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A Highly Sensitive Flexible Piezoresistive Sensor Based on Wrinkled CNT-PDMS

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ABSTRACT

This paper presents a highly sensitive flexible piezoresistive sensor based on wrinkled structure. By adding carbon nanotube(CNT) into the mixing of polydimethylsiloxane(PDMS), conductive PDMS can be fabricated. Patterned with monolayer wrinkle structure, this stretchable CNT PDMS can be used as a thin and flexible pressure sensor. The wrinkle structure enables the sensor with high sensitivity (8.3 kPa-1) in low pressure region(0-0.1kPa). In addition, the result of force image test shows that the sensor array can be used into detecting pressure distribution and measuring force images.

I. INTRODUCTION

With the development of electronic skins and wearable devices, flexible sensors have drawn a lot of attention, especially flexible piezoresistive pressure sensor[1-3]. However, the conventional sensors based on silicon doesn't meet the requirement of flexibility due to its high mechanical modulus[4]. Polydimethylsiloxane (PDMS) as one of the most used polymers is a good choice to realize the flexibility feature due to its low modulus, but it is not conductive. To solve the problem, introducing conductive materials like carbon nanotubes(CNTs) into the PDMS mixture is a potential method which can greatly improve the conductivity of PDMS[5]. Meanwhile, research shows that to improve the dispersion of CNTs in PDMS mixture, some organic solvents like toluene or hexane are necessary[6,7].

As a sensor, the functional structure is crucial. Micro-texture surfaces of PDMS such as pyramids[8] or micro-pillars[9] have been widely used and developed in the application of pressure sensor. Compared with these conventional micro-structures, wrinkle structure which exists everywhere in nature, is a great candidate for flexible sensing due to its unique advantages in fabrication, such as simple and low-cost mass production[10]. Cheng et al discovered that implementing C_4F_8 plasma on an uncured PDMS surface will obtain homogeneous and disordered monolayer wrinkle structures which can be controlled by plasma treating time and RF power[10,11]. The wave-like structure[12-14] of the wrinkle increasing the real contact area of the device and showing high aspect ratio has been demonstrated improving the performance of electronic devices[15].

II. EXPERIMENTAL PROCEDURES

2.1 FABRICATION PROCESS

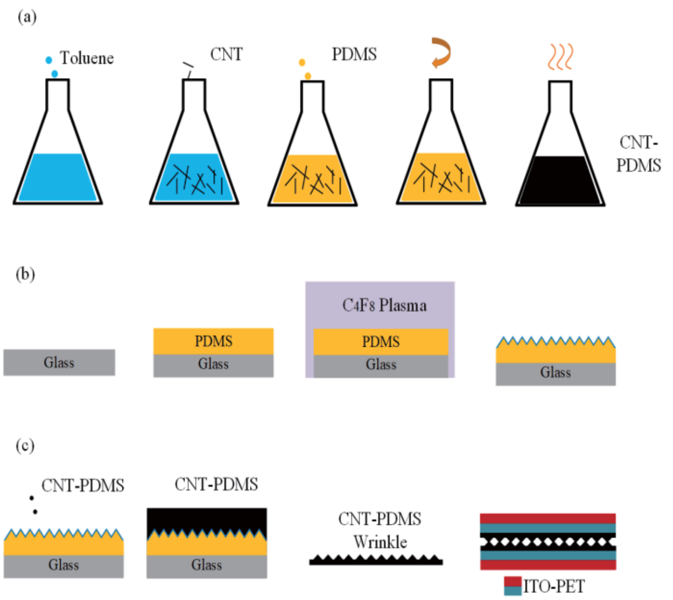

Fig. 1 Fabrication process of highly sensitive piezoresistive sensor based on wrinkled CNT-PDMS. (a) flow chart of preparing conductive CNT-PDMS; (b) schematic illustration of forming monolayer wrinkle structure on PDMS molds; (c) reversing mould and assembling the sensor.

The detail fabrication process of the piezoresistive sensor based on wrinkled CNT-PDMS is diagramed in Fig. 1. As shown in Fig. 1(a), firstly prepare 15 ml toluene and add 0.35g CNTs. Next, pour 5g base solution of commercial PDMS(Sylgard 184, Dow Corning Corporation) and mix them with vigorous stirring for about 4hours. Then, drop 0.5g curing agent of PDMS into the mixture, stir and then heat the mixture at 80°C for about 15 minutes to remove toluene and obtain relatively viscous solution. The preparation of CNT-PDMS solution is done. The second step is to prepare a monolayer wrinkle structure mold. As illustrated in the Fig. 1(b), a C_4F_8 plasma is implemented on uncured PDMS mixure (the base solution to curing agent ratio is 10:1) for 100s. Heat the plasma-treated PDMS at 80 °C for 30 minutes, after which monolayer wrinkle structure can be obtained on the PDMS surface. Finally, pour the toluene-removed uncured CNT-PDMS mixture on the wrinkle structure and heat it till the curing of CNT-PDMS. After which, peel off the conductive wrinkled CNT-PDMS film. Due to the fluorocarbon layer on the surface of the wrinkle which works as a mold-release agent, the CNT-PDMS can be easily peeled off. To test the performance of the piezoresistive sensor, the indium tin oxide coated polyethylene terephthalate(ITO/PET) films are covered on the smooth surface of wrinkled CNT-PDMS film as top and bottom electrodes.

2.2 MEASUREMENT AND ANALYSIS

The fluorocarbon plasma treatment was conducted using an inductively coupled plasma(ICP) etcher (Surfacing Technology Systems plc, Multiplex ICP 48443). The gas flow rate and pressure were set at 40 sccm and 3 Pa, respectively. The RF power is 75w. The structure and morphology of the monolayer wrinkle were characterized using microscopy (Eclipse E200, Nikon Co.) and scanning electron microscopy (SEM, Quanta 600F, FEI Co.). The mechanical response including strain and stress of the piezoresistive sensor was measured by a tension tester (HSV, HANDPI).

III. RESULTS AND DISCUSSION

3.1 STRUCTURE AND MORPHOLOGY OF CNT-PDMS

The wrinkle structure is well obtained by the impact of C_4F_8 plasma and uniformly and randomly distributes though single wrinkle structure seems disordered as shown in Fig. 2(a). The SEM images of monolayer wrinkle structure on the surface of CNT-PDMS is shown in the Fig. 2(b)&(c). Compared with the pre-fabricated monolayer wrinkle mold, the reverse mold technique is successful in transferring wrinkle patterns onto CNT-PDMS surface. The wavelength of the wrinkle is about 10 μm. And the fabricated CNT-PDMS film is stretchable as shown in Fig. 3a. Fig. 3b shows the flexibility of the whole device.

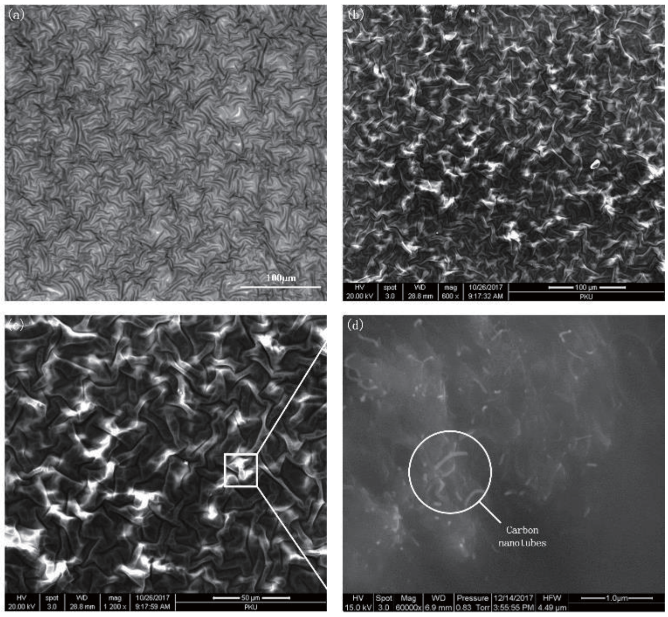

Fig. 2 (a) Optical photo of the monolayer wrinkle mold; (b)&(c) SEM images of monolayer wrinkle structure on the surface of CNT-PDMS with the scale bar of (b) 50μm and (c) 100μm; (d) CNTs on wrinkle structure.

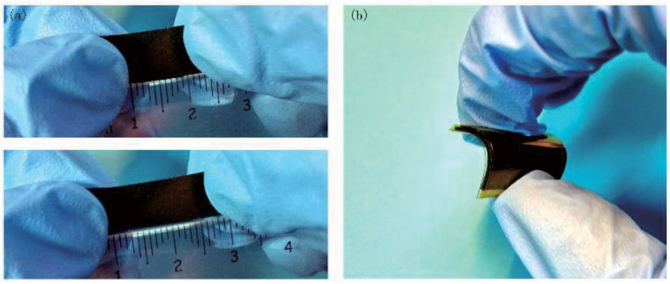

Fig. 3 (a) Stretchability of wrinkled CNT-PDMS film; (b) Flexibility of the pressure sensor packaged by ITO-PET.

3.2 WORKING PRINCIPLE OF THE PIEZORESISTIVE SENSOR BASED ON WRINKLED CNT-PDMS

Fig. 4 shows the working principle of the piezoresistive sensor based on wrinkled CNT-PDMS. The wrinkle structure on CNT-PDMS surface has two contact modes: point-to-point contact and gear shaping contact. As shown in Fig. 4a, the simulation results show that the contact area is increasing at the contact point with the increasing compress strain, which leads to the better conductivity performance according to the law of resistance: $R = \frac{\rho l}{S}$, where R, ρ, l and S are resistance, resistivity, length of the materials and the area, respectively. While the wrinkle structure contacts as gear shaping as shown in Fig. 4(b), the resistance decrease mainly due to the increasing contact area and decreasing channel length for electrons to flow. From a micro-perspective, the increasing area of wrinkle structure also improves the contact of CNTs exposed on the surface of wrinkle structure and decrease the resistance.

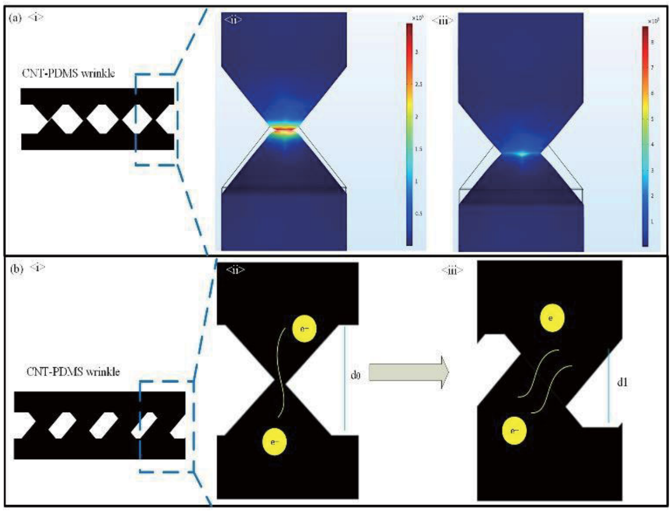

Fig. 4 Working principle of the piezoresistive sensor based on wrinkled CNT-PDMS. The wrinkle structure on CNT-PDMS surface has two contact modes. (a)<i> point-to-point contact; <ii&ii> simulation result of the point-to-point contact mode by compressing 2μm <ii> and 5μm <iii>; (b)<i>gear shaping contact; <ii> schematic illustration of electrons flowing through the narrow channel before compressing; <iii> schematic illustraton of electrons flowing through the channel with larger area under compressing.

3.2 PERFORMANCE OF THE PIEZORESISTIVE PRESSURE SENSOR

As a piezoresistive material, wrinkled CNT-PDMS enables the sensor with high sensitivity and good response performance. Fig. 5(a) illustrates the piezoresistive pressure sensor works under the applied force. The two ITO layer works as top and bottom electrodes. PET layers protect the device from other chemical and mechanical damages and improve the robustness of the pressure sensor. Fig. 5(b) shows piezoresistive feature of the sensor: rapidly decreasing trend of the resistance as the pressure increase. The sensitivity of the piezoresistive sensor shown in Fig. 5(c) can reach to 8.3kPa-1 at the relatively low pressure region (0-0.1kPa). Fig 5(d) demonstrates the high Gauge Factor (about 120) of the sensor in the relatively low strain region (0-0.5%) which means even the tiny compress strain can sensitively result in the change of the resistance. Because of the micro-scale wrinkle structure, the resistance decrease sharply at the low pressure region which makes the device sensing tiny strain. Fig. 5(e) shows great stability of the piezoresistive sensor. The pressure sensor responses with little changes under the pressure of 0.2kPa even after 1000 times cycles. As shown in Fig. 5(f), the feature of timely response to different pressures can be attributed to the good mechanical properties of wrinkle structure. Wrinkle structure is a kind of dynamic and reversible structure which can be easy to compress and recover.

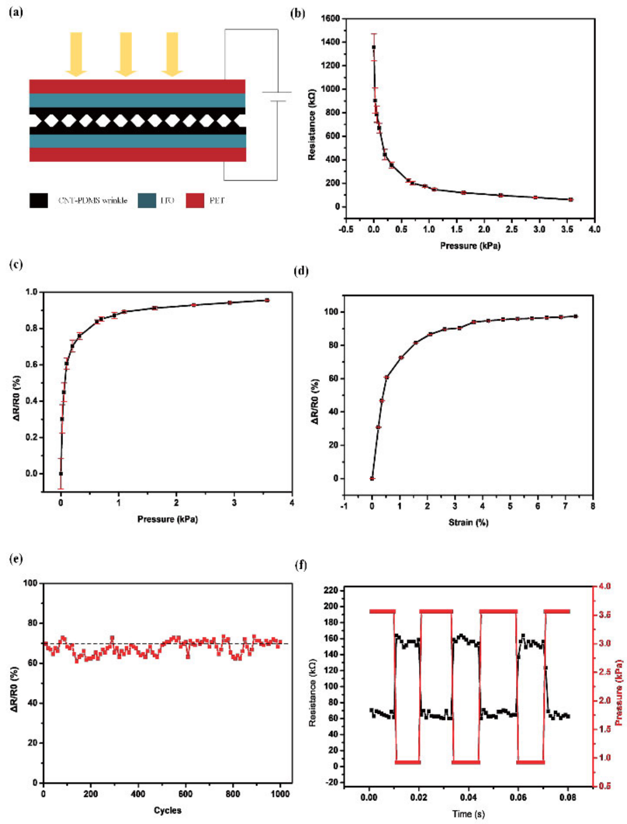

Fig. 5 Performance of the piezoresistive sensor based on wrinkled CNT-PDMS. (a) Schematic illustration of the sensor in piezoresistive performance test; (b)piezoresistive feature of the sensor: rapidly decreasing trend of the resistance as the pressure increase; (c) The sensitivity of the piezoresistive sensor can reach to 8.3kPa-1 at the relatively low pressure region (0-0.1kPa); (d) The ΔR/R0 vs strain. The highest gauge factor, 120 was obtained in the relatively low strain region (0-0.5%); (e)stability test: repeatedly applying the pressure of 0.2kPa; (f) response of the resistance as the pressure changed.

To demonstrate the function of sensor array, we fabricated a 4×4 sensor array by cross stacking ITO/PET-packaged and stripe-like piezoresistive sensors on the glass and covering a piece of Polyimide (PI) film. Fig. 6(b)-(d) show single-touch and multi-touch tests. And Fig. 6(f)-(h) show the response of the sensor array which not only clearly distinguishes single-touch and multi-touch, but also senses the pressure distribution derived from the finger. The flexible sensor arrays based on wrinkled CNT-PDMS can be integrated into the robots as a kind of electronic skins and assist them to sense the external mechanical force. Meanwhile, force images measuring shows a great efforts on braille reading which is meaningful to the visually challenged.

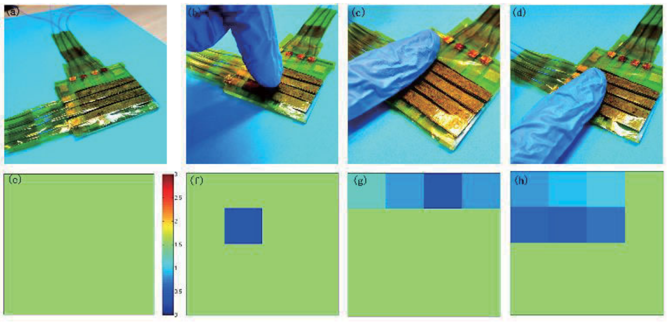

Fig. 6 The fabricated 4×4 wrinkled CNT-PDMS-based sensor arrays was used to detect pressure distribution and measure force images. (a) the photo of the sensor arrays; (b) single touch; (c)&(d) multi-touch; (e)-(h) the corresponding outputs under no touch, single-touch and multi-touch at each pixel.

IV. CONCLUSIONS

In summary, we fabricated a highly sensitive piezoresistive pressure sensor based on CNT-PDMS wrinkle. Monolayer wrinkle was firstly utilized in piezoresistive pressure sensor. By mixing carbon nanotubes with PDMS, soft and flexible conductive polymer can be fabricated. Monolayer wrinkle structure can be fabricated by implementing C_4F_8 plasma onto uncured PDMS. Using reverse mould technique, the wrinkle patterns were successfully transferred onto the CNT-PDMS surface. The fabricated piezoresistive pressure sensor shows great response to the external force with high sensitivity (8.3kPa-1) and great stability under 1000 times cycles. As for application, the flexible and highly sensitive piezoresistive pressure sensor array can detect pressure distribution and measure force images, which shows great potential in the application of electronic skins and wearable devices.

ACKNOWLEDGEMENTS

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