	R_{Fy1}	R_{Fy2}	R_{Fz1}	R_{Fz2}	R_{Fz3}	R_{Fz4}	R_{My1}	R_{My2}	R_{My3}	R_{My4}	R_{Mx1}	R_{Mx2}	R_{Mx3}	R_{Mx4}	R_{Mz1}	R_{Mz2}
Fx	+	-	0	0	+	+	-	-	+	+	-	-	0	0	0	0	+	-
Fy	0	0	+	-	0	0	0	0	0	0	0	0	+	+	-	-	0	0
Fz	=	=	=	=	+	-	-	+	+	-	-	+	+	-	-	+	0	0
My	0	0	0	0	+	-	+	-	+	-	+	-	0	0	0	0	+	-
Mx	0	0	0	0	0	0	0	0	0	0	0	0	+	-	+	-	0	0
Mz	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	=

where S_{CFx} is defined as the circuit sensitivity of the *Fx*-bridge. By contrast, R_{Fy1} and R_{Fy2} in the *Y*-axial beam have no change in resistance because the normal stresses in them are mostly 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_{Fz1} and R_{Fz4} have the same absolute magnitude, but in opposite sign, (Fig. 4), so $\Delta R_{Fz1} = -\Delta R_{Fz4}$. Analogously, $\Delta R_{Fz2} = -\Delta R_{Fz3}$. Therefore $V_{outFz} = 0$, or the *Fz*-bridge has no sensitivity to the force *Fx*. Similarly, the *My*-bridge has no response. In the *Y*-axial beam, shearing stresses with the same magnitude but opposite sign will exist in four-terminal piezoresistors R_{Mz1} and R_{Mz2}, (Fig. 5), so the total output voltage of the *Mz*-circuit is still zero. Note that four-terminal piezoresistors with crystal directions mentioned above are not sensitive to normal stresses, (see Eq. (4)).

The detection of tangential force *Fy* is analogous to *Fx*.

Detection of *Fz*

When a vertical force *Fz* is applied to the sensing chip, from the table 1 and Fig. 7 (a), the resistance changes in the four piezoresistors of the *Fz*-bridge can be written as $\Delta R_{Fz1} = \Delta R_{Fz4} = -\Delta R_{Fz2} = -\Delta R_{Fz3}$. Consequently, the *Fz*-bridge is unbalanced, and the output response is different from zero:

$$V_{outFz} = \frac{\Delta R_{Fz1}}{2R_{Fz1}} V_{in} \text{ and } S_{CFz} = \frac{V_{outFz}}{\frac{\Delta R_{Fz1}}{R_{Fz1}}} = \frac{V_{in}}{2} \tag{10}$$

where S_{CFz} is defined as the circuit sensitivity of the *Fz*-bridge. The other bridges have no response to this force *Fz*.

Detection of *Mx* and *My*

Similarly, when a moment My around the Y-axis is applied to the sensing chip, as can be seen from the FEM result, (Fig. 4), the normal stresses in the four piezoresistors of the My-bridge can be written as $\sigma_{R_{My1}} = -\sigma_{R_{My4}} = -\alpha\sigma_{R_{My2}} = \alpha\sigma_{R_{My3}}$, where α is a constant depending upon the width and length of the beam; in this study, $\alpha \approx 3/4$. Therefore, the resistance change in the My-bridge can be written by $\Delta R_{My1} = -\Delta R_{My4} = -\alpha\Delta R_{My2} = \alpha\Delta R_{My3}$. The output voltage and circuit sensitivity of the *My*- bridge are expressed by:

$$V_{outMy} = \frac{(1+\alpha)\Delta R_{My3}}{4R_{My3}} V_{in} \text{ and } S_{CMy} = \frac{(1+\alpha)V_{in}}{4} \tag{11}$$

The outputresponse of the Fx-bridge, Fy-bridge, Fz-bridge, Mx-bridge, and Mz-circuit are zero, (see table 1, Fig. 7 (a), and Fig. 7 (b)). Note that R_{Fx1} and R_{Fx2} are specified to lie at the positions where the normal stress, induced by moment *My*, is equal to zero, (Fig. 4).

The detection of moment Mx is analogous to My.

Detection of *Mz*

When a moment around the Z-axis Mz is applied to the sensing chip, only shearing stresses exist in the piezoresistors. These stresses are equal in magnitude and sign at R_{Mz1} and R_{Mz2}, (Fig. 5), so the total output voltage in the *Mz*-circuit is non zero:

$$V_{outMz} = 2\,V_{outMz\,1} = 2\,S_{gs}\tau_s V_{in} = S_{CMz}\,S_{gs}\tau_s \tag{12}$$

where $S_{CMz} = 2\,V_{in}$ is the circuit sensitivity of the *Mz*-circuit. The other bridges have no response to these shearing stresses.

FABRICATION PROCESS

Figure 8 shows the major steps in the fabrication process for the sensing chip. At each step, the main processes, typical geometry, and the desired dimensions are listed.

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

Step 2: A 0.3μm-thick insulator layer SiO_2 was formed by thermal oxidization process.

Step 3: Piezoresistors were patterned so as their principal axes align with the crystal directions $<1\bar{1}0>$ and $<11\bar{2}>$. Boron ions were diffused to form p-type piezoresistors. A drive-in process was done to activate boron ions deeper into the Si substrate. In order to reduce the temperature sensitivity of piezoresistors, the impurity concentration was controlled at about $5\times10^{19}\,\mathrm{cm}^{-3}$.

Step 4: Contact holes were opened to assure there are not any unexpected insulator layers sandwiched between piezoresistors and electrodes.

Step 5: 0.6 μm-thick aluminum wires and bonding pads were formed by vacuum evaporation, photolithography, and etching processes. Next, the sintering process was performed in a dry N_2 environment for 30 minutes at 400℃ to make firm contact between electrodes and piezoresistors.

Step 6: Crossbeam pattern was defined by photolithography using a double-sided mask aligner. Then, frontside 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 backside. Thick photoresist was adopted as passivation layer during D-RIE process. Figure 9 is a micrograph of a fabricated sensing chip.

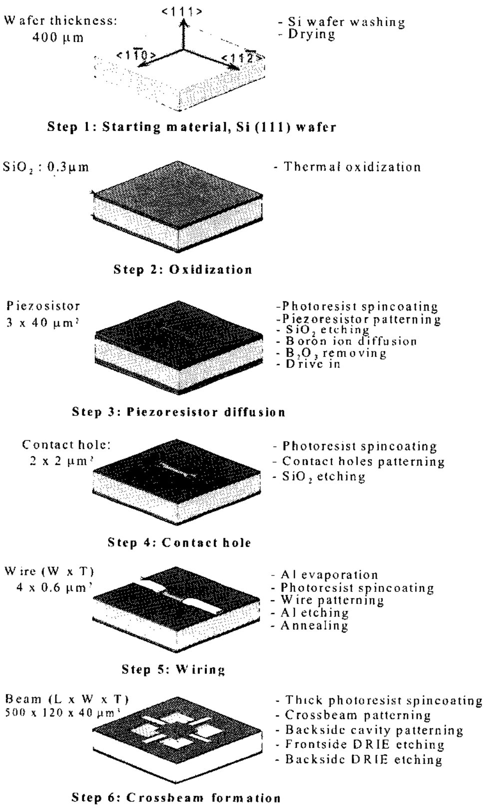


Fig. 8. Fabrication process for sensing chip.

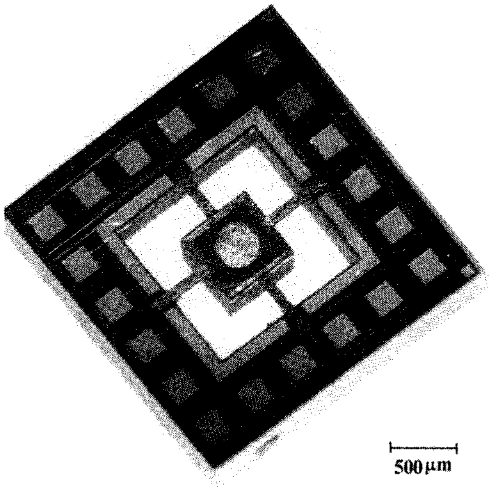


Fig. 9. Micrograph of sensing chip.

OUTPUT RESPONSE

The output characteristics and the sensitivity have been thoroughly analyzed. In response to the i^{th} component, L^i, of force or moment, the output voltage V_{out}^i is given by $V_{out}^i = S_{L^i} L^i = S_g^i S_{St}^i S_C^i L^i$, where S_g^i, S_{St}^i, S_C^i are stress, structural and circuit sensitivities for *Li* component. S_{St}^i was defined in Eq. (1), S_g^i is determined by Eq. (7), and S_C^i can be calculated following one of the equations from Eq. (9) to Eq. (12), depending on the specific component the L^i. Table 2 shows the output characteristics of the sensing chip. In this paper, the sensing chip has been designed for application in hydraulics, where the horizontal force of liquid flow *Fx* (or *Fy*) is much larger than that in the vertical direction, so the structural stiffness with force in horizontal direction was higher than that in the vertical direction. These sensitivities can be balanced by changing the length and thickness of the beams or by using amplifiers. Calibration is now being performed, and initial results have confirmed the designed value of the *Fz*-sensitivity. An ultra small load indenter, controlled by a computer, was used to generate a precise force *Fz* during calibration. The output voltage of *Fz*-bridge varied linearly up to 120 mV, as the applied force

Fz was increased from 0 to 100 mN, (V_{in}= 5V). Therefore, a sensitivity of 1.20 mV/mN was obtained, very closed to the design value as shown in Table 2.

Table 2. Output characteristics of the sensing chip.

Loads	Sensitivities
Fz	1.23 mV/mN
Fx or *Fy*	9.5 x 10^{-2} mV/mN
Mx or *My*	4.9 x 10^{-3} mV/mN.μm
Mz	7.9 x 10^{-4} mV/mN.μm

(Supply voltage V_{in} = 5V).

CONCLUSION

The design concept and working principle of a 6-DOF force-moment sensing chip have been presented. By combining normal and shear piezoresistors in Si (111), and the way of arranging them on a crossbeam, connecting them into measurement circuits, their number was considerably reduced in comparison with prior art 6-DOF piezoresistive force-moment sensors known to the authors; consequently, the sensing chip is smaller, more sensitive, and consumes less power. The agreement between the first calibration results and the estimated Fz-sensitivity, (1.20 mV/mN, V_{in}= 5V), proved that the fabrication process, (including Boron ions diffusion, crossbeam formation, etc.) of the sensing chip was well controlled. Calibration of the remaining components is being performed, and its results are being analyzed.

This design of the sensing chip can potentially be applied to fabricate 6-DOF micro accelerometers and tactile sensors.

REFERENCES

[1] T. Von Papen et al, MEMS surface fence sensor for wall shear stress measurement in turbulent flow areas, Transducer 01, pp. 1476-1479.

[2] S. M. Kumar et al, MEMS based transducers for boundary layer control, IEEE MEMS Conference, pp. 135-140, 1999.

[3] K. Okada, Flat-type six-axial force-sensor, Tech. Digest of The 9th Sensor Symposium, pp. 245-248, 1990.

[4] J. C. Wells, Y. Yamamoto, Y. Yamane, S. Egashira, and Nakagawa, P.I.V. in the cross-stream plane of a turbulent channel flow, Proceedings of IUTAM Symposium on Geometry and Statistics of Turbulence, pp. 357-364, 2001.

[5] F. W. Sinden, and R. A. Boie. A planar capacitive force sensor, IEEE Robot Conf. Proc., pp. 1806-1814, 1986.

[6] Ogata, et al, Measuring Technology , No.11, Vol.15, Japan, 1987.

[7] C. G. Kang, Closed-form force sensing of a 6-axis force transducer based on the Stewart platform, Sensors and Actuators A 2876, pp. 1-7, 2001.

[8] Grahn, Allen R., Triaxial normal and shear force sensor , US Patents No. RE37065, 2001.

[9] J. J.Wortman et al, Youngs modulus, shear modulus ..., J. Appl. Phys., vol. 36, No. 1, pp. 153-156, 1965.

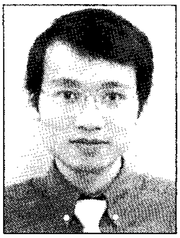
[10] S. M. Sze, Semiconductor Sensors, pp. 160-185, John Wiley & Sons Inc., 1994.

[11] Y. Kanda, Graphical representation of the piezoresistance coefficients in Si shear coefficients in plane, Japanese J. Appl. Phys., vol. 26, No. 7, pp. 1031-1033, July 1987.

[12] W. G. Pfann and R. N. Thurston, Semiconducting stress transducers utilizing the transverse ..., J. Appl. Phys., Vol.32, No.10, pp. 2008-2019, Oct. 1961.

[13] O. N. Tufte, and E. L. Stelzer, Piezoresistive properties of silicon diffused layers, J. Appl. Phys., vol. 34, No. 2, pp. 313-318, 1962.

著者紹介



Dao Viet Dzung

Dao Viet Dzung was born in 1973 Apr. 19. He received excellent B.S. (95) and M.S. (97) in Mechanics-Informatics from Hanoi University of Technology (HUT). He worked as assistant lecturer (95-97) and lecturer (from 97 to the present) in Fundamentals of Machine Design Department, Faculty of Mechanical Engineering, HUT. From 1995 to 1999 he worked for Alcatel Telecom Corp. in Hanoi. Currently, he is a Ph.D. student in the Graduate School of Science and Engineering, Ritsumeikan University, Japan. His present research interests are MEMS-based mechanical sensors. He is a member of IEE of Japan.

John C. Wells

John C. Wells received a B.S. (83) and M.S.(87) in Agricultural Engineering from Cornell University, and a Doctorate (92) in Mechanics from the University of Grenoble I, France. After two postdoctoral fellowships at Osaka University and Tokyo Institute of Technology, and a year at Sharp Corporations Print Products Development Laboratories, he has been on the faculty of Ritsumeikan University, Japan, since 1997. His research has focused on detailed mechanisms of soil erosion and particle transport by fluid flow. It includes experimental work on the structure of vortices in the turbulent boundary layer, as well as theoretical work on mechanics of interparticle contacts, and on the fluid force on a body in the presence of a vortex. He is a member of JSME and JSCE.

Toshiyuki Toriyama

T. Toriyama received the B.S. degree in 1985, the M.S. degree in 1987, in Mechanical Engineering from Ritsumeikan University, Shiga, Japan, and a Ph.D. degree in 1994 from Kyushu University, Fukuoka, Japan. He is now a research fellow in New Energy and Industrial Technology Development Organization (NEDO). His current interests are piezoresistance in advanced semiconductor materials and its application to micro mechanical sensors.

Susumu Sugiyama

S. Sugiyama received the B.S. degree in Electrical Engineering from Meijo University, Nagoya, in 1970, and the Dr. Eng. degree from Tokyo Institute of Technology, Japan, in 1994. From 1965 to 1995, he was with Toyota Central Research & Development Laboratories, Inc., where he worked on semiconductor strain gages, silicon pressure sensors, integrated sensors and micromachining. While there, he was a Senior Researcher, Manager of the Silicon Devices Laboratory, and Manager of the Device Development Laboratory. Since 1995 he has been with Ritsumeikan University, Shiga, Japan, where he serves as a Professor in the Department of Robotics, Faculty of Science and Engineering. He is Director of Research Institute for Micro System Technology, Ritsumeikan University, CEO of Nano Device and System Research Inc., Vice Director of the Synchrotron Radiation Center at Ritsumeikan University, and Editor-in-Chief of journal *Sensors and Materials*. His current interests are microsensors and microactuators and high aspect ratio microstructure technology. He is a member of the IEEE, Japan Society of Applied Physics and the Robotics Society of Japan.