

Flexible and Sensitive Foot Pad for Sole Distributed Force Detection

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Abstract—We develop highly flexible and compressible 3D interconnected porous PDMS structures by using sugar cubes as templates. The porous structures can be compressed to more than 80% without any side-wall buckling comparable with bulk polymers. Force sensitive resistors were fabricated by filtration of the CNT solution inside the porous structure of PDMS. We found that sufficient acid treatment can increase the adhesion and bonding between CNTs and PDMS. Force sensitive resistors respond the applied pressure and compressive strains by high linearity ($R^2 > 0.97$) and sensitivity ($GFs > 2$) with a reliable manner. Finally, as an application of our force sensitive resistors, a flexible foot pad containing force sensitive resistors arrays is developed for the foot sole distributed force detection.

I. INTRODUCTION

Development of flexible, stretchable and wearable electronic devices has recently drawn tremendous attention due to their numerous applications in biomedicine and robotics [1-4]. For example, flexible, stretchable and wearable strain sensors were utilized for the human motion detection [1, 5]; artificial electronic skins were developed for the pressure sensing and visualization [2, 6]; ultra-thin flexible sensors were used for continuous temperature monitoring of the human skin [7] or flexible and transparent batteries were employed for the endoscopy application [4].

Pressure sensors transduce the pressure to the electrical changes such as resistance and capacitance. Capacitive type pressure sensors are made by a dielectric layer laminated between two electrodes. These types of pressure sensors exhibit a good linearity with low hysteresis. However, low sensitivity, limited pressure measurement ranges and low compressibility are main drawbacks of the capacitive type pressure sensors [8]. Furthermore, piezoresistive type pressure sensors respond to external stimuli by the change of resistance. Even though they might have high sensitivity and wide pressure measurement ranges, pressure sensors have suffered from nonlinearity and high hysteresis [9]. In particular, high performance pressure sensors are need for foot plantar pressure measurements because of their potential applications in rehabilitation and personal health monitoring, sport performance and injury prevention, footwear design and diagnosing disease [9]. High linearity, low hysteresis, temperature independency, wide pressure measurement ranges (*i.e.* 0-2 MPa for typical applications and up to 3 MPa for extreme conditions), reliability and low cost of fabrication

are among minimum requirements of pressure sensors for the foot plantar pressure measurement devices [9].

Herein, we describe force sensitive resistor (FSR) sensors based on the CNTs-porous PDMS composites. To overcome the bulk mechanism of compressibility for polymers, we proposed the porous polymer structure which achieves high flexibility, stretchability and compressibility (up to 80%) without any side-wall buckling. The porous PDMS structures were fabricated by using sugar cubes as templates. FSR sensors were made by the filtration of CNTs inside the 3D interconnected porous structure of PDMS. We found that acrylic acid treatment can remarkably improve the interfacial adhesion and bonding between CNTs and polymer. FSR sensors respond to 70% of the compressive strain with a linear manner ($R^2 > 0.97$), high sensitivity ($GFs > 2$) and good reliability. As an application of our FSR sensors, we fabricated a foot plantar measurement device for the foot sole distributed force detection.

II. MATERIALS AND SAMPLE FABRICATION

Multi-walled carbon nanotubes (MWCNTS) with an average length (10-30 μm) and diameter (20-30 nm) were purchased from Cheap Tubes Inc. 0.5 wt.% of CNTs in isopropyl alcohol (IPA) solution was sonicated for an hour in sonication bath. The solution was further stirred for an hour and well-suspended CNT solution was stored for further experiments.

Fabrication processes of the porous PDMS are illustrated in Figure 1. A very simple and low cost porous structured PDMS was fabricated by using sugar cubes as templates [10, 11]. The liquid PDMS with 7.5 wt.% of curing agent was cast on a sugar cube. The liquid PDMS penetrated into the 3D interconnected porous structure of sugar cube owing to the low viscosity and low surface energy of the liquid PDMS [1]. The sugar cube casted with liquid PDMS was then put into a vacuum chamber for an hour to facilitate the penetration. After complete penetration of the liquid PDMS into the porous structure of the sugar cube, the liquid PDMS was cured at 70 °C for 2 hours forming a composite of the sugar powders and PDMS. Then, excess PDMS was trimmed away and the sugar powder-PDMS composite was immersed into the hot water at 80 °C for 2 hours to completely dissolve the sugar powders (Figure 1). Highly 3D interconnected porous structured PDMS was obtained by washing and drying the samples. Even though the structure is highly porous, it is very robust and stretchable. Unlike the bulk polymers, the porous PDMS is very compressible (compressibility > 80%) without side-wall buckling. Therefore, the porous PDMS structures would be quite useful for the pressure sensing applications

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where a very large structural deformation should be accommodated by the sensors.

FSR sensors were fabricated by absorbing of CNTs into the 3D interconnected porous structure of PDMS. To this end, porous PDMS was immersed into the beforehand prepared CNT solution and squeezed several times. Releasing the squeezed porous PDMS sucked the CNT solution inside its 3D interconnected porous network and made it electrically conductive (compare Figure 1e and Figure 2a). We investigated the electromechanical properties of the conductive CNTs-porous PDMS composites. But, we observed detachment of some CNTs from PDMS under cyclic compressive strain/releasing due to weak interfacial adhesion between CNTs and PDMS. Detachment of CNTs decreases the number of electrical pathways, increasing the resistance of samples under cyclic loading/unloading irreversibly. To enhance the bonding between CNTs and polymer, CNT-porous PDMS nanocomposite was immersed into acrylic acid for 30 min to introduce carboxylic acid groups into the CNTs and polymer [12]. Moreover, carboxylic acid groups bond to the two ends and surface defects of CNTs. This acid treatment is a well-known method for CNT suspending in the solvents due to the purification of CNTs [13]. In addition, improvement of the interfacial adhesion and bonding between functionalized CNTs and polymers has been studied by several research groups [14, 15]. Here, instead of the CNT functionalization before mixing with the polymer matrix, attached CNTs on the surface of PDMS were immersed into the acrylic acid solution. Better interfacial adhesion and bonding between CNTs and porous PDMS was observed after acid treatments.

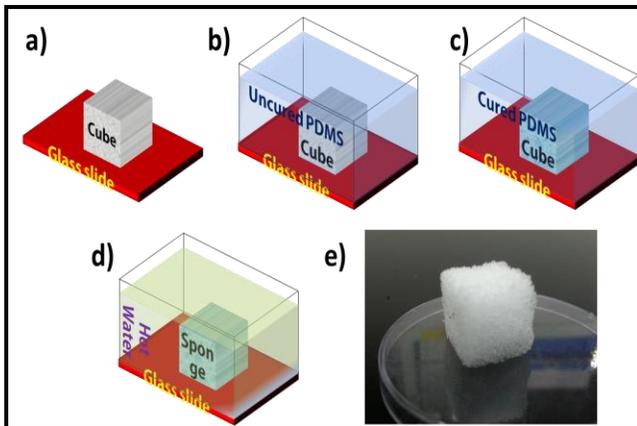


Figure 1. Fabrication processes of the porous PDMS: a) Sugar cube preparation. b) Casting the liquid PDMS on a cube and keeping it in vacuum for an hour to facilitate the penetration of the liquid PDMS into 3D interconnected pores. c) Curing the liquid PDMS at 70 °C for 2 hours. d) Dissolving the sugar powders in the hot water at 80 °C for 2 hours. e) Photograph of the fabricated porous PDMS.

III. RESULTS AND DISCUSSION

Figure 1a shows a photograph of the porous PDMS cube after immersing into the CNT solution. White color of the porous cube changed to the black color showing well suction of CNTs into the 3D porous structure of the PDMS cube

(compare Figure 1e with Figure 1a). The conductivity of samples could be controlled by the number of immersions into the CNT solution. To investigate the interfacial adhesion properties of CNTs and porous PDMS before and after acid treatment, a simple adhesive tape experiment was conducted. An adhesive tape was pressed three times on the surface of the pristine CNTs-porous PDMS composite and acid-treated CNTs-porous PDMS samples and then the number of detached CNTs from the surface of the porous PDMS were compared. As Figure 2b depicts, many of CNTs were peeled off from the surface of the porous PDMS due to the weak adhesion of CNTs and porous PDMS. On the other hand, a strong adhesion between CNTs and porous PDMS was observed after acrylic acid treatment so that only a few CNTs were peeled off from the surface of the porous PDMS, as shown in Figure 2c.

Figure 2d shows SEM image on the surface of the porous PDMS. As the figure illustrates, the porous PDMS composed of bulk PDMS separated with 3D interconnected pores. The porosity and pore size of the porous PDMS could be controlled by the size and concentration of sugar powders. The porosity measured by the volume absorbance of water is approximately 85% showing highly porosity of the structure. The pore sizes varied from 25 to 400 μm , depending on the size of the sugar powders.

SEM images on the surface of the CNT penetrated porous PDMS before and after acid treatment are represented in Figure 2e and 2f, respectively. As Figure 2e shows, the networks of CNTs are attached on the surface of PDMS providing electrical conductivity within percolation networks. Moreover, a white layer of carboxylic acid groups on the surface of the CNTs-PDMS composite is illustrated in Figure 2f. This adhesive layer covered the CNT network on the surface of PDMS and provided a strong interfacial adhesion between CNTs and PDMS, which made the total conductive network very robust.

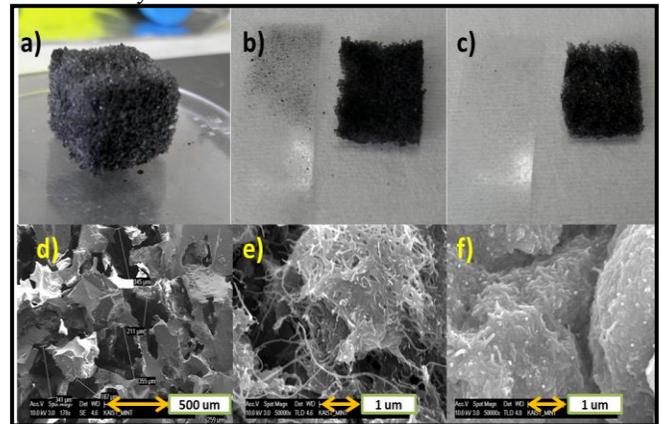


Figure 2. a) Photograph of the CNT-porous PDMS nanocomposite; white color of the porous PDMS was changed to black color due to the penetration of the CNT solution into the porous structure of PDMS. b and c) Adhesive test before and after acrylic acid treatment, respectively. d) SEM image of porous PDMS. e and f) SEM image of the doped CNTs before and after immersing into acrylic acid, respectively.

To characterize the electromechanical properties of the FSR sensors, copper wires were attached to the top and bottom surface of the sensors with silver paste. For cyclic

loading/unloading, compressive/release strains were applied to the samples with a motorized moving stage (Future Science Motion Controller, FS100801A1P1) while the current was measured by a potentiometer (CH Instruments, Electrochemical Workstation, CHI901D). Figure 3 shows the current-voltage curve for a FSR sensor. The CNTs-porous PDMS composites show semi-conductive behavior and the current gradually increases by the applied compressive strain.

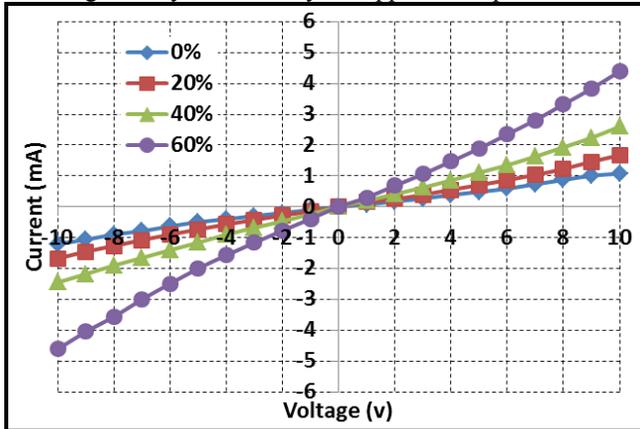


Figure 3. Current-voltage characteristics of a FSR sensor under different strains.

Piezoresistive response of a FSR sensor is illustrated in Figure 4. The sensor was subjected to compressive strain from $\epsilon=0\%$ to $\epsilon=70\%$ while the current was recorded. The sensor shows excellent linearity ($R^2 \sim 0.97$) in logarithmic scale with an excellent sensitivity ($GFs > 2$). When the compressive strain is applied to the sensor, the density of CNTs in the percolation network increases thereby increasing the number of electrical pathways and consequently increasing the current.

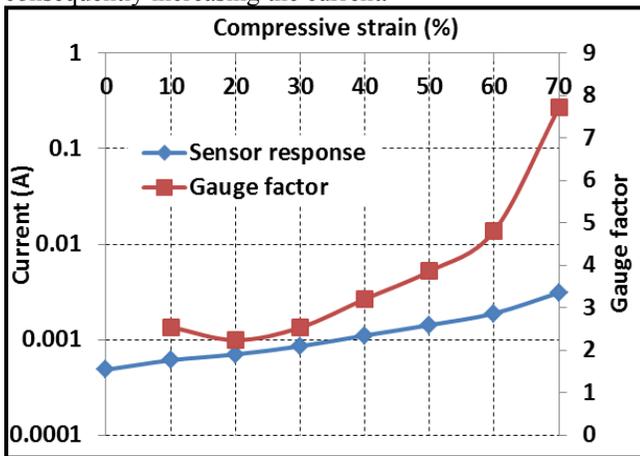


Figure 4. Electrical current versus compressive strain for a FSR sensor.

For long-term performance and stability of the FSR sensors, we performed a reliability test. More than 1,000 cyclic compression/release (from $\epsilon=10\%$ to $\epsilon=70\%$) were applied to a FSR sensor while the response of the FSR sensor was monitored. The sensor shows a good stability and reliability performance to the cyclic loading/unloading, as shown in Figure 5.

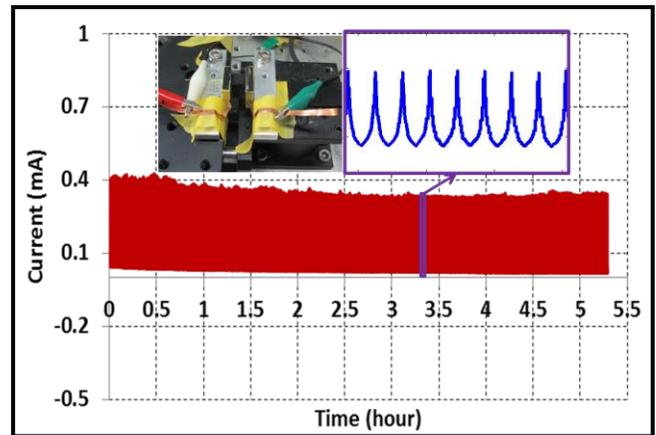


Figure 5. Reliability test on a FSR sensor; the sensor was compressed to $\epsilon=70\%$ and released to $\epsilon=10\%$ for more than 1,000 cycles.

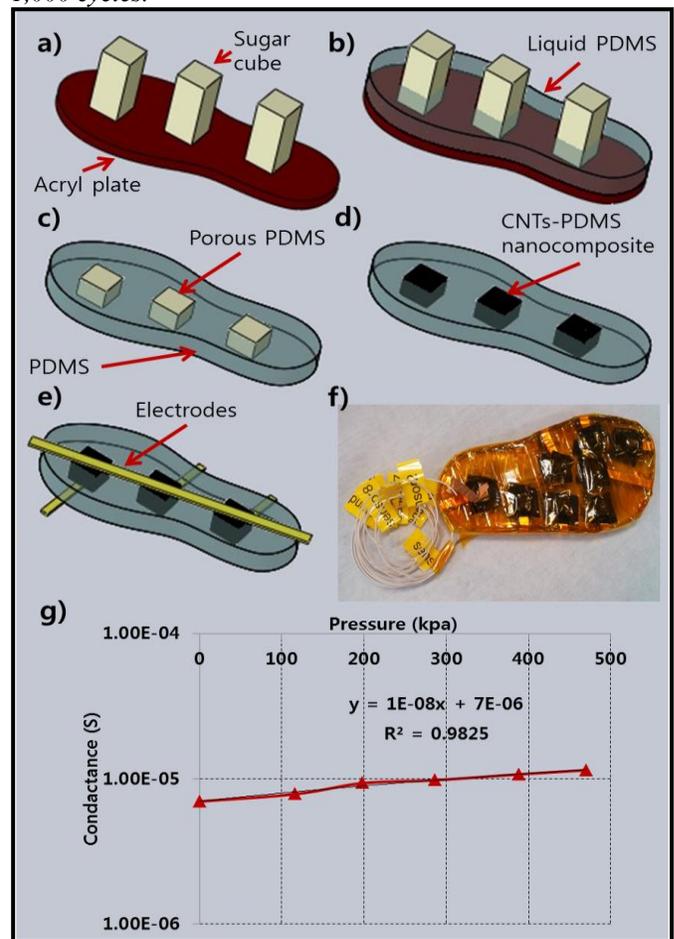


Figure 6: a-e) Fabrication process of the foot pad: a) Sugar cube preparation. b) Casting the liquid PDMS on cube and keeping it in vacuum for an hour and curing the PDMS at 70°C for 2 hours. c) Removing the acryl plate and dissolving the sugar cube in the hot water and drying. d) Sucking the CNT solution into the porous PDMS region using vacuum filtration. e) Attaching the electrodes to each sensor. f) Photograph of the fabricated device. g) Response of a cell to the applied pressure; good sensitivity, fast response with a linear manner ($R^2 \sim 0.98$).

As an application of our sensitive and reliable FSR sensors, a flexible foot pad was developed for the foot sole distributed force detection, as shown in Figure 6. Porous PDMS structures were synthesized in the desirable locations and then FSR sensors were fabricated by filtration of the CNT solution inside the porous PDMS. All sensors were connected to data acquisition (DAQ) system by LabVIEW programming. Figure 6g shows pressure sensing measurement of a FSR. Pressure was gradually applied (from 0 kPa to 480 kPa) to sensor while the response was measured. The sensor responded to the applied pressure with a good linearity ($R^2 \sim 0.98$) and sensitivity.

IV. CONCLUSIONS

In this paper, highly compressible and sensitive FSR sensors were developed based on the CNTs-porous PDMS composite. We found that acrylic acid treatment can improve the interfacial adhesion and bonding between CNTs and PDMS. Compressibility and GFs of the sensors are 80% and more than 2, respectively. The CNTs-porous PDMS composite based FSR sensors exhibit a good reliability performance with excellent linear response ($R^2 \sim 0.97$). Finally, a foot plantar pressure measurement device was fabricated by using our FSR sensors as sensing elements. The foot pad shows a very fast response to the pressure with good linearity and sensitivity.

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