A triaxial tactile sensor without crosstalk using pairs of piezoresistive beams with sidewall doping

Hidetoshi Takahashi\textsuperscript{a,}\textsuperscript{*}, Akihito Nakai\textsuperscript{a}, Nguyen Thanh-Vinh\textsuperscript{b}, Kiyoshi Matsumoto\textsuperscript{a}, Isao Shimoyama\textsuperscript{a,b}

\textsuperscript{a} Information and Robot Technology Research Initiative, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
\textsuperscript{b} Department of Mechano-Informatics, Graduate School of Information Science and Technology, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan

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\textbf{A B S T R A C T}

This paper reports on a triaxial tactile sensor using piezoresistive beams. The sensor chip is composed of two pairs of sidewall-doped Si beams for shear stress sensing and one pair of surface-doped Si beams for normal stress sensing. The sizes of the shear- and pressure-sensing beams are 180 \(\mu\)m \(\times\) 15 \(\mu\)m \(\times\) 20 \(\mu\)m and 250 \(\mu\)m \(\times\) 50 \(\mu\)m \(\times\) 20 \(\mu\)m (length \(\times\) width \(\times\) thickness), respectively. The sensor chip is embedded in a PDMS sheet 10 mm \(\times\) 10 mm \(\times\) 2 mm in size. Because the simple beam structure can be fabricated easily, the proposed sensor is compatible with semiconductor device fabrication. The fabricated sensor was evaluated for normal and shear stress (0–400 kPa and 0–100 kPa, respectively). The responses of the corresponding beam pairs were found to be proportional to the magnitude of the applied stresses without the influence of the other stresses. The relationship between the angle of shear stress and the responses of each beam pair was also evaluated. Each beam pair detects only one axis’s shear stress and showed little reaction to the other axes’ shear stress. As a result, the proposed sensor can measure the three axial components of normal and shear stress independently.

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1. Introduction

Recently, many types of tactile sensors that use microelectromechanical systems (MEMS) have been studied in a variety of fields [1]. In the field of robotics in particular, triaxial tactile sensors have been developed for the manipulation of robot hands [2,3]. To control a manipulation with optimal force, it is important to measure not only the normal stress (the external normal force per unit area) but also the shear stress (the external lateral force per unit area) that occurs along the interface between the target object and the robot hand.

Several types of triaxial tactile sensors have been developed in the past. Normal stress can be detected with relative ease by MEMS laminate structures. It has been difficult, however, to develop MEMS structures that can detect shear stress. Thus, in the development of the triaxial tactile sensor, one of the most important factors has been how to detect shear stresses.

One of the conventional types of sensors uses a diaphragm with a tactile bump [4–6]. The diaphragm has several strain detectors located at positions where the maximum strain occurs on the diaphragm. When a moment is applied to the bump, these sensors perceive the responses of the detectors as a shear stress. Because the sensors are unable to detect shear stress directly, a diaphragm several millimeters in size and a bump of a certain height are needed to serve as the sensing elements. To attach tactile sensors to robot hands, further miniaturization of the sensor is needed. Additionally, complicated inverse calculations are needed to isolate one axial component of triaxial stresses from the sensor outputs.

Another type of tactile sensor uses standing piezoresistive cantilevers as the shear stress detectors [7,8]. These cantilevers were able to maintain a large angle due to the residual stresses of the evaporating metal layers or an external magnetic field. When shear stress is applied on the elastic surface in which the cantilevers are embedded, the resistance of the cantilever changes due to the deformation of the cantilever’s hinges where the piezoresistance is formed. These types of sensors are highly sensitive to shear stresses. However, their fabrication process is incompatible with semiconductor device fabrication. Furthermore, there is crosstalk between the stresses when the cantilever does not stand vertically.

In this paper, a triaxial tactile sensor that produces no crosstalk and is compatible with semiconductor device fabrication is proposed. The proposed sensor also achieves the goals of miniaturization and disturbance cancelation. These characteristics are thought to be important to the practical application of tactile sensors in the field of robotics. In the proposed sensor, pairs of piezoresistive beams with sidewall doping are used as the shear stress detectors. By forming piezoresistors symmetrically on the sidewall of the beam pair, the beam pair responds only when shear...
stress is applied on the elastic surface in which the beam pair is embedded perpendicularly. Because the simple beam structure can be fabricated easily, the proposed sensor is compatible with semiconductor device fabrication before embedding in an elastic body. Additionally, the elastomer of the sensor can be thin because the beam is flat against the sensor surface.

The sidewall doping process has been facilitated mainly by the development of multi-axis force-sensing cantilevers [9,10]. Previous research has demonstrated a tactile sensor that can detect shear stress using sidewall-doped cantilevers [11]. However, the resistance of the cantilevers changed with not only target shear stress but also other axial stresses.

A triaxial tactile sensor chip composed of two pairs of sidewall-doped beams and one pair of surface-doped beams was designed and fabricated. The fabricated sensor chip was embedded in polydimethylsiloxane (PDMS). The sensor was then evaluated when normal and shear stresses were applied.

2. Principle

The concept of the proposed tactile sensor is illustrated in Fig. 1. The sensor chip is composed of two pairs of sidewall-doped Si beams for shear stresses and one pair of surface-doped Si beams for normal stress. Two pairs of sidewall-doped beams are arranged orthogonally to detect shear stresses in two directions. The sensor chip is covered with an elastic body. The sidewall-doped beams have a piezoresistor on the center of the beams. One surface-doped beam has a piezoresistor on the center of the beam and another has piezoresistors at both ends of the beam.

Fig. 2 shows the principle of shear stress detection by the sidewall-doped beams. The sidewall-doped areas are formed only on the inner sidewall of each beam pair. When shear stress is applied to the surface of the elastic body, the pair of sidewall-doped beams that is perpendicular to the shear stress direction is bent, as shown in Fig. 2(a). The resistance area on one beam stretches, while that on another beam compresses. Therefore, the resistance of one beam is increased and the resistance of the other beam is decreased. Using this beam pair as the resistances of a bridge circuit, as shown in Fig. 2(b), the output voltage is expressed as follows:

\[
\frac{\Delta V_{\text{out}}}{V_S} = \frac{\Delta R}{2R} \times G
\]

(1)

where \(\Delta V_{\text{out}}\) (V), \(V_S\) (V), \(\Delta R\) (kΩ) and \(R\) (kΩ) are the output voltage, the voltage applied to the bridge circuit, the change in resistance and the initial resistance of a beam, respectively, assuming that the resistance changes of the two beams are \(\pm \Delta R\) and that \(G\) is the gain of an amplifier. The pair of the beams is symmetric with respect to a line that is perpendicular to the direction of detectable shear stress. Thus, when the other directional shear stress is applied, the beams deform little, and the resistance does not change. When a normal stress is applied to the surface of the elastic body, the resistance of the shear stress-sensing beams cancels each other in the bridge circuit because the two resistance changes are of the same magnitude. Additionally, the resistance changes due to heat and light emission cancel out. The influence of light emissions can also be eliminated by embedding the sensor chip in a colored, opaque elastic body.

The detection of normal stress using a pair of surface-doped beams uses conventional methods [12]. When normal stress is applied, the strains, and thus the resistances, where the piezoresistors are formed on the beams increase and decrease as the beams extend and compress. Using a bridge circuit with this beam pair, as with the sidewall-doped beams, the normal stress is detected. By designing the width of the surface-doped beams to be large compared with their thickness, the surface-doped beams deform little when shear stress perpendicular to the beams is applied. When shear stress horizontal to the beams is applied, the beams also do not deform, and the resistance does not change. Additionally, the pair of surface-doped beams can cancel the resistance changes depending on temperature and light emission, like the pair of sidewall-doped beams.

3. Design and fabrication

3.1. Sensor design

The design of the sensor chip is shown in Fig. 3(a). We define three pairs of Si beams as X-axis, Y-axis and Z-axis detectors. The beams of the X-axis and Z-axis detectors are arranged in parallel. The size of the sensor chip is 2 mm × 2 mm × 0.3 mm. The length and width of the beams for shear stress (the X-axis and Y-axis detectors) are 180 μm and 15 μm, respectively, as shown in Fig. 3(b) and Table 1. The length and width of the beams for normal stress (the Z-axis detector) are 250 μm and 50 μm, respectively, as shown in Fig. 3(c) and Table 1. The thickness of all beams is 20 μm. The gap between two beams for normal and shear stresses are 30 μm and 40 μm, respectively. A metal layer is formed on both ends of the shear-stress-sensing beams to form electrodes. The lengths of the metal layer parts are a quarter of the beam length. For the
normal-stress-sensing beams, a metal layer is also formed on both ends of one beam and at the center of another beam. The lengths of these metal layer parts are a quarter of the beam length and half of the beam length, respectively. There are through holes below both beams for shear and normal stresses. The sizes of the through holes are 180 \( \mu \text{m} \times 400 \mu \text{m} \times 300 \mu \text{m} \) and 250 \( \mu \text{m} \times 250 \mu \text{m} \times 300 \mu \text{m} \), respectively. By embedding the sensor chip in PDMS, the sensor can detect a triaxial stress of several dozen kilopascals, which is a suitable magnitude for robot hands to manipulate objects [7,8,12].

3.2. FEM simulation

A finite element model (FEM) was developed to analyze the performance of the sensors using simulation (COMSOL Multiphysics, COMSOL), as shown in Fig. 4(a). In this study, PDMS (Young’s modulus: 600 kPa) was used as the polymer material, and the sensing beam material was Si (Young’s modulus: 170 GPa). The sensor chip was covered with PDMS, and the thickness of the PDMS was defined as 1 mm. The shear and normal stresses were applied on the PDMS surface.

Fig. 4(b) shows the simulation result that describes the strain distribution on the beams after applying a shear stress in the X-axis direction. The amplitude of the applied shear stress was 1 kPa. The sidewall-doped beams of the X-axis detector were strongly deformed compared with the other beams, as shown in Fig. 4(b)(i). The strain changed from positive to negative at the boundary of the quarter beam length. The average strains where a piezoresistor was formed by an X-axis detector and Y-axis detector were 1.2 \( \times 10^{-6} \) and 3.9 \( \times 10^{-8} \), respectively. Those of the pair of Z-axis detectors were –1.3 \( \times 10^{-8} \) and –2.1 \( \times 10^{-9} \), respectively. These results show that the X-axis detector had the largest strain. Assuming that the gauge factor of the piezoresistor was 100, the fractional resistance change of the X-axis detector was calculated to be 1.2 \( \times 10^{-4} \). Thus, the sensitivity to shear stress was \( \Delta R_s/R_x = 1.2 \times 10^{-4} \) (units for \( \tau \) are kPa), assuming that the amplitude of shear stress was proportional to the amplitude of strain. The sensitivity (kPa\(^{-1}\)) was defined as the ratio between the fractional resistance change (dimensionless) and the applied stress (kPa). Fig. 4(c) shows the result that describes the strain distribution on the beams after applying a shear stress in the Y-axis direction. The result is similar to the result for shear stress in the X-axis direction.

The strain distribution on the beams after applying a normal stress is shown in Fig. 4(d). The amplitude of the applied normal stress was 1 kPa. The amplitudes of the deformations of the beams were approximately equal. The pairs of the sidewall-doped beams exhibit the same strain change where the piezoresistors were formed. Thus, the resistance change was canceled in a bridge circuit. In contrast, the mean strains where piezoresistors were formed for the Z-axis detector were \( –1.5 \times 10^{-7} \) and \( 9.0 \times 10^{-8} \), respectively. The sensitivity to normal stress, calculated in the same way as the sensitivity to shear stress, was \( \Delta R_n/R_z = 1.2 \times 10^{-5} \) (units for \( p \) are kPa).

3.3. Fabrication process

Fig. 5 shows birds-eye and cross-sectional views of the fabrication process of the sensor chip. In the process, a p-type silicon-on-insulator (SOI) wafer was used as the starting material. In this device, the device Si layer of the SOI wafer was 20 \( \mu \text{m} \) thick, the SiO\(_2\) layer was 2 \( \mu \text{m} \) thick, and the handle Si layer was 300 \( \mu \text{m} \) thick. First, two doping holes were etched on the device’s Si layer with inductively coupled plasma-reactive ion etching (ICP-RIE), as shown in Fig. 5(a). The hole was formed between the pair of the sidewall-doped beams. Second, an n-type piezoresistor layer was formed on both the device’s Si surface and the sidewalls of the etched holes with rapid thermal diffusion [10,13]. The thickness of the doped layer was approximately 100 nm [14]. The entire surface

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<th>Table 1 Design of the piezoresistive beams.</th>
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<td>Length l (( \mu \text{m} ))</td>
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of the sidewall-doped beam was also doped to facilitate the fabrication process. Third, a positive photoresist layer was patterned, and Cr/Au layers were deposited. The thicknesses of the Cr/Au layers were 10 nm and 50 nm, respectively. By removing the photoresist layer, the Cr/Au layers were patterned, as shown in Fig. 5(b). Using lift-off patterning, Cr/Au deposition on the sidewall of the etched holes was prevented. The Cr/Au layers were then etched again to form electrodes, and the device’s Si layer was etched by ICP-RIE to form the beam structures, as shown in Fig. 5(c). The handle Si layer was etched by ICP-RIE from the back side to form the through holes, as shown in Fig. 5(d). Finally, the beams were released by etching the SiO₂ layer with HF vapor. The released sensor chips were able to be wire-bonded on a substrate and embedded in an elastic body.

Fig. 5 shows a photograph of the fabricated sensor chip and SEM images of the shear and pressure detectors, respectively. All of the initial resistances of the sidewall-doped beams and surface-doped beams were 1.0 kΩ and 0.5 kΩ, respectively.

4. Experiment and result

4.1. Tactile sensor

We measured the response of the fabricated sensor embedded in PDMS (Dow Corning Toray Silpot 184: the mixture ratio of the PDMS and its polymerization initiator was 10:1) to normal and shear stresses. The sensor was embedded in a 10 mm × 10 mm × 2 mm (length × width × thickness) PDMS sheet with a 0.25 mm thick flexible substrate that was electrically connected to the sensor chip, as shown in Fig. 7(b). The electrical interconnect between the substrate and sensor chip was achieved by bonding Al wire with a diameter of 30 μm prior to embedding. This dimension corresponded to the thickness of the PDMS layer on the sensor chip being approximately 1.5 mm. The flexible substrate was attached to a rigid plate to readily secure the sensor to the experimental setup. The pair of piezoresistors on the beams was used as the resistors in a Wheatstone bridge circuit. The bridge circuit was connected to an oscilloscope through an instrumentation amplifier (AD623, Analog Devices). The source voltage of the bridge circuit was 1.0 V. The gain factor of the amplifier circuit was 300 when measuring resistance changes due to heat or 1000 when measuring responses to triaxial stresses.

4.2. Resistance changes due to heat

The relationships between the temperature change and fractional resistance changes of three pairs of beams (ΔR/R) are shown in Fig. 8. The fractional resistance changes were calculated using Eq. (1). The fabricated sensor was placed in a temperature-controlled chamber for testing at temperatures ranging from 22
to 60 °C. As a comparison, we also measured the temperature-dependent coefficient of a single surface doped beam embedded in PDMS. The resistance of the beam was measured using the one-gauge method in a Wheatstone bridge circuit. The temperature coefficients of $\Delta R_x/R_x$, $\Delta R_y/R_y$, and $\Delta R_z/R_z$ were obtained using least-squares regression and were found to be $1.4 \times 10^{-6}$, $9.5 \times 10^{-7}$ and $2.2 \times 10^{-7}$ (°C$^{-1}$), respectively. However, the temperature coefficient of the comparison beam was found to be $1.6 \times 10^{-4}$ (°C$^{-1}$). Therefore, the resistance changes as a function of temperature were minimized to less than one hundredth of the response from a single piezoresistor. These results suggest that the resistance change due to heat was able to be canceled out.

### 4.3. Response to triaxial stresses

The experimental setup used to measure the sensor response to normal and shear stresses is shown in Fig. 7(a) and (c). The fabricated sensor was attached to an xyzθ stage through a 6-axis force sensor (Minebea, OPFT-220) and goniometer stage. By moving the xyzθ stage in the z direction, the fabricated sensor was pressed to an acrylic plate. A normal stress was then gradually applied to the surface of the fabricated sensor. After the fabricated sensor was attached to the acrylic plate, shear stress was applied gradually by moving the xyzθ stage in the x or y direction. The shear stress angle was changed by rotating the xyzθ stage before moving the xyzθ stage in the x or y direction. The 6-axis force sensor measured the normal stress and shear stress applied to the fabricated sensor. We then obtained the sensor responses and the magnitude of the applied stresses simultaneously. Through the acrylic plate, we could observe the contact surface and adjust the PDMS surface parallel to the plate surface by the goniometer stage. In this experiment, normal and shear stresses from 0 to 400 kPa and from 0 to 100 kPa, respectively, were applied. There was no slippage between the PDMS surface and plate surface. At this point, the displacements were approximately 0.08 mm and 0.35 mm, respectively. The direction of the shear stress was varied from 0° to 360° in 15-degree increments. We defined the angle of the shear stress direction as 0° when the shear stress direction was perpendicular to the beams of the X-axis detector.

The relationships between normal stress and the fractional resistance changes of three pairs of the beams ($\Delta R/R$) are shown in Fig. 9(a). When normal stress was applied, the fractional resistance change of the Z-axis detector was proportional to the amplitude of the stress. The fitted line $\Delta R_z/R_z = 1.3 \times 10^{-5} p$ was obtained by least-squares regression. Thus, the sensitivity to normal stress was $1.3 \times 10^{-5}$ (kPa$^{-1}$). The coefficient of determination $R^2$ was 0.9995. The ratios $\Delta R_x/R_x$ and $\Delta R_y/R_y$ were $\Delta R_x/R_x = 3.4 \times 10^{-6}$ $p$ and $\Delta R_y/R_y = 2.0 \times 10^{-6}$ $p$, respectively. The sensitivity to normal stress was approximately equal to the simulation result. The responses of $\Delta R_y/R_y$ and $\Delta R_z/R_z$ to normal stress were small but did not remain the same. This was thought to have occurred because the sideward-doped beams were not located at the center of the PDMS sheet, so shear stress was generated.

The relationship between a shear stress of 0° and the outputs of three pairs of the beams is shown in Fig. 9(b). The response corresponding to a normal stress of 400 kPa was first subtracted from $\Delta R_y/R_y$. When a shear stress of 0 degrees was applied, the $\Delta R_y/R_y$ mainly changed. The fractional resistance change was also proportional to the amplitude of the stress. The fitted line was $\Delta R_y/R_y = 4.6 \times 10^{-3} \tau_x$, with an $R^2$ of 0.995. The ratios $\Delta R_y/R_y$ and $\Delta R_z/R_z$ were $\Delta R_y/R_y = 1.4 \times 10^{-6} \tau_x$ and $\Delta R_z/R_z = 3.0 \times 10^{-6} \tau_x$, respectively.

In the same way, $\Delta R_x/R_x$ mainly changed with good linearity with respect to the shear stress in the Y-axis direction, as shown in Fig. 9(c). The fitted line was $\Delta R_x/R_x = 4.5 \times 10^{-2} \tau_y$, with an $R^2$ of 0.997. In contrast, the ratios $\Delta R_x/R_x$ and $\Delta R_z/R_z$ were $\Delta R_x/R_x = 9.5 \times 10^{-7} \tau_y$ and $\Delta R_z/R_z = 2.0 \times 10^{-6} \tau_y$, respectively. Thus, the sensitivity to shear stress was approximately $4.5 \times 10^{-5}$ (kPa$^{-1}$). The sensitivity to shear stress was equal to half of the simulation result. The fabricated shear stress detectors were composed of a piezoresistor on the sideward and the surface of the beams. The resistances were approximately equal. Therefore, the extra parallel
resistance of the surface of the beams reduced the actual sensitivity of the shear stress detectors.

Fig. 10 shows the relationship between the angle of shear stress and the sensitivity to shear stress, which was defined as the slope of the fitted line. The magnitudes of the sensitivity of the X-axis and Y-axis detectors followed a sinusoidal curve. Additionally, the phase of the magnitudes shifted 90°. The sensitivity of the Z-axis detector was rather small at every angle that was tested. We could observe a small sinusoidal curve as the phase shifted. This was thought to have occurred because the acrylic plate deviated slightly from being parallel to the surface of the xyz stage. The Z-axis detector responded when the shear stress was applied. These results indicate that each axis detector detected the stress only of one axis and showed little reaction to stresses of the other axes.

It was confirmed that the sensor was able to detect the three axes' components of normal and shear stresses independently, without crosstalk from the other axis's stress. The differences in the sensitivities of each axis detector between the simulation results and the experimental result were thought to be caused by the influence of fabrication error. The experimental results suggest that our proposed sensor requires no complicated calculations to extract one axial component of stress. This advantage facilitates the use of MEMS sensors in robotics.

5. Conclusion

In this paper, we have proposed a tactile sensor using piezoresistive beams with sidewalk doping for shear stress detectors. The size of the sensor chip is 2.0 mm × 2.0 mm × 0.3 mm. The sizes of the beams for shear and normal stress are 180 μm × 15 μm × 20 μm and 250 μm × 50 μm × 20 μm, respectively. The sensor chip is embedded in a PDMS sheet. The fabricated sensor was evaluated for normal and shear stress ranges of 0–400 kPa and 0–100 kPa, respectively. Each detector response was proportional to the magnitude of the applied stress. It was confirmed that the sensor was able to detect the three axes’ components of normal and shear stress independently. A tactile sensor using these surface- and sidewalk-doping beams would be useful in the field of robotics.

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References


Biographies

Hidetoshi Takahashi was born in August 15 1983. He received bachelor degree in 2006, master degree in 2008 and Ph.D. in 2011, respectively, in the University of Tokyo. Since 2011, he has been a Postdoctoral Fellow in Information and Robot Technology Research Initiative, the University of Tokyo. His current research interests include MicroElectroMechanical Systems, insect locomotion.

Akihito Nakai was born in Japan in 1978. He received bachelor degree in 2000, master degree in 2002, and Ph.D. in 2005, respectively, from the University of Tokyo. He is currently working as a project assistant professor in Information and Robot Technology Research Initiative at the University of Tokyo and as a Vice President, CTO at Touchence Inc. His research interests include MicroElectroMechanical Systems, tactile sensors, contact mechanics and tribology.

Kiyoshi Matsumoto was born in April 12 1961. He received bachelor degree in 1985, master degree in 1987, respectively, in the University of Tokyo. Since 2006, he has been a professor in Information and Robot Technology Research Initiative, the University of Tokyo. His current research interests include MicroElectroMechanical Systems.

Isao Shimoyama was born in January 6 1955. He received bachelor degree in 1977, master degree in 1979 and Ph.D. in 1982, respectively, in the University of Tokyo. Since 2001, he has been a Professor in Department of Mechatronics Informatics, Graduate School of Information Science and Technology in the University of Tokyo. His current research interests include Robotics and MicroElectroMechanical Systems.

Fig. 10. Relationship between the shear stress angle and the sensor response.