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A FLEXIBLE THREE-AXIAL FORCE MEASURING ARRAY FOR TACTILE SENSING APPLICATIONS

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Abstract – We report a high-performance flexible tactile sensor capable of measuring 3-axial forces, which consists of an array with a size of 8 × 8 integrated in an area of 10 mm^2. Each cell has four strain gauges to detect 3-axial forces. The strain gauge is made of an inorganic silicon membrane. We fabricated the tactile sensor through a combination of a conventional batch micromachining process and a dry-transfer-printing technique. The fabricated tactile sensor showed a repeatable error less than 1 %, a minimum detectable force better than 0.5 g and a minimal crosstalk among 3-axial forces.

Keywords: force sensor, array, tactile sensor, flexible, 3-axis

1. INTRODUCTION

The sense of touch plays an important role in interaction. We can manipulate and recognize objects and even be aware of harmful situations with the help of sensory data for touch sensing provided by our skin, which is located at the interface between our bodies and the outside world. Similarly, robotic and biomedical systems require tactile sensing capability for their advanced and complex tasks.

For the last few decades, a considerable amount of tactile sensing technologies have been introduced for robotic or medical applications but their further advances toward tactile sensors on a par with human skin have been hampered by lack of available technologies to fulfil all of the requirements at the same time that human skin has, such as flexibility, mechanical and chemical robustness, high-sensitivity, high-repeatability, multi-modal measurements (pressure, vibration, temperature, slip detection), deployment of many sensing elements, covering any shaped surface with 3-dimensional curvature (e.g. a sphere), and sensor addressing for arrays.

In our previous article [1,2], we introduced a new concept of the flexible tactile sensor array that uses two materials; inorganic silicon and polymers that have complementary material properties to each other and demonstrated the feasibility of using this concept by fabricating a 8 × 8 force-sensing array with on/off switches. In this paper, we report an improved tactile sensing array that has 8 × 8 sensing elements spaced 1.25 mm with 3-axis force measuring capability.

2. SENSOR DESIGN

In order to detect 3-axial forces (e.g., vertical Z force, transverse X and Y forces) simultaneously with minimum crosstalk, each tactile cell (dubbed as taxel) should have four strain gauges and an appropriate load concentrating structure like a bump. The bump structure produces moments when transverse forces are applied so that strain gauges facing each other undergo opposite strain. Fig. 1 shows a schematic of the sensor array. Each taxel has four 'L' shaped silicon strain gauges positioned at corners and a bump positioned at centre.

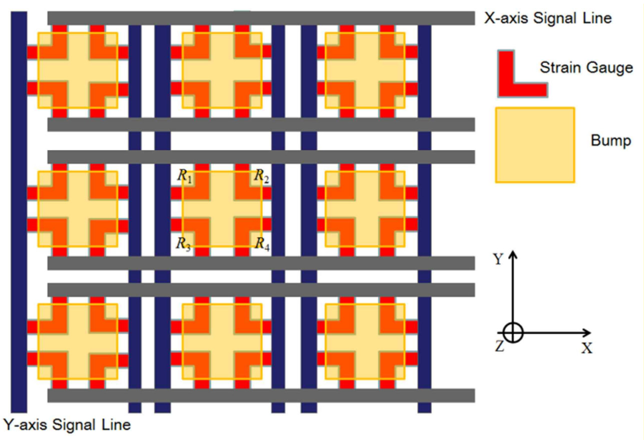


Fig. 1. A schematic plan view of the design of 3-axial force sensing array (only 3 × 3 array is shown for clarity)

The z-directional force F_z, x-directional force F_x and y-directional force F_y can be calculated using (1), (2) and (3), respectively.

$$F_z = S_z(\sum_{i=1}^{4} R_i - R_{z0}) \quad (1)$$

$$F_x = S_x(R_1 + R_3 - R_2 - R_4 - R_{x0}) \quad (2)$$

$$F_y = S_y(R_3 + R_4 - R_1 - R_2 - R_{y0}) \quad (3)$$

,where S_x, S_y, S_z are sensitivities in x, y and z-directions, respectively and R_{x0}, R_{y0}, R_{z0} are resistances in x, y and z-directions at initial state (i.e., no loading condition). The 'L' shape of the strain gauge permits relatively easier electrical wiring for multiplexing because electrical lines can be aligned horizontally and vertically with a grid formation.

3. DEVICE FABRIATION

The device was fabricated through a combination of conventional micro-fabrication processes and a dry-transfer-printing technique as described elsewhere [2]. The fabrication steps are schematically shown in Fig. 2.

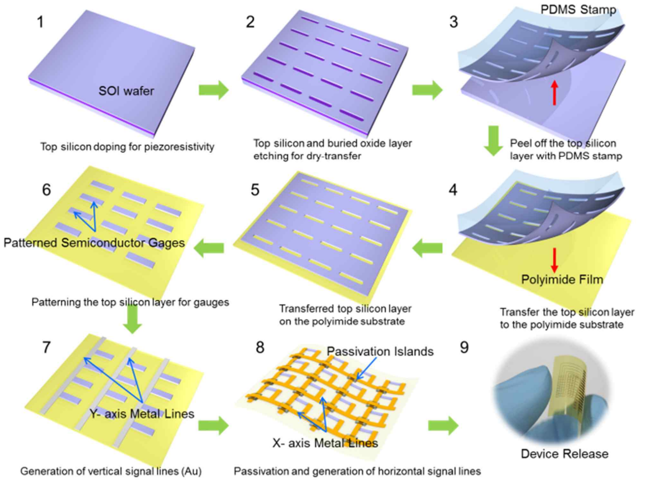


Fig. 2. Fabrication steps including the dry-transfer printing technique and microfabrication processes

The fabrication starts with silicon-on-insulator (SOI) wafers with a 100 nm-thick top silicon layer. The top silicon layer was doped using boron with a concentration of 1×10^{19} ions/cm^3 through an ion-implantation process so that the top silicon layer has a piezoresistive property. Then, the doped silicon layer was transferred to 25 μm-thick plastic substrate (polyimide film) by so-called 'dry-transfer-printing' technique [3]. The transferred silicon layer was etched to form L-shaped 16 × 16 gauge arrays. The arrayed strain gauges are interconnected by 16 row and 16 column signal lines. The signal lines were formed by depositing metal layers (5 nm Cr layer and 200 nm Au layer) using e-beam evaporating process and the following etching process. For passivation at cross area between row and column signal lines, polymer islands made of SU-8 with a thickness of 500 nm have been formed at cross area. The microscope images of the fabricated sensor device are shown in Fig. 3.

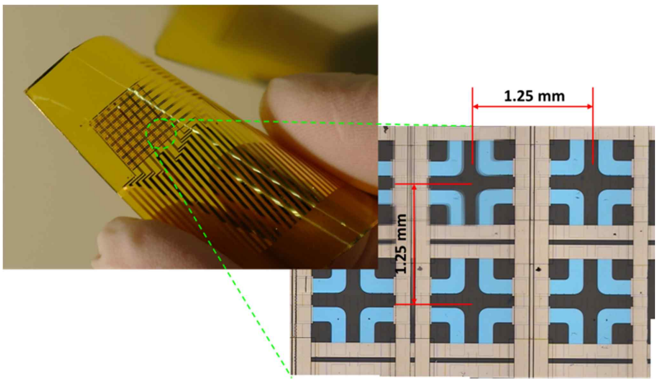


Fig. 3 Microscope images of the fabricated tactile sensor

To create a bump layer for concentrating loads to the strain gauges, a silicon wafer is etched to form a mold for the bump patterns. Then, a 10 nm-thick C4F8 layer is deposited on the substrate to weaken PDMS adhesion to the substrate for detachment. The PDMS is spin-coated on the substrate by approximately 100 μm and vulcanized. PDMS fills the 300 μm bump molds pretty quickly and uniformly. The fabrication process for the bump layer and its optical image are shown in Fig. 4. Finally, the fabricated device layer and the bump layer are aligned and bonded together using a special aligner with a microscope. Before bonding, O_2 plasma treatment was applied to the contact surfaces of both layers to increase bonding force.

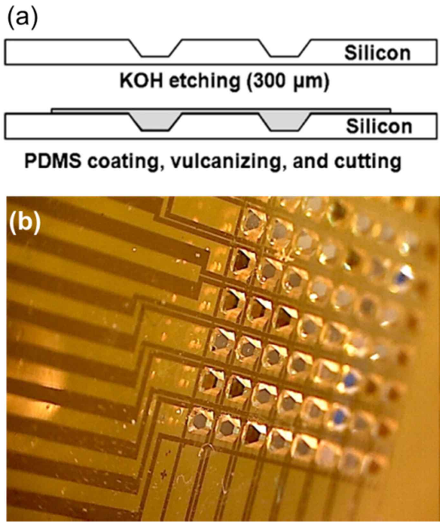


Fig. 4 (a) A bump layer fabrication process, (b) the final device after bonding two layers

4. EVALUATION

The fabricated tactile sensor was tested using an experimental setup consisting of a precision balance with 0.01 g resolution and an indenter with a tip diameter of 1 mm. We applied stepwise z-directional forces up to approximately 40 g on each taxel (tactile pixel) by pressing its bump with the tip while measuring the contact force with the balance and simultaneously acquiring the signal output from the taxel through the signal processing system at each step. The loads were sequentially loaded up and down repeatedly five times in order to observe the repeatability and the hysteresis of the taxel output. The result in Fig. 5(a) demonstrates that each taxel shows good performance in terms of repeatability (a dispersion of 5 increasing data), hysteresis (a difference between increasing and decreasing data), and zero return error (a difference between increasing and decreasing data at zero load), which is measured at a value smaller than 1 %, 1 % and 1 % of the rated output, respectively. Fig. 5(b) represents a taxel response for small steps of 0.5 g. It is clear that each taxel can discriminate a very small force better than 0.5 g. Fig. 6(a) and 6(b) show responses of a taxel when it is only loaded by x-directional and y-directional shear forces, respectively. As shown in Fig. 6, each taxel can discriminate x and y-directional forces with low crosstalk. When only x-directional load is applied, only x-direction output changes in proportion to x-directional load while the other two outputs keep constant.

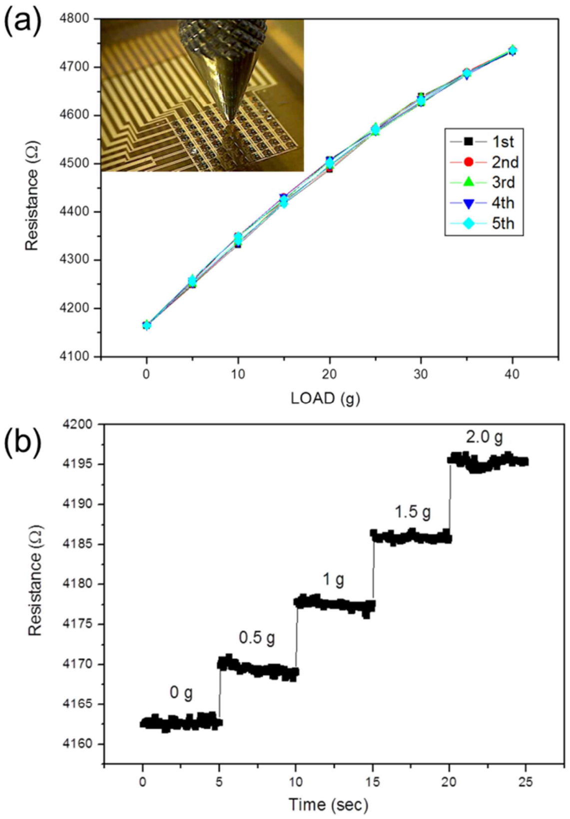
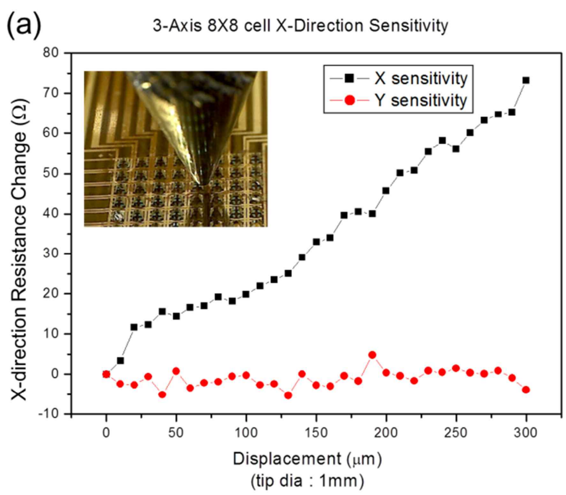


Fig. 5. Taxel output in response to z-directional forces (a) output-force curves (b) 0.5 g force steps



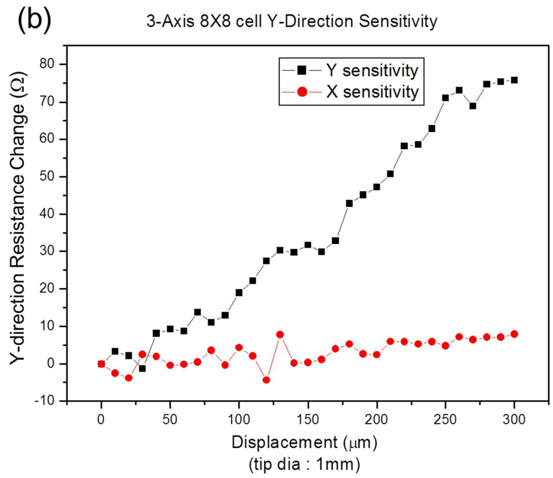


Fig. 6. Taxel outputs when it is loaded only in (a) x-directional force and (b) y-directional force.

4. CONCLUSIONS

We fabricated a flexible tactile sensor that has measuring capabilities of 3-axis forces using a thin and highly-doped single-crystal silicon membrane as sensing elements and polymers with no diaphragm or no membrane as a spring element. Such a combination can provide high-sensitivity and repeatability while giving more mechanical robustness along with flexibility.

The prototype tactile sensor showed good performance on force measurements, with a resolution better than 0.5 g, repeatability better than 1 %, a hysteresis less than 1 %, and a zero-return error less than 1 %. The fabricated sensor also shows little crosstalk among 3-axial force outputs, which indicates a slip detection is possible like a human skin.

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