TACTILE ARRAY SENSOR WITH INCLINED CHROMIUM/SILICON PIEZORESISTIVE CANTILEVERS EMBEDDED IN ELASTOMER

M. Sohgawa1*, T. Mima1, H. Onishi1, T. Kanashima1, M. Okuyama1, K. Yamashita2,1, M. Noda2,1, M. Higuchi3, and H. Noma4

1Osaka University, Toyonaka, Osaka, JAPAN
2Kyoto Institute of Technology, Matsugasaki, Kyoto, JAPAN
3Omron Corporation, Kizugawa, Kyoto, JAPAN
4Advanced Telecommunications Research Institute International, Seika, Kyoto, JAPAN

ABSTRACT
Tactile array sensor of the micro-cantilevers embedded in the elastomer has been fabricated to detect normal and 2-axes shear stresses. It is demonstrated that tactile array sensor with 3 x 3 detective elements can be fabricated with excellent yield. The sensor element is sensitive to both normal and shear stresses applied on entire sensor surface. Moreover, it has good directional characteristics so that it is shown that magnitude and direction of shear stress can be obtained by difference of output voltages of adjacent sensor cantilevers. The sensor output has good reproducibility for multiple measurement. The output from sensor element drastically changes with shifting applying position of force. It is considered that we can obtain pressed position from distribution of output from sensor element array.

KEYWORDS
tactile sensor, micro cantilever, polydimethylsiloxane, surface micromachining, shear force detection

INTRODUCTION
Recently, robots for nursing-care, house work and industry field, especially humanoid robots, have attracted much attention from viewpoint of suppression of heavy job and efficient production. To assure more activity and safety of these robots, external conditions should be detected by many kinds of sensors, especially tactile sensor similar to human tactile organ is very important [1]. However, the tactile sensors have not been developed so much in comparison with the other sensors such as optical detector, sonic sensor and accelerometer. Almost of the developed tactile sensors can detect either normal or shear stress, but not them simultaneously. So, we have proposed a tactile sensor which can detect both normal and shear stresses independently and have human-friendly surface[2]. Proposed tactile sensor has many inclined cantilever elements which can be bent to both normal and shear stresses and show piezoresistive response. In previous works [3,4], we have confirmed that the normal and shear stresses can be distinguished by using two face-to-face inclined cantilevers which are deformed to the same direction by normal stress or to the opposite direction by shear stress and can be measured as summation and difference of piezo resistances of them, respectively. These cantilevers are covered with elastomer (PDMS), and this tactile sensor is highly safe for human body. Although the responses of a single element was obtained in the previous work, integration of the sensor array is require to recognize stress distribution and object shape adequately.

In this work, we have fabricated a tactile array sensor including 3 x 3 sensing elements and have detected stress distribution applied at tactile sensor surface.

CANTILEVER STRUCTURE AND FABRICATION
Figure 1 (a) shows a cross-sectional view of the cantilever structure which consists of multilayer of Si, SiN and Cr thin films. Boron ions were implanted into surface of SOI wafer to form p+-Si piezoresistive layer. The cantilever structure was fabricated by the Si surface micromachining technology using sacrifice etching and stress-derived curling and it has upward deflection because of internal stress in Cr layer deposited on Si layer by electron beam evaporation. This inclined cantilever structure can be deformed by both normal and shear stresses. Deformation of the cantilever by applying external stresses is detected as output voltage from Wheatstone bridge circuit with p+-Si piezoresistor.

Figure 1: The structure of tactile sensor, (a) inclined cantilever structure, (b) one sensor element.
One sensor element consists of four cantilevers arranged in a cross shape as shown in Fig. 1 (b), and sensor elements are arranged in a 3 by 3 array. The cantilevers are embedded in PDMS (polydimethylsiloxane) elastomer. PDMS is soft elastomer, protects detective element and transfer stress to cantilever.

Figures 2 (a) and (b) show photographs of a device wired on circuit board and a center part of a chip of fabricated tactile array sensor, respectively. The size of tactile sensor chip is 18 mm square and is mounted on the printed-circuit board with connector terminals, as shown in Fig. 2 (a). Nine tactile sensor elements are arranged in 3 mm square, as shown in Fig. 2 (b) and their density is similar to human organ. It is found that all cantilevers have inclined shape without destruction because they are dark by irregular reflection of microscope light. Tip height of the cantilever is 25±5 μm. It is demonstrated that tactile array sensor with nine sensor elements can be fabricated with excellent reproducibility.

Detection Circuit

The sensor output was precisely measured by using Wheatstone bridge circuit as shown in Fig. 3 for application of external normal and shear stresses. Reference resistances are also formed on wafer. The piezoresistor in the cantilever is changed when the cantilever is deformed by external stress application. As the resistance change is extremely small, the output voltage \( V_o \) is expressed by following equation,

\[
V_o = \frac{\Delta R V_i}{4R_0}
\]

where \( V_i \), \( \Delta R \) and \( R_0 \) is source voltage supplied to the Wheatstone bridge circuit, the change of resistance by external stress application and resistance without stress, respectively.

RESULTS AND DISCUSSION

Output Induced by Normal and Shear Stress

Normal stress was applied through metal rod attaching entire sensor by inserting glass plate between the rod and the elastomer and was monitored by the other standard force stress sensor, as shown in Fig. 4. Figure 5 shows output voltage of one sensor element as a function of normal stress applied to entire surface of the tactile sensor. Four symbols (circle, square, triangle and diamond) indicate outputs obtained from cantilevers directed upward, downward, left and right, respectively. It is found that all cantilevers have similar linear dependence on applied normal stress and have wide detection ranges from 0 to 130 kPa without destruction of the cantilever structure and stress resolution is estimated to be 5 kPa. However, there is scattering in the sensitivity of each cantilever. It is due to the variation of the tip height of cantilever (±5 μm). This scattering is considered to be caused by structural variations such as nonuniform cantilever and incomplete contact of the metal rod caused by nonparallel faces between the rod and the elastomer. Nonetheless, this variation of the sensitivity is expected to be controlled and corrected by calculation considering adaptive learning circuit.
Shear stress was applied also through the metal rod which pressed the sensor surface and was simultaneously shifted laterally by movable stage, as shown in Fig. 4. Normal stress is set to be 20 kPa. Figures 6 and 7 show output voltage of one sensor element as a function of x and y directional shear stresses applied to entire surface of the tactile sensor, respectively. It is found that left and right cantilevers have responses to x-directional shear stress as shown in Fig. 6. Moreover, left and right cantilevers have the opposite gradient to shear stress. On the other hand, upward and downward cantilevers have small response to x-directional shear stress. These characteristics are similar to y-directional shear stress as shown in Fig. 7. It means that fabricated tactile sensor element has better isolation of the directional characteristics so that direction of shear stress in xy-plane can be detected from output of the sensor element.

Reproducibility of Sensor Output

Figure 8 shows the output voltage measured in one sensor element when normal stress is applied 3 times. The measurement was done after enough stabilization time (more than 10 min), because the sensor element has initial drift of output voltage[5]. One measurement time from 0 to 130 kPa is 20 min and interval time between each measurement is 20 sec as deformation of the elastomer should be stabilized. By this way, almost same output can be obtained in 3 measurements. Therefore, it is considered that the sensor has a good reproducibility without irreversible deformation. Figure 9 shows the output voltage measured in from one sensor element when shear stress is applied 3 times. The condition of measurement is similar to the case of normal stress. The fabricated sensor element can also detect the shear force with reproducibility.
Shear Stress

Figure 9: Reproducibility measurement of output voltage of the sensor element to shear stress application.

Sensor Output toward Pressed Position

Additionally, dependence of sensor output on distance between sensor element and pressed position has been investigated. Output voltage of sensor element on upper-left in the tactile sensor array was measured when it was pressed at some different positions. The pressing part is a plastic ball with 10 mm diameter in order to give the same stress distribution even when force direction is not precisely normal to the elastomer plane. The output of the sensor drastically changes with the position of applied force. The sensitivity of the sensor element becomes the maximum value on position which is the nearest position to measured sensor element. However, once the sensitivity rapidly decreases with increasing distance from the sensor element, the sensitivity increases again with increasing distance, unlike instinctive prediction. It is considered that this behavior reflects complex deformation of the elastomer. Therefore, improvement of shape of elastomer is required for measurement of accurate force distribution.

CONCLUSION

Tactile array sensor of the micro-cantilevers embedded in the PDMS elastomer to detect normal and 2-axes shear stresses has been fabricated and characterized. The tactile array sensor with nine sensor elements can be fabricated with excellent yield. The 4 cantilevers in one sensor element have linear dependences on normal stress applied on entire sensor surface although there is a variation in the sensitivity of each sensor. Moreover, fabricated tactile sensor element has good directional characteristics and direction of shear stress can be detected. As a result of multiple measurement of sensor output, it is shown that fabricated sensor element can detect applied stress with good reproducibility. The output of fabricated tactile sensor array much depends on applied position of the force.

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REFERENCES


CONTACT

* M. Sohgawa, tel: +81-6-6850-6331; sohgawa@ee.es.osaka-u.ac.jp