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Development of a Large-Area 8 × 8 Tactile Sensing Array with High Sensitivity

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In this work, a large-area tactile sensing array with high sensitivity is reported. The sensing elements of the array consist of multiwall carbon nanotubes dispersed in polydimethylsiloxane polymer. A novel fabrication process using a universal applicator is proposed for realizing large-area conducting polymer films. In addition, a nylon membrane filter is employed as a mold for creating microdome patterns, which are essential for increasing the sensitivity. The major advantages of the proposed device include ultrahigh sensitivity, flexibility, and a simple fabrication process. The sensing mechanism involves utilizing the contact resistance between the electrode and the conductive polymer film. A demonstration of the application of the tactile sensing array is presented.

1. Introduction

The development of tactile sensors has received attention because of their potential applications in many areas such as robotics,[1,2] biomedical devices,[3] and artificial skin.[4–6] Tactile sensors are one of the essential sensing mechanisms for providing information from the interaction between robots and both their environment and human beings. During the past decade, many novel designs of tactile sensors have been proposed. Zhong *et al.* reported a paper-based active tactile sensor array.[7] The performance of the proposed device remained satisfactory when parts of the array were removed, which indicates its potential application for customized electronic skins. Kolesar *et al.* realized a robotic tactile sensor by assembling a polyvinylidene fluoride (PVDF) polymer film with a silicon integrated circuit.[8] Yang *et al.* presented a system based on graphene woven fabrics (GWF) for highly sensitive strain sensing.[9] The sensors can be employed for applications such as human motion detection, sound signal acquisition, and external stress distribution monitoring. Saccomandi *et al.* presented a fiber-optic tactile sensor based on fiber Bragg grating (FBG) technology.[10] The static metrological properties and relatively high spatial resolution make the proposed device attractive for robotic hands.

Furthermore, tactile sensing elements embedded with microstructure arrays, which enable high sensitivity and fast response, have received attention in recent years. Su *et al.* proposed a bio-inspired flexible pressure sensor with high sensitivity. The microstructures on the sensor substrates were created by the direct molding of natural mimosa leaves.[11] Zhang *et al.* developed flexible

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temperature-pressure sensors based on microstructure-frame-supported organic thermoelectric materials.[12] Obviously, the embedded microstructures on the sensing elements play an important role in providing excellent performance characteristics such as high sensitivity and a fast response. However, special and expensive molds have usually been needed to realize these microstructured arrays.

In our previous work, we proposed a novel lithography process for realizing a tactile sensor array using a mold made of SU-8 and for transferring microstructures from nylon membranes onto sensing elements.[13] In this work, we present a new process for fabricating a large-area tactile sensing array with microdome structures, and a new electrode configuration which simplifies the device assembly. The proposed device is designed for a sensing system deployed on the handlebar of a robot that assists humans in walking. A fabrication process is proposed to form conducting polymer films with large areas by using a universal applicator for transferring microdome structures from nylon membrane filters onto polymer films. The proposed sensing array is assembled by combining the conductive polymer film with a flexible printed circuit board (FPCB) with arrays of interdigital electrode pairs. The characteristics and uniformity of the large-area conductive polymer sheet are also investigated.

2. Material and Methods

2.1 Device design

Figure 1(a) shows a schematic of the proposed sensing array. The device consists of three layers: a PE film, a conductive polymer with microdome structures, and an FPCB with an array of interdigital electrodes. Figure 1(b) shows the cross-sectional view of a sensing element. Each sensing element includes a pair of interdigital electrodes and the conductive polymer above the electrode pair.

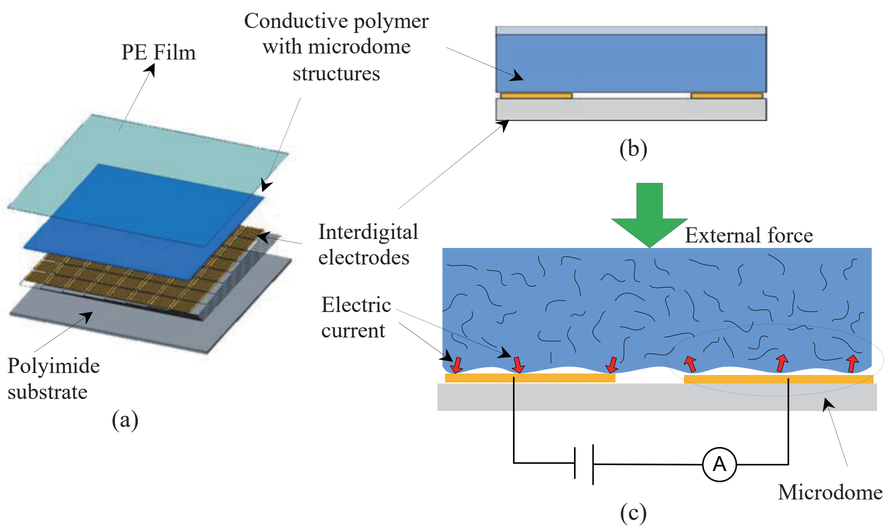


Fig. 1. (Color online) (a) Schematic of sensing array. (b) Cross section of sensing array. (c) Operating principle of the tactile sensing array.

The operating principle of the proposed tactile sensing array is shown in Fig. 1(c). As an external pressure is applied, the contact area between the microdome structures and the interdigital electrodes increases sharply, which in turn rapidly reduces the resistance between the polymer and the electrode.[14] The change in resistance can be easily measured via the interdigital pairs. This type of tunneling piezoresistive device is much more sensitive (at least two orders of magnitude higher sensitivity) than the pressure-sensing devices fabricated with typical conductive polymer materials without microstructures.[14] In addition, the sharp change in the contact area due to pressure-induced deformation of the microdome structures gives a much more rapid response (about 10 times faster) in the form of a change in resistance than a device using a typical conductive polymer material.

2.2 Polymer film fabrication

Figure 2 shows a schematic of the preparation of the prepolymer for the carbon nanotube (CNT)–polydimethylsiloxane (PDMS) composite. First, multiwalled CNTs are dispersed in hexane and PDMS prepolymer (Sylgard 184 A, Dow Corning) in a ratio of 12:5. The CNT concentration in the prepolymer is 6 wt%. A magnetic stirrer is employed to stir the mixture thoroughly for 12 h. Hexane serves as the dispersant during blending. To cure the prepolymer, the mixture is mixed with a curing agent (Sylgard 184 B, Dow Corning) in a 1:10 ratio and is stirred for 50 min. Then, the prepolymer is degassed in a vacuum chamber for 3 h to evaporate the volatile hexane,[15] after which it is ready for patterning microstructures using an applicator (Zehntner Testing Instruments, ZUA 2000.220).

The fabrication process of the conductive polymer film is shown in Fig. 3. A nylon membrane filter (Finetech Research and Innovation Co., Nylon Membrane, M-Nylon 5.0I) is placed on a glass plate [Fig. 3(a)]. The prepared prepolymer is dispensed on the membrane [Fig. 3(b)] using a computer-controlled dispenser. By squeezing the dispensed prepolymer using the applicator, a conductive polymer film is formed [Fig. 3(c)]. The film is held at room temperature for 12 h for

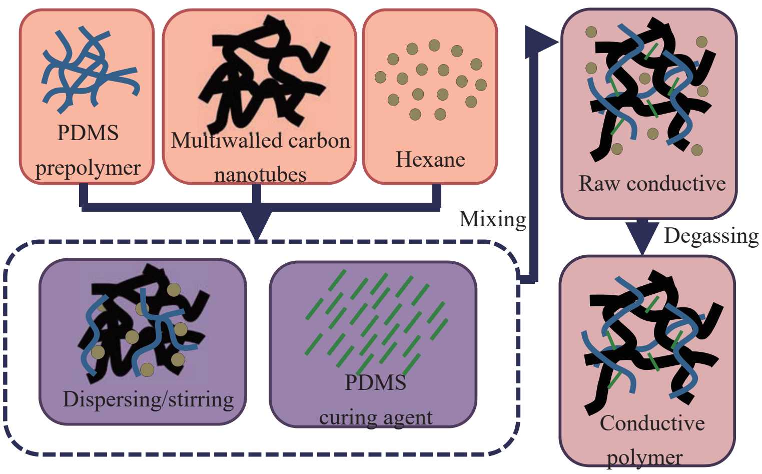


Fig. 2. (Color online) Preparation of the conductive polymer.

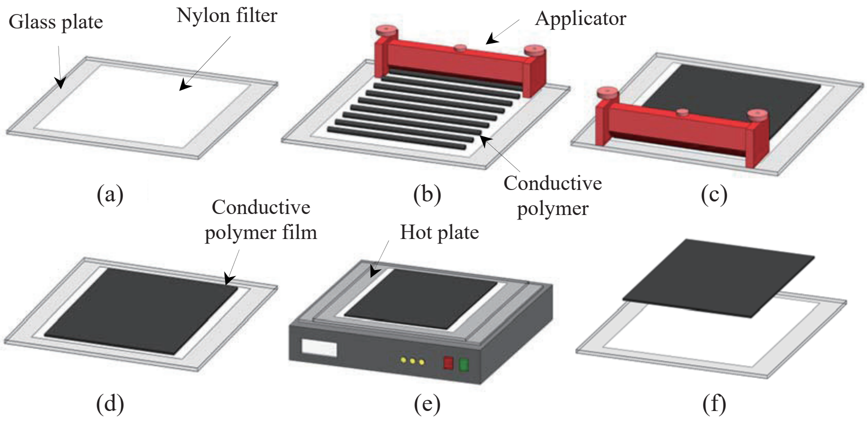


Fig. 3. (Color online) Fabrication process of the proposed large-area conductive polymer: (a) Place a nylon filter on a glass plate. (b) Disperse the prepared conductive polymer on the filter. (c) Form a uniform polymer film using an applicator. (d) Hold at room temperature for 12 h for smooth evaporation of the solvent (hexane). (e) Cure the film using a hot plate. (f) Peel the conductive film from the filter.

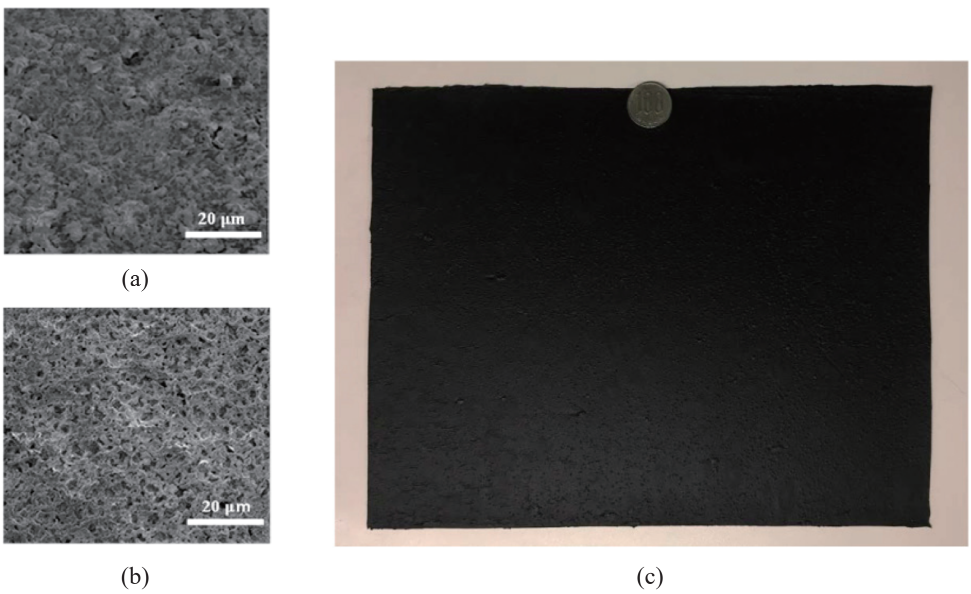


Fig. 4. (Color online) (a) SEM image of the surface of a nylon membrane filter with numerous tiny pores. (b) SEM image of the surface of a conductive polymer film with numerous microdomes. (c) Image of a fabricated large-area conductive polymer film.

smooth evaporation of the solvent [Fig. 3(d)]. Then, the film is cured at 50 °C for 3 h using a hot plate [Fig. 3(e)]. The conductive polymer film is then peeled from the membrane filter [Fig. 3(f)]. On the polymer surface, numerous microdome structures transferred from the filter membrane can be observed.

A scanning electron microscopy (SEM) image of the surface of the nylon membrane filter is shown in Fig. 4(a). The figure clearly shows numerous filtering pores on the surface. Figure 4(b) is a SEM image of the conductive polymer film. The microdome structures, whose average base width is about 7 µm, were transferred from the membrane filter.

3. Results and Discussion

The experimented setup for characterizing the conductive polymer film is shown in Fig. 5. A force gauge (HF-1, ALGOL Engineering Co.) was fixed on a vertical (z-axis) translational stage that had a displacement resolution of 1 μm. The maximum resolution of the force gauge was 1 mN. A polymethylmethacrylate (PMMA) cylindrical rod was attached to the sensing probe of the force gauge. The PMMA rod was moved downward by the vertical translational stage. Normal forces on the conductive polymer film were induced as the PMMA rod came in contact with the conductive polymer film. The change in the resistance of the polymer film was measured using a source meter (Model 2400, Keithley Instruments). The dimensions of the conductive film were 30 × 22 cm^2. The film was partitioned into 16 regions (i.e., a 4 × 4 array), and the resistance of the center of each region was measured. During the measurement of each region, an interdigital electrode pair (on a 5.5 × 3.5 cm^2 FPCB) was placed under the region of the polymer film. Figure 6(a) shows the measured

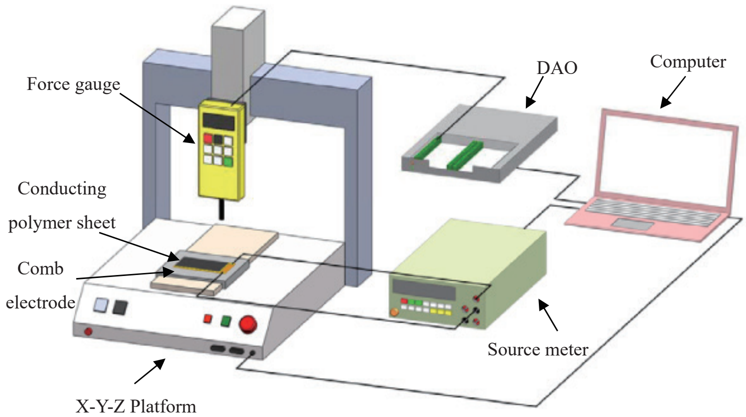
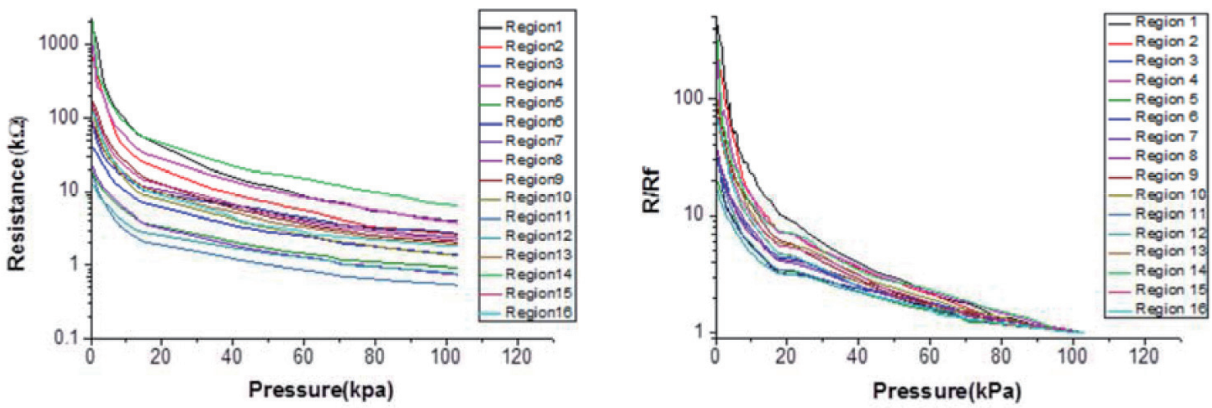


Fig. 5. (Color online) Experimental setup for measuring the dynamic response of the sensing array induced using a piezoelectric actuator.



(a) (b)

Fig. 6. (Color online) (a) Measured responses of sensing elements at different applied pressures. (b) Normalized measured responses of sensing elements at different applied pressures.

relationships of electrical resistance versus applied pressure in different regions. Figure 6(b) shows the normalized resistance for these regions. Note that in the figure Rf is the final resistance in each measurement for each region. These results indicate that the variation between the regions near the edge of the film and the regions around the center is relatively large.

Figure 7 shows a histogram of variations at the 64 sensing locations under two uniform pressures of 1.2 and 1.8 kPa. In this case, the polymer film was assembled with an FPCB with an 8 × 8 array of interdigital pairs. There were 64 sensing locations in total. A resistance value can be easily retrieved using a scanning circuit.[16] The abscissa in Fig. 7 is the resistance variation (ΔR) of a sensing location with respect to the average measured resistance of the 64 sensing locations (R_A) under a specific uniform pressure force.

Figure 8(a) is a photograph of an assembled tactile sensing array. The sensing array can be fixed on a robot surface by attaching the array using a typical thin stick tape. Figures 8(b) and 8(c) show the images of the force induced by pressing the 8 × 8 sensing array with one hand. The image of the measured force shows that the shape of the hand is clearly resolved.

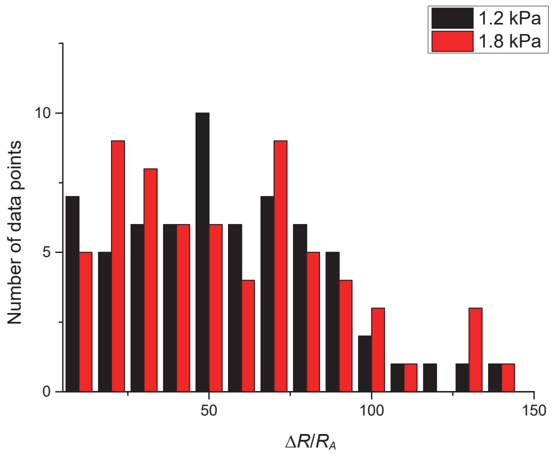
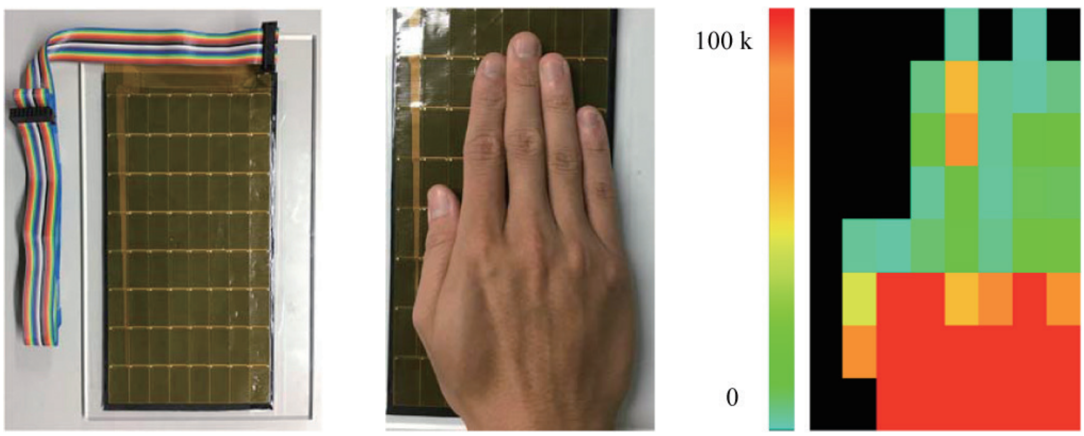


Fig. 7. (Color online) Histogram of variations at 64 sensing elements (on the 8 × 8 array) under uniform pressures.



(a) (b) (c)

Fig. 8. (Color online) (a) Assembled tactile sensing array. (b) Measurement of force induced by pressing the sensing array with a palm. (c) Measured force captured by the tactile sensing array.

4. Conclusions

In this report, we presented the development of a large-area, highly sensitive tactile sensing array using a conductive polymer film embedded with microdome structures. A novel fabrication process was proposed for realizing large-area conducting polymer films using a nylon membrane filter and an applicator. The uniformity of the fabricated conductive polymer sheets was also investigated. The characteristics of the proposed device were measured and studied. A demonstration of the sensing capability of the array was also presented.

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