High-sensitivity triaxial tactile sensor with elastic microstructures pressing on piezoresistive cantilevers

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A B S T R A C T

In this paper, we proposed a design to increase the sensitivity of a piezoresistive-type triaxial tactile sensor. Using conventional piezoresistive tactile sensors, in which the piezoresistive elements were completely embedded inside an elastic block, our proposed tactile sensor design features an air cavity underneath the piezoresistive elements. The cavity was created by pressing an elastic cap with microstructures onto the piezoresistive cantilevers of a sensor chip. We confirmed that the proposed design increased the sensitivity of the tactile sensor by approximately 150 times and 100 times in response to normal and lateral forces, respectively.

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1. Introduction

MEMS-based three-dimensional tactile sensors have been developed for many applications, including in robotic systems, minimal invasive surgery, and the manipulation of robot hands [1,2]. Various types of tactile sensors have been proposed, which can be categorized as piezoresistive [3–9], piezoelectric [10,11], capacitive [12,13], and optical [14] sensors according to the transducer method employed.

The piezoresistive-type tactile sensor, which detects force using the resistance change of a piezoresistor due to deformation, has attracted significant attention. The piezoresistive tactile sensor has several advantages compared to other types of tactile sensors, including a high sensitivity, a high spatial resolution, a simple read-out circuit, and well-established fabrication techniques. In this type of sensor, piezoresistive silicon elements are typically embedded inside a protective elastic body, e.g., polydimethylsiloxane (PDMS) [3–9]. This elastic body enables the soft interaction between the sensor and target object and prevents the fragile piezoresistive elements from fracturing. Piezoresistive sensing elements can be miniaturized to several micrometers and enable the measurement of delicate forces on the order of micronewtons [15–17]. However, once embedded inside an elastic body, the deformation of the piezoresistive elements is restricted by the surrounding elastomer, and thus, the sensitivity of the sensor decreases [1].

In this paper, we propose the structure of a PDMS cap with convex microstructures pressing on the piezoresistive cantilevers, as shown in Fig. 1(a), to increase the sensitivity of the piezoresistive tactile sensor while maintaining the elastic cover. Our proposed structure features a cavity under each cantilever, which provides more room for the cantilever to deform (Fig. 1(b)). Therefore, under the same pressure, the deformation of the cantilevers in our sensor will be greater than in the case where the cantilevers are completely confined inside an elastic body. In other words, our sensor achieves a higher sensing sensitivity.

The PDMS cap functions as a cover that protects the cantilevers and interacts with target objects. The forces acting on the surface of the PDMS cap are transmitted to the cantilevers through the microstructures. The prototype sensor using a PDMS cap with pyramid-shaped microstructures was reported in MEMS 2013 [18]. In this paper, sensors with three types of convex microstructures, namely, pyramid-shape, pillar-shape, and ring-shape, were fabricated and evaluated. The sensitivities of these sensors were compared with that of a sensor in which the cantilevers were completely embedded inside the PDMS.

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Furthermore, by using the structure in which four cantilevers are aligned with the four microstructures of the PDMS cap, we demonstrated the capability of the proposed sensor to detect the forces in both the normal and lateral directions.

2. Sensing principle

The normal force- and lateral force-sensing principles, for example, in the case of a PDMS cap with pyramid-shaped microstructures, are shown in Fig. 2. Notice that we design our sensors so that, even in the load-free state, the pyramids are pre-pressed on the cantilevers, causing the initial deformation of each cantilever.

2.1. Normal force-sensing principle

As shown in Fig. 2(a), when a normal force is applied to the PDMS cap, the deformation of all four cantilevers becomes larger than their initial deformations. Thus, we can detect the applied normal force from the average of the resistance change of the four cantilevers.

2.2. Lateral force-sensing principle

As shown in Fig. 2(b), when a force in the lateral direction is applied to the surface of the PDMS cap, there is a torque around the center pillar of the PDMS cap. This torque causes the surface of the PDMS cap to rotate slightly. As a result, one cantilever will have a smaller deformation and the opposite cantilever will have a larger deformation compared to their initial deformations. The force in the lateral direction can be established based on the difference between the resistance changes of these two cantilevers.

3. Design

The design parameters of the sensor chip and PDMS caps are shown in Fig. 3(a). The dimensions of the chip are 2 mm × 2 mm × 0.3 mm. The sensor chip consists of a hole in the center with diameter of 300 μm. Four cantilevers are arranged in a cross shape around the hole. The size of a cantilever is 125 μm × 100 μm × 5 μm. The piezoresistors are formed on the surface of the two hinges of the cantilever where the strain is concentrated when the cantilever bends. The size of each hinge is 25 μm × 25 μm × 5 μm.

The design of the PDMS cap with pyramid-shaped microstructures is shown in Fig. 3(b). The size of the PDMS cap is 10 mm × 10 mm × 1 mm. A cylinder-shaped shaft with a diameter...
mold fabricated by anisotropic etching, the angle of the pyramid is determined by the crystal structure of silicon. Therefore, the height of the pyramid is determined by the size of its base, which is approximately 100 µm in this design. The distance between the tips of two pyramids on the same axis is 650 µm, which is equal to the distance between two of the sensor chip’s cantilevers on the same axis.

For the PDMS caps with pillar-shaped and ring-shaped microstructures, the design parameters are shown in Fig. 3(c). The center shaft has the same diameter as that of the PDMS cap with a pyramid-shaped microstructure. The size of the pillar is 100 µm × 100 µm × 220 µm. The inner diameter, outer diameter, and height of the ring-shaped microstructure are 325, 275, and 220 µm, respectively.

In the PDMS cap designs, the vertical distance between the tip of the microstructure and the base of the cap is 280 µm, which is 20 µm smaller than the thickness of the sensor chip. Therefore, when the PDMS cap is attached to the sensor chip, the microstructure is pressed on the cantilevers even in the load-free state.

4. Finite element model simulation

A simulation was carried out using the simulation software COMSOL Multiphysics to analyze the deformation of the cantilevers under a normal load. The purpose of the simulation was to investigate the effect of the air cavity underneath the cantilevers on the sensitivity of the sensor. As shown in Fig. 4(a), two finite element models (FEMs) were used in the simulation, one with an air cavity and the other with an elastic block confined to the space underneath the cantilever. The cantilevers had the same design parameters as mentioned above. The size of the air cavity or elastic block underneath a cantilever was 500 µm × 500 µm × 300 µm. In our simulation, the cantilever and elastic block were composed of silicon (Si: Young’s modulus: 170 GPa, Poisson ratio: 0.28) and PDMS (Young’s modulus: 750 kPa, Poisson ratio: 0.4999), respectively. The bottom bases of the sensor chip and PDMS block were constrained in all directions. The PDMS block and sensor chip were glued to form a union. We used the free tetrahedral-type element to create the mesh, and there were 10,099 elements for the model with an air cavity and 132,671 elements for the model with a PDMS block.
Fig. 4(b) shows the deformation and strain in the X-axis direction of the cantilevers after applying a normal force of 1 kPa. The force was applied on the surface of the cantilever with the air cavity, whereas the force was applied on the surfaces of both the cantilever and PDMS block in the cantilever with a PDMS block. The results demonstrate that the deformation of the cantilever with the air cavity was much larger.

Fig. 5 illustrates the strain in the X-axis direction along the line AA' on the surface of the cantilever. The average strain in the X-axis direction of the cantilever hinge were calculated to be $2.3 \times 10^{-3}$ (for the air cavity) and $8.7 \times 10^{-4}$ (for the PDMS block underneath the cantilever). These results indicate that the air cavity could enhance the sensitivity of the cantilever by approximately 260 times.

5. Fabrication

5.1. Fabrication of the cantilever

The fabrication process of the cantilevers in our sensor chip is illustrated in Fig. 6(a). First, an SOI wafer was doped by rapid thermal doping [17]. Then, a gold (Au) layer was deposited and patterned. In the next step, the cantilevers were formed by etching the device Si layer. After the Au layer on the cantilever’s hinges was removed, the handle Si layer was etched using ICP-RIE. Finally, the glass layer was etched by HF vapor to release the cantilevers.

5.2. Fabrication of the PDMS cap

5.2.1. PDMS cap with pyramid-shaped microstructure

As shown in Fig. 6(b), in the fabrication process of the PDMS cap, a glass layer was first formed on a Si wafer by thermal oxidation. Then, the glass layer was patterned, and the molds for the pyramids were fabricated by anisotropic etching using Trimehylammonium hydroxide (TMAH) 20% solution at 80 °C. Next, the center hole was etched using ICP-RIE, and a layer of CxFy was deposited on the Si mold as an anti-adhesive layer. Finally, the cap was casted from the Si mold with PDMS (Sylgard 184, Dow Corning Corp.). In our fabrication, the mixture ratio between the PDMS polymer base and its polymerization agent was 10:1, resulting in a Young’s modulus of approximately 750 kPa for the PDMS cap.

5.2.2. PDMS caps with pillar- or ring-shaped microstructures

The fabrication of the PDMS caps with pillar- and ring-shaped microstructures was similar to that of the pyramid-shape microstructure (Fig. 6(c)). However, instead of anisotropic etching, the mold for the pillar or ring was etched using ICP-RIE with aluminum patterns as the etching mask.

5.3. Sensor device assembly

The fabricated sensor chip was first bonded and wired to an outer electrode board. Then, the PDMS cap was aligned on the sensor chip using the alignment setup shown in Fig. 7. The position of the PDMS cap was controlled using three-dimensional precision stages (Sigma Koki). The sensor chip was attached on a rotation stage. Because of the high transparency of PDMS, it was possible to observe the relative position of the microstructures and cantilevers. First, the X- and Y-axis positions of the cap were adjusted to align the central pillar of the cap with the central hole of the sensor chip. Then, the sensor chip was rotated around the Z-axis to align the microstructures with the cantilevers. Finally, the PDMS cap was attached onto the electrode board using rubber glue (CA-552 PPX, Cemedine). The CA-552 PPX primer and glue liquid
were coated beforehand on the PDMS cap and electrode board, respectively. Then, the PDMS cap was pressed against the electrode board for 30 min at room temperature to complete the attachment process. The bond strength between the PDMS pad and copper surface of a printed circuit board (PCB), which was used in our sensor, was measured after being attached by CA-552 PPX. The surface area of the PDMS cap was 10 mm × 10 mm. The experimental set up is shown in Figure S1 (Supplementary Information). The pulling force required to detach the PDMS cap from the PCB was 102 N, which corresponded to a bond strength of approximately 1 MPa. Therefore, the bond strength between the PDMS and electrode board was sufficient for our designed tactile sensor within the sensing range of 100 kPa.

5.4. Fabrication results

The SEM images of the fabricated sensor chip and cantilever are shown in Fig. 8(a) and (b). The SEM images of the silicon mold and PDMS cap with four pyramids are shown in Fig. 8(c) and (d). The cross-sectional view of the PDMS cap obtained using SEM is shown in comparison to the designed profile (shown by the red dashed line). The height of the central shaft was slightly higher (by approximately 20 μm) than the design value, likely due to an error in the initial thickness of the Si wafer used to fabricate the mold. However, by making a hole through the electrode board beneath the sensor chip, we allow the central shaft to be unconstrained by the electrode board, such that the pyramids are pressed on the cantilevers after assembling the PDMS cap (see also Fig. 9(b)).

Fig. 9(a) presents the assembled sensor device using the PDMS cap with four pyramids aligned on the four cantilevers of a sensor chip. The top view of the sensor device is shown in Fig. 9(b), which clearly confirms that the pyramids are pressed on the cantilevers even in the load-free state. The SEM images in Fig. 9(c) and (d) illustrate the cross-section of the PDMS cap with the pyramids aligned with the cantilevers of the sensor chip.

The top views of the sensors using the PDMS cap with pillar- and ring-shaped microstructures are shown in Fig. 10. The SEM images of the side view of PDMS caps with pillar- and ring-shaped microstructures are shown in Fig. 10(c) and (d), respectively. A part of the ring was cut to permit observation of the central shaft, as shown in the top right of Fig. 10(d). The measured profiles (shown by the red dashed line) fitted the design profile well. Furthermore, the upper surfaces of the pillar and ring were convex due to the ICP-RIE etching of the mold. The assembled sensor devices with pillar- and ring-shaped microstructures are shown in Fig. 10(e) and (f). The cantilevers are well observed through the microstructures, indicating that the microstructures are pressed onto the cantilevers.
6. Experiments and results

6.1. Experimental setup

The experimental setup to evaluate the response of our sensor to normal and lateral forces is presented in Fig. 11(a). The applied forces were measured using a digital force gauge (IMADA Inc., DS2-50N) attached to a linear stage. The force in the lateral direction was applied by pulling the acrylic plate attached to the PDMS cap with a weight of 50 g placed on it.

In our experiment, the resistance change of each cantilever was measured using the Whitestone bridge circuit shown in Fig. 11(b). The resistance change of the cantilever was calculated from the output voltage as \( \Delta R/R = 4\Delta V_{\text{out}}/V_{\text{cc}} \). The output voltage of the bridge circuit was amplified 1000 times before being measured by an oscilloscope.

We defined the signals \( S_x \), \( S_y \), and \( S_z \) as corresponding to the force on the X-, Y-, and Z-axes, respectively, as shown at the top of Fig. 11(c). The signal \( S_z \) corresponding to the normal force is the average resistance change of all four cantilevers of the sensor chip. The signal corresponding to the lateral force in the X- and Y-axis directions are the difference in the resistance change of the two cantilevers on the X- and Y-axes, respectively.

6.2. Experimental results

6.2.1. Responses of the sensors to the normal and lateral forces

The responses of our sensors to the normal and lateral forces are shown in Fig. 12. The relationship between the signals \( S_x \), \( S_y \), \( S_z \) and the applied forces \( f_x \), \( f_y \), and \( f_z \) in the case of the PDMS caps with pyramid-, pillar-, and ring-shaped microstructures are shown in Fig. 12(a)–(c), respectively. \( f_x \), \( f_y \), and \( f_z \) were defined as the applied force per unit area. The results demonstrate that for all types of microstructures, the signal corresponding to an axis was dominantly determined by the force in that direction. Moreover, the relationships between \( S_x \), \( S_y \), and \( S_z \) and \( f_x \), \( f_y \), and \( f_z \) were linear. The matrices of the proportional coefficients between the output signals and applied forces in the case of the PDMS caps with pyramid-, pillar-, and ring-shaped microstructures are provided in Eqs. (1)–(3), respectively. Using these matrices, the three components of the forces applied on the sensors can be backcalculated from the output signal of the sensors.

![Fig. 10. Fabricated PDMS caps with (a) and (c) pillar- and (b) and (d) ring-shaped microstructures. The side view of each PDMS cap in comparison with designed profile shown in (c) and (d) was taken by SEM. A part of the ring-shaped microstructure was cut to enable the observation of the central shaft. Top views of the completed sensor devices using the PDMS caps with (e) pillar- and (f) ring-shaped microstructures. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)](image)

![Fig. 11. Experimental setup for evaluating the responses of our sensors to normal and lateral forces. The definition of the output signals corresponds to the forces in the normal and lateral directions.](image)

\[
\begin{align*}
\begin{bmatrix}
S_x \\
S_y \\
S_z
\end{bmatrix} &=
\begin{bmatrix}
1.89 & -0.20 & 0.41 \\
-0.11 & 1.14 & 0.95 \\
-0.20 & -0.15 & 2.00
\end{bmatrix}
\begin{bmatrix}
f_x \\
f_y \\
f_z
\end{bmatrix}
\quad \text{[MPa]} \\
S_x &= \frac{\Delta R_1}{R_1} \\
S_y &= \frac{\Delta R_2}{R_2} \\
S_z &= \frac{\Delta R_3}{R_3} \\
S_x &= -\frac{1}{4} \frac{\Delta R_1}{R_1} + \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} + \frac{\Delta R_4}{R_4}
\end{align*}
\]
6.2.2. Increase in sensitivity by the cavity

We confirmed the increased sensitivity of our proposed sensor design with cavities by comparing the sensitivities of our sensors with that of a completely embedded structure. The embedded sensor was fabricated by simply casting a PDMS block onto the sensor chip. Because the liquid-state PDMS filled the space underneath the cantilevers, there was no cavity below the cantilevers in the embedded-type sensor. The responses of the fabricated embedded-type sensor toward the normal and lateral forces were evaluated using the same experimental set up as described in Section 6.1. The sensitivities were defined as the proportional coefficient between the output signals and corresponding applied forces.

The results for a normal force are shown in Fig. 13(a). The sensitivities of the proposed sensors with PDMS caps having pyramid-, pillar-, and ring-shaped microstructures were 2.00, 1.38, and 1.91 MPa⁻¹, respectively. In contrast, the sensitivity of the completely embedded structure was 0.008 MPa⁻¹. This result confirmed that the sensor design with cavities increased the sensitivity to a normal force by more than 150 times, which is in good agreement with the FEM simulation results.

Fig. 13(b) presents the results for a lateral force. Sensors using PDMS caps with pyramid-, pillar-, and ring-shaped microstructures could obtain sensitivities of 1.14, 1.38, and 2.19 MPa⁻¹, respectively, whereas that of the completely embedded structure was only 0.011 MPa⁻¹. Therefore, in the case of a lateral force, the cavity created by the PDMS cap could increase the sensitivity of the sensor by more than 100 times.

7. Discussion

7.1. Sensing range

In this paper, we proposed a design to increase the sensitivity of a piezoresistive triaxial tactile sensor by creating an air cavity under the cantilevers. The air cavity allowed the cantilevers to deform...
more easily, and therefore, the sensitivity of the sensor increased. However, because the output of the sensor is proportional to the deformation of the cantilevers, the increased sensitivity leads to a reduction in the sensing range of the sensor. Therefore, the proposed sensors aim to measure the forces varying within a narrow range, for example, the forces in the manipulation of robot hands or in minimal invasive surgery.

7.2. Effects of the PDMS Young’s modulus and cantilever thickness

The sensitivities of our sensors can be improved by reducing either the stiffness of the PDMS cap or the thickness of the cantilever because in our sensor design, the deformation of the cantilever is determined by the bending stiffness of both the PDMS cap and cantilevers. Therefore, using either the softer PDMS cap or thinner cantilevers will allow for greater deformation of the cantilevers and thus improve the sensitivities of the sensors. The simulation results (Supplementary Information) demonstrated that the sensitivities of the sensors with respect to normal force and lateral force increased by 1.45- and 1.63-fold, respectively, as the Young’s modulus of the PDMS changed from 5 to 0.5 MPa. Moreover, as the cantilever thickness changed from 10 to 2 μm, the sensitivities with respect to normal and lateral force increased by 13.3- and 9.7-fold, respectively. Because the Young’s modulus of Si is much higher than that of PDMS, for the cantilever with thickness of several micrometers, the change in cantilever thickness resulted in a significant change in the sensitivity.

7.3. Effect of the shape of the microstructures

In this paper, three types of microstructures with pyramid, pillar, and ring shapes were tested. The variation in the shape of the microstructures had an insignificant effect on the sensitivity of the sensors. The main factor that helped to improve the sensitivity of the sensor was the cavity underneath the cantilevers. In our sensors, the role of the microstructures was to transfer the force acting on the surface of the PDMS cap to the cantilevers. Among the proposed shapes of the microstructures, the pyramid-shaped microstructures were easily fabricated, whereas the ring-shaped microstructures could be easily aligned with the cantilevers of a sensor chip because of the microstructures’ symmetry.

8. Conclusions

In this paper, we proposed a design to increase the sensitivity of a piezoresistive triaxial tactile sensor. In conventional sensors, the piezoresistive structures are completely embedded inside an elastic body, and thus, the deformation of the silicon elements is restricted by the surrounding elastic material, reducing the sensor’s sensitivity. We proposed a tactile sensor with an air cavity underneath the piezoresistive cantilevers by aligning and attaching a PDMS cap with microstructures onto the cantilevers. The role of the cavity was to provide additional room for the cantilevers to deform and thus increase the sensitivity of the sensor. Prototype sensors with pyramid-, pillar-, and ring-shaped microstructures were fabricated, and their sensitivities to both normal and lateral forces were evaluated. Compared to the completely embedded sensor, the cavity was confirmed to enhance the sensitivities of our proposed sensor by 150 times and 100 times to normal and lateral forces, respectively.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.sna.2013.09.002.

References


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