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# A piezoresistive tactile sensor based on carbon fibers and polymer substrates

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ABSTRACT

This paper presents a new structure of a flexible tactile sensor that uses carbon fibers as the sensing elements. The principal concept is the replacement of piezoresistors in the current, piezoresistive, tactile sensors with carbon fibers. Owing to the replacement of piezoresistors with carbon fibers, several advantageous characteristics of the fibers can be fully utilized in the measurement of contact forces. The micro-machined, piezoresistive, tactile sensor array has been successfully fabricated by the use of a polymer MEMS process. The response of the integrated CFs to a normal stress loading was also experimentally evaluated by the use of a motorized XYZ stage and an optical microscope.



## 1. Introduction

Tactile sensors are one of the important technologies for future application in robotics and interactive electronics. Other potential applications of the sensor include the sensing of organic tissue either at the end of a catheter or on the fingers of an endoscopic-surgery. On the basis of the sensing mechanism, MEMS-based tactile sensors are generally categorized into four types: piezoresistive [1]; capacitive [2]; piezoelectric [3]; and optical [4]. While silicon-based, micro-machined tactile sensors offer a high spatial resolution, high sensitivity, and direct integration with signal-processing electronics, the long-term mechanical reliability is unresolved due to the brittleness of the silicon materials. Another drawback of the tactile sensors is the difficulty of packaging on to robotics hands with curved surfaces. In the case of silicon micromachining, the dimensions of tactile sensing skin in the future are also limited by the finite sizes of silicon wafers.

For several reasons, polymer-based tactile sensors are an alternative [5]. Polymer materials are mechanically robust, chemically resistant, and stable. Further, some polymers, such as SU-8 and polyimide, are easy to pattern on a substrate by the thanks of photosensitive. Polyimide substrates with metal strain gauges have been developed by J. Engel [6] for application in tactile sensing. The multimodal sensing capability of flexible polyimide substrate is an important advantage. However, the proposed tactile sensors also have a drawback in terms of sensitivity because the gauge factor of metal foil that was employed as a sensing element in the research is less than five. The employment of a doped silicon wire as the sensing element is also quite difficult due to the low melting temperature of polymer materials.

In this paper, we present a new structure of a flexible tactile sensor that uses PAN-based carbon fibers (CFs) as the sensing elements. The principal concept is the replacement of piezoresistors in the current tactile sensors with CFs. The current piezoresistors, whose electrical resistance changes with an applied force, are normally made from thin metal or highly-doped silicon thin-films. Owing to the replacement of piezoresistors with CFs, several advantageous characteristics of CFs can be fully utilized in the measurement of contact forces. Compared with the previous tactile sensors, the carbon-fiber-based tactile sensors may possess superior sensitivity because the piezoresistive behavior of CFs is very sensitive to even very small deformations of the fibers that are caused by tiny forces. An array of the proposed tactile sensors is fabricated by the use of simple processes. The feasibility of the fabricated tactile sensor is successfully demonstrated.

## 2. Design and fabrication of CF-based flexible tactile sensors

Fig. 1 shows the basic structures of carbon-fiber-based flexible tactile sensors with effective areas of $10 \times 10\,mm^2$ and $20 \times 20\,mm^2$, respectively. It consists of two polydimethyl-siloxane (PDMS) substrates and a CF array as the sensing element. The CF that is 10 μm in diameter is aligned between two electrodes by the use of a motorized micro-manipulator. The length of CFs depends on the size of the effective area. Details of electrical properties are explained in our earlier paper [7,8]. Each strain-sensing element is connected to an upper PDMS substrate with signal-transfer electrodes.

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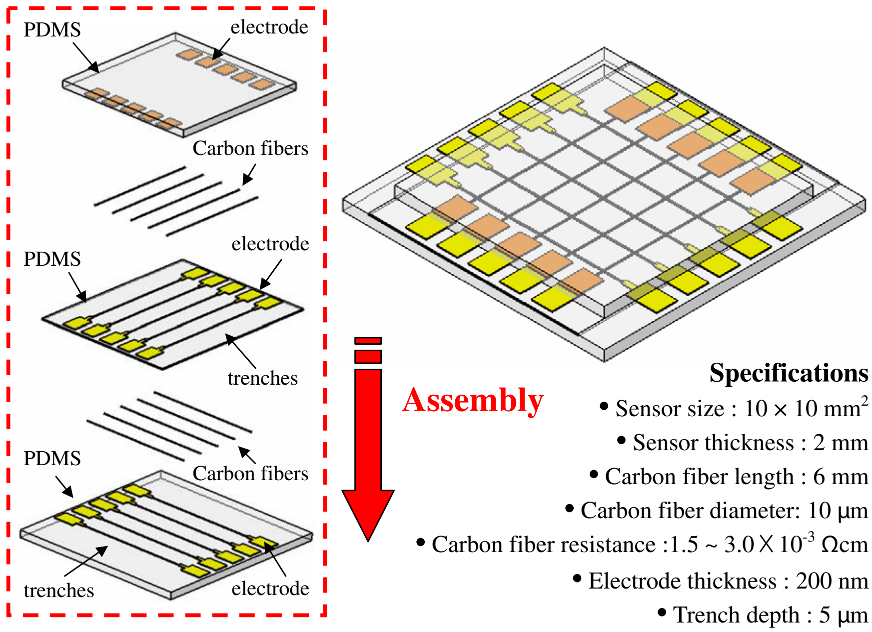


**Fig. 1.** Schematic representation of the CF-based flexible tactile sensor.

The CF sensors that are embedded in the PDMS substrates can measure strain solely in the direction that is normal to the substrates. Signals from the sensing elements of the 5 × 5 array tactile sensor can be read-out one row at a time.

The performance of CF-based tactile sensors is expected to be strongly dependent upon the electrical properties of CFs as well as the geometry of the PDMS substrate. Among the many techniques proposed for obtaining a uniform thickness across the whole region of the PDMS substrate, a simple and robust technique was adopted to fabricate the flexible body of tactile sensors. The key consideration of the proposed method is the use of SU-8 molds that are coated on Si wafers. The PDMS substrates can be easily peeled off from the SU-8 molds after a process of curing in an oven. This method can provide precise control of the thickness and the surface roughness of the lower PDMS substrate. The geometric configuration of the CF location will also affect the sensitivity of the tactile sensor. Further optimized processes should be developed for the easy alignment of CFs and the batch-fabrication of tactile sensors.

The fabrication of tactile sensors was accomplished in two steps, shown in Fig. 2. The lower substrate with CFs was fabricated by the following process-sequence. First, a 10 μm-thick SU-8 photoresist (PR) was spin-coated on a 4 in. Si wafer (Fig. 2a). Next, the SU-8 layer was exposed to UV light through a photo-mask and was developed in an organic solvent solution (Fig. 2b and c). Here, we controlled the intensity of light by changing the exposure time. The reason for the reduced exposure was to develop half the thickness (5 μm) of the SU-8 layer. Then, PDMS was spin-coated on the

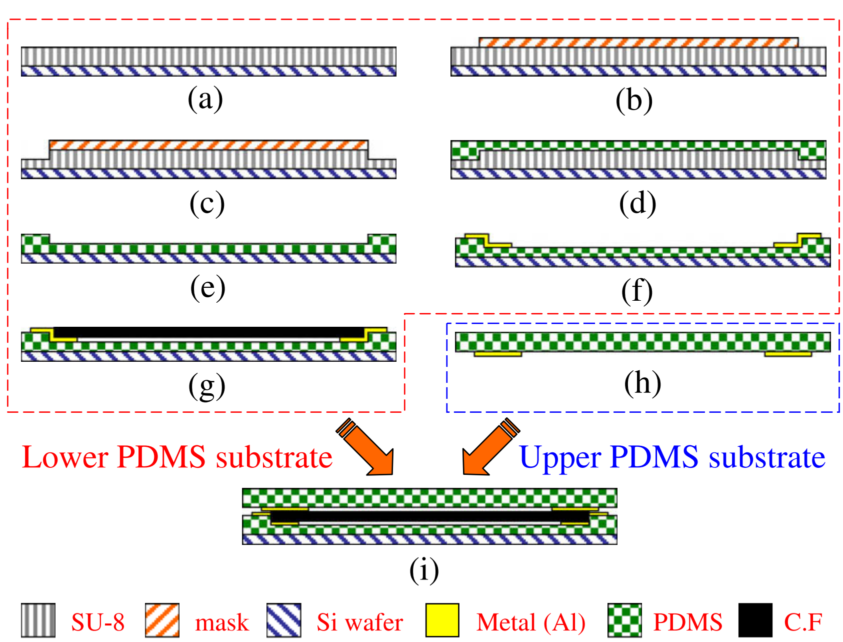


**Fig. 2.** Fabrication process for the tactile sensor.

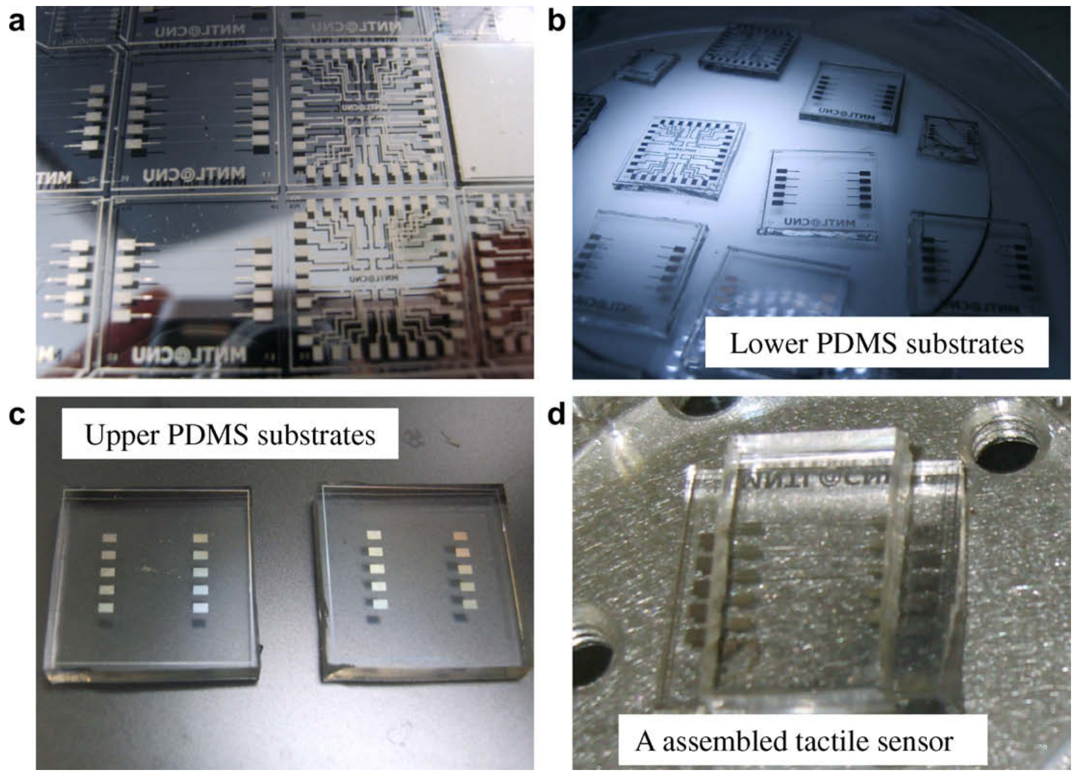


**Fig. 3.** Optical images of: (a and b) the lower substrate based on PDMS; (c) the upper substrate; and (d) the fabricated CF-based tactile sensor.

fabricated SU-8 mold and cured at 90 °C in an oven (Fig. 2d). Next, the PDMS layer was peeled off from the SU-8 mold and placed on a dummy silicon wafer (Fig. 2e). When the PDMS is patterned in the manner of trenches with a depth of 5 μm, it serves as guide-lines during the alignment of CFs. Al wires and pads were formed on the PDMS substrates by the use of a liftoff process (Fig. 2f). The CFs were aligned between metal electrodes by the use of a micro-manipulator under a microscope (Fig. 2g). The upper substrate was also fabricated by the same process as for the lower substrate (Fig. 2h). Finally, the two prepared PDMS substrates were bonded together following surface-treatment of the PDMS that used oxygen plasma (Fig. 2i). The trenches that form in the lower PDMS substrate are very important because they also help to fix the CFs during the bonding process.

The reduction in the contact resistance between the CFs and electrodes is strongly desired for minimizing electrical noise from signals. A good electrical connection was achieved by the bonding of two PDMS substrates with Al electrodes. Fig. 3, respectively shows the optical images of: several types of the fabricated lower substrate (Fig. 3a and b); the upper substrates (Fig. 3c); and prototypical tactile sensors with aligned CFs that are the sensing elements (Fig. 3d). The effective areas of application of the flexible tactile sensor are $10 \times 10\ mm^2$ and $20 \times 20\ mm^2$, respectively. The size of the sensing elements is about $250 \times 250\ \mu m^2$, with a 1 mm spacing between individual elements. The size and thickness of the tactile sensor can be easily modified by changing the photomasks.

## 3. Experimental results

Fig. 4 shows the experimental setup for the measurement of the piezoresistive sensitivity with respect to the applied normal force. First, the fabricated tactile sensor was electrically tested to determine the continuity of interconnections within the array. A high-resolution XYZ micro-manipulator was used to position the needle,

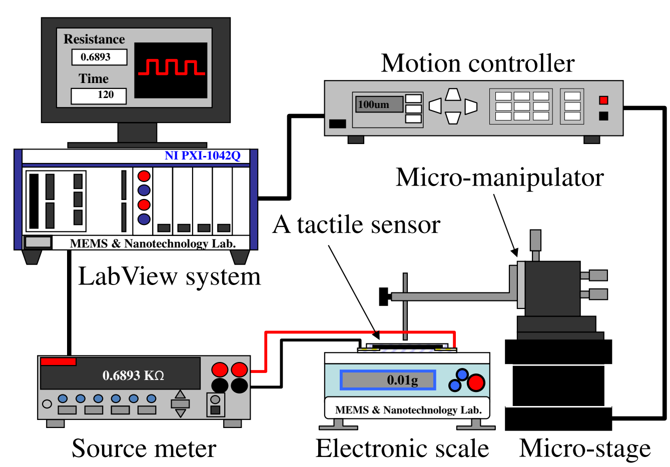


**Fig. 4.** Schematic of the measurement setup that uses a motorized XYZ manipulator and a LabView system.

with a predetermined weight, on the sensor. The fabricated sensor and the measurement systems were placed under a microscope for visual inspection. Output electrodes on the tactile sensor were connected to the LabView system to measure the change in the resistance of the CFs when a force was applied. Finally, the relationship between the applied force and the change in resistance was obtained.

The repeatability of the sensor outputs was also measured by the use of a micro-stage and a Teflon structure. The micro-stage moved incrementally in the normal direction at a velocity of 12 mm/s. The total displacement of the micro-stage was 100 μm. The movement was repeated several times for examining the variation in the change of resistance of the CFs. The plot of the variation in the read-out resistance vs. the applied normal force is shown in Fig. 5. The forces that were applied to the tactile sensor

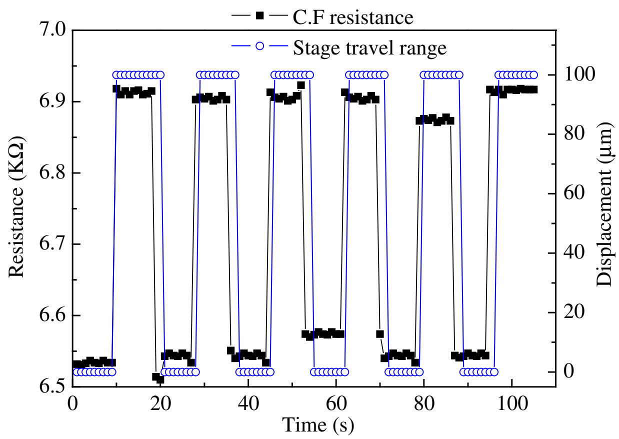


**Fig. 5.** Feasibility test that uses the fabricated CF-based tactile sensor.

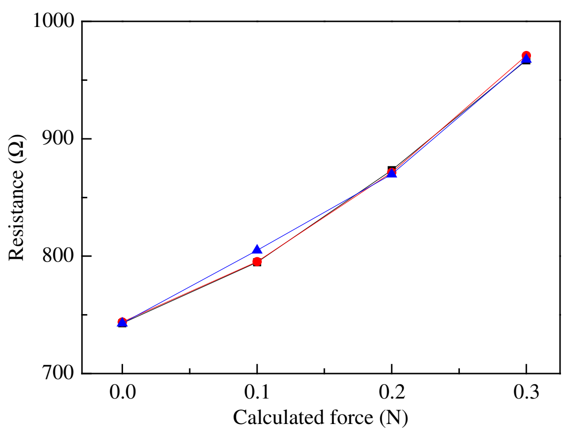


**Fig. 6.** Plot of resistance vs. calculated force.

were estimated from displacement data by the use of a numerical method. PDMS structures shrank by about 100 μm when a normal force of about 0.1 N was loaded on the surface of the PDMS, which approximately corresponded to a sensitivity of 5.88%/0.1 N $\{(\Delta R/R)/N\}$. The initial resistance of CFs for the first sample was about 6.5 kΩ. The resistance increased by about 400 Ω at a displacement of 100 μm, which corresponded to an applied force of 0.1 N. Sensor responses, as a function of the applied force from 0.1 N to 0.3 N and corresponding to displacements of 100–300 μm, were also observed by the use of the same measurement systems. Linear behaviors of the sensor output were successfully confirmed, as shown in Fig. 6. The variation of the initial resistance is due to the differences in geometry across the used CFs. In the near future, a Wheatstone-bridge configuration will be employed to use voltage signals that correspond to the change in the resistance. Such a configuration may help to measure extremely small changes in the resistivity of CFs.

## 4. Conclusions

A new tactile sensor array with CFs as sensing elements has been successfully fabricated by the use of a polymer MEMS process. The principal concept of the proposed tactile sensor was the replacement of piezoresistors in the current piezoresistive tactile sensors with the CFs. The response of the integrated CFs to a normal stress loading was experimentally evaluated by the use of a motorized XYZ stage and an optical microscope. Through preliminary tests and studies of characterization, the sensor array was shown to meet the design objectives. Additional tests of the dependence on the operating temperature and the hysteresis behavior need to be conducted. The packaging issue of tactile sensors also must be addressed for practical applications.

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