Fabrication and Normal/Shear Stress Responses of Tactile Sensors of Polymer/Si Cantilevers Embedded in PDMS and Urethane Gel Elastomers

Y. M. Huang*, Member
M. Sohgawa*, Member
K. Yamashita*, Member
T. Kanashima*, Non-Member
M. Okuyama*, Member
M. Noda**, Member
H. Noma***, Non-Member

Cantilever-type tactile sensors of silicon-polymer beam structures were fabricated by surface micromachining and covering with elastomers. Two kinds of elastomers with different Young's modulus PDMS and urethane gel have been used to control deflection of the cantilevers and adjust the sensitivity cantilever-type tactile sensors. The resistance change of the sensor with PDMS has linear dependence on normal and shear stresses, but that of the sensor with urethane gel is nonlinear to normal and shear stresses. However, the sensitivity of urethane gel type sensor is about 30 times larger than PDMS type sensor.

Keywords: tactile sensor, cantilever, elastomer, strain gauge

1. Introduction

Recently, robots especially the human-support robots are sincerely requested to be developed for practical applications such as nursing care of patient, holding objects and machine operation (1-3). Many sensors are used to inspect the condition of the objects for robot operation, and especially tactile sensor is useful to identify the position and mechanical condition. So, tactile sensing is very important to assure the safety of human body and accurate control and various tactile sensors for the robots have been proposed (4-6). However, micro and integrated tactile sensor, which can simultaneously detect normal and shear stresses, have not been developed so well yet.

We have proposed an integrated multi-axis tactile sensor with cantilevers on Si wafer fabricated by surface micromachining and elastomer-coating technologies (7-11). Strain gauge are formed on each micro cantilever, and these cantilevers are arranged in this proposed tactile sensor. These cantilevers are embedded is elastomer to transfer the stress to small displacement. Therefore, the cantilevers are reinforced and this sensor can directly touch on the human body. The tactile sensor with polymer(deflection control layer)/Pt/Ti/Si multilayer structures have been reported (11-12).

In this paper, we have used two kinds of elastomers (PDMS and urethane gel) that have different Young's modulus to cover polymer/Pt/Ti/Si multilayer structures for the tactile sensors, and characterized sensitivity.

2. Operation Principle of Tactile Sensor

Structure and operation of tactile sensor sensitive to normal and shear stresses are shown in Fig. 1. Each cantilever with strain gauge film can be deformed by both normal and shear stresses. Resistance changes of the strain gauge on cantilevers which are arranged in face-to-face manner have the same signs against normal stress and have the opposite signs against shear stress, respectively. So, normal stress can be basically calculated by the summation of the resistance changes, and shear stresses can be calculated by the difference of those. Therefore, two pairs of cantilevers arranged in X and Y direction shown in upper-left part of Fig. 1 can be used to detect stresses in all directions.

Fig. 1. Structure and operation principle of tri-axial tactile sensor.
3. Fabrication of Tactile Sensor

The cantilever structure of tactile sensor is schematically illustrated in Fig. 2. SOI wafers (top Si layer: 1.5 μm/buried oxide (BOX) layer: 2-6 μm/Si wafer: 650 μm) were used as substrates. Pt/Ti thin films for the strain gauge of resistance of about 20 kΩ were formed by RF sputtering and patterned by lift-off method as shown Fig. 3. Before Pt/Ti sputtering, the groove (depth: 500 nm) was formed on Si surface by reactive ion etching (RIE) using SF6 plasma to facilitate lift-off and prevent peeling off of electrode. The thickness of Pt/Ti layer was 50 nm/10 nm. CYTOP CTL-813NMD (Asahi Glass Co. Ltd.) was used to form the polymer layer. CYTOP was spin-coated on the wafer and cured at 100-200°C for 1 hour. Thickness of polymer layer was 1.5 μm. The polymer layer and Si were patterned by reactive ion etching (RIE) using oxygen and SF6 plasma, respectively. Finally, the BOX layer as a sacrificial layer was etched by buffered HF solution to form the cantilever structure. After etching the sacrificial layer, the sample was rinsed in ultra-pure water and tetra-butyl alcohol (TBA) successively and dried by vacuum-freeze-drying method to prevent the cantilever from sticking to the substrate surface. The fabricated structure was covered with polydimethylsiloxane (PDMS; SILPOT 184, Dow Corning Corp.) or urethane gel (Hitohada gel, EXSEAL Corp.)

Fig. 2. Structure of cantilever in tri-axial tactile sensor.

(a) Photolithography  (b) Etching Si by RIE
(c) Sputtering of Pt/Ti thin film  (d) Lift-off

Photoresist  SOI wafer  Pt/Ti thin film

Fig. 3. Fabrication process of the micro structure of Pt/Ti film.

4. Results and discussion

4.1 Microscopic observation of fabricated tactile sensor

Figure 5 shows SEM image of the fabricated cantilever before covering with elastomer. The cantilever is deflected by internal strain caused by difference of thermal expansion coefficient between Si (4.2×10^-6 K^-1[13]) and polymer (7.4×10^-6 K^-1[13]) layers. The curling curvature radius is about 700 μm in the case of 3 μm-thick polymer. We have already reported that the deflection controllability of polymer/Si beam structure is good (11,12). The photographs of fabricated tactile sensor chips with PDMS and urethane gel are shown in Fig. 6. (a) and (b), respectively. The chip size is 2 cm × 2 cm and there are 4 cantilevers facing mutually in the elastomer. The other strain gauge patterns outside elastomer are resistances for bridge circuit. PDMS is transparent and urethane gel is milk-yellow and opaque.

Fig. 5. SEM image of fabricated cantilevers.

(a) PDMS  (b) Urethane gel

Fig. 6. Photograph of fabricated tactile sensors covered with (a) PDMS and (b) urethane gel.

4.2 Stress detection

The responses of fabricated sensor sample against normal and shear stresses were obtained by measurement system shown in Fig.7. The normal stress is applied by pressing the sensor with columnar rod with the 6-axes force sensor (UFS 2A-05, Nitta Corp.) fixed to Z-axis stage, and on the other hand, the shear stress is applied by moving X and Y-axes stage horizontally under pressing with columnar rod. The normal stress, Sx, and shear stress, Si (i= x,y), are calculated by following equations,

\[ S_x = \frac{F_z}{A} \]  
\[ S_i = \frac{M_i}{L} \frac{1}{A} (i = x, y) \]

where \( F_z \) is force along z direction, and \( M_i \) and \( M_z \) are moments in the X and Y directions obtained by force sensor, respectively.
is surface area of the elastomer (PDMS: $0.81 \times 10^{-4}$ m$^2$, Urethane gel: $1.32 \times 10^{-4}$ m$^2$), and $L$ is the distance between the center of force sensor and edge of the rod. The bottom area of the columner rod is larger than $A$. The resistance of strain gauge was measured by the digital multimeter (R6581, Advantest).

Figure 8 shows the relative variation of resistance of Pt/Ti strain gauge on the cantilever when normal stress is applied to elastomer surface. It can be seen that the relative variations of the resistance are the same during pressing and releasing at large normal stress. The sensor is not destroyed when large pressure of 150 kPa is applied on the PDMS elastomer. Comparison of relative change of the resistance $\Delta R/R$ against normal pressure between PDMS and urethane gel type sensors is shown in Fig. 9. It is found that the sensitivity of urethane gel type sensor under small normal stress less than about 1 kPa is about 30-50 times larger than PDMS type sensor. It is considered that cantilever deformation in urethane gel (0.03 MPa) is 50 times larger than that of PDMS (1.5 MPa). However, $\Delta R/R$ saturates almost over about 2 kPa. It seems that the change of resistance has a nonlinear hysteresis characteristic. This nonlinearity can be explained by following reason. Supposing that the elastomer has a rubber elasticity, the relationship between surface stress $\sigma$ and extension ratio $\lambda$ is expressed by Eq. (3).  

$$ \sigma = \frac{E}{3} \left( \frac{1}{\lambda} - \lambda^2 \right) $$

(3)

$$ \lambda = 1 - \frac{\Delta d}{d} $$

(4)

where $E$ and $d$ are Young's modulus and the initial thickness, respectively. Figure 10 shows the measured and calculated deformation of the elastomer as a function of stress for Young's moduli of 1.5 MPa for PDMS and 0.03 MPa for urethane gel by using Eq. (3). For comparison, the thermal expansion coefficient of PDMS is $3.1 \times 10^{-4}$ K$^{-1}$ so that deformation of the elastomer by thermal expansion is much smaller than that by several kPa surface stress ($10^{-2}$) and it can be neglected in the case of use around room temperature.

Fig. 7. Measurement system of sensor response against normal and shear stresses.

Fig. 8. Resistance change of platinum strain gauge covered with PDMS as a function of normal stress.

Fig. 9. Experimental resistance change of platinum strain gauge covered with Urethane gel and PDMS and normal as a function of stress.

Fig. 10. Measured (solid line) and calculated (dotted line) deformation as a function of normal stress in the elastomers with Young's modulus 0.03 MPa and 1.5 MPa.
In the case of $E = 1.5$ MPa in Fig. 10, deformation of the elastomer has a linear dependence on stress. However, in the case of $E = 0.03$ MPa, deformation of the elastomer is not proportional to stress. So, if the cantilever in the elastomer deforms similar with the elastomer, resistance change of strain gauge on the cantilever is not also proportional to stress under strong stress. Therefore, the response of the urethane gel type sensor has a nonlinear characteristic as shown in Fig. 9.

Figure 11 shows resistance change of strain gauge covered with PDMS as a function of shear stress when normal stress 73 kPa. Resistance of strain gauge has an almost linear dependence on shear stress, is the same as shown in Fig. 9. Comparison of resistance change between PDMS type sensor and urethane gel type sensor against shear stress is shown in Fig. 12. It is found that the sensitivity of urethane gel type sensor to shear stress is about 20-30 times larger than PDMS type sensor. However, resistance values of start and end points do not coincide, and so it seems that the resistance change also has hysteresis characteristics of the elastomer. Nevertheless, the sensitivity of urethane gel type sensor is better than PDMS type sensor in detection of both shear and normal stresses. To lift both light and heavy things, a wide measurement range is needed for tactile sensing in the robots\(^{16}\). According to this purpose, in this research we succeeded in detecting pressure in range of 5~150 kPa, as shown in Figs. 8, 9, 11, 12.

To check effect on the resistance by ambient temperature, we measured the change in resistance of the platinum strain gauge covered with the elastomer as a function of the temperature, as shown in Fig. 13. The resistance change of platinum strain gauge has a linear dependence on temperature because of high temperature coefficient of resistance \((3.9\times10^{-3} \text{ K}^{-1})\)\(^{17}\). To suppress the temperature effect, it is considered that materials with low temperature coefficient of resistance is needed.

### 5. Conclusions

Tactile sensor of silicon-polymer beam cantilever embedded in elastomer has been fabricated by using surface micromachining and elastomer coating. The resistance responses to normal and shear stresses of the tactile sensor have been measured. There is a linear relationship between the resistance change of PDMS type sensor and shear stresses. On the other hand, the sensitivity of urethane gel type sensor is larger about 30 times than PDMS type sensor, but, the urethane gel type sensor has a nonlinear response to normal stress. It is thought that urethan gel deformation has rubber elasticity with nonlinear relation to stress. It becomes clear that fabricated tactile sensor can detect normal and shear stresses simultaneously and sensitivity of the sensor can be controlled by Young’s modulus of elastomer. However, the response of the urethane gel sensor has hysteresis between increasing and releasing the stress.

### Acknowledgement

This study was carried under the research project of “Research and Development of Nanodevices for Practical Utilization of Nanotechnology” from New Energy and Industrial Technology Development Organization (NEDO).
References


(14) CYTOK catalogue (Asahi Glass)


Yu Ming Huang (Student member) was born in Tainan, Taiwan, on October 24, 1977. He received the M. E. degree from Southern Taiwan University of electrical engineering Science. He is a Ph.D. student in the Graduate School of Engineering Science, Osaka University. He is engaged in research on tactile sensor devices.

Masayuki Sohgawa (Member) was born in Wakayama, Japan, on April 4, 1977. He received the Ph. D. degree in engineering in 2005 from Osaka University. He is now a assistant professor at Graduate School of Engineering Science, Osaka University since 2007, working on MEMS physical sensors.

Kaoru Yamashita (Member) was born in Kyoto, Japan, in 1967. He graduated at Osaka University in 1990 and received his Ph. D. from Osaka University in 2002. He was a research associate, an assistant professor at Osaka University since 1994, and has been an associate professor at Kyoto Institute of Technology since 2007. He is currently working in the field of micro mechanical devices for sensors and actuators using functional thin films and development of application systems using the transducers.

Takeshi Kanashima (Non Member) was born in Japan on 1968. He received the M. E. and D. E. degrees from Department Electrical Engineering, Osaka University, Japan, in 1993 and 1996, respectively. He is associate professor now of Osaka University. His main field of research is thin film preparation of photo-assisted CVD, characterization of surface and interface, ferroelectric thin films and those applications such as memory. He is a member of the Japan Society of Applied Physics and the Japan Society for Synchrotron Radiation Research.

Masanori Okuyama (Member) received the B.S., M.S. and D.E. degrees in electrical engineering from Osaka University, Osaka Japan in 1968, 1970 and in1973, respectively. He was a researcher of Japan Society for the Promotion of Science from 1973 to 1974 and a Research Associate the Faculty of Engineering Science, Osaka University, from 1974 to 1986, and Associate Professor from 1986 to 1991. Since 1991,
he has been a Professor of Faculty of Engineering Science with Osaka University. His current interests are preparation and characterization of ferroelectric thin films and their applications to electronic devices including memory devices, sensors and actuators, and characterization of gate insulator films on Si.

**Minoru Noda** (Member) received the B. S. and M. S. degrees in electrical engineering from Osaka University, Osaka Japan in 1981, 1983, respectively. He was an engineer in Mizubishi company since 1983, and associate professor at Osaka University from 1997 to 2006. Since 2007, he has been a professor at Kyoto Institute of Technology.

**Haruo Noma** (Non Member) Received the B.E. degree and Ph.D. degree from University of Tsukuba, Ibaraki, Japan, in 1989 and 1994, respectively. In 1994, he joined ATR, where he was working on the force display, locomotion interface, their applications to the manipulation in virtual space, sensor network system, and MEMS sensor. At present, he is a group leader of ATR Knowledge Science Lab. He is members of the VRSJ, IEICE, RSJ, SICE, SICE, ACM and IEEE.