Flexible capacitive pressure sensor based on multi-walled carbon nanotube electrodes

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Flexible pressure sensors offer the advantages of flexibility, low cost, and easy to large area fabrication, and they have wide applications in many fields. This work proposes a flexible capacitive pressure sensor that exhibits a sandwich-like structure, a good performance, and a simple process. Multi-walled carbon nanotube (MWNT) is used to fabricate the two electrodes of the sensor because this low cost material possesses good mechanical and electronic properties. Meanwhile, MWNT naturally forms numerous micro–nano structures that can enhance the sensitivity of a sensor. In addition, the dielectric layer of the sensor composed of parylene C (poly(chloro-p-xylylene)) is sandwiched between the two electrodes. The experimental results show that the pressure sensor demonstrates high sensitivity and a rapid response. The average sensitivity is 1.33 kPa^{-1} at a pressure that ranges from 0 to 758 Pa and the response time reach to millisecond level. Given that low cost, good property and simple process, the sensor has wide application prospects in electronic skins, health monitoring devices, and other wearable electronic products.

1. Introduction: Flexible pressure sensors offer advantages, such as flexibility, low cost, and easy to large area fabrication [1–5], and they play an important role in electronic skins, health monitoring devices, and other wearable electronic products [6–9]. Attracted by the above mentioned advantages, researchers have recently studied a variety of flexible materials and processes to fabricate flexible pressure sensors. Some materials, such as polydimethylsiloxane (PDMS), polyimide, and carbon nanotube (CNT) [10–13], can serve as flexible and stretchable devices. PDMS film is a well-known flexible substrate material because of its low Young's modulus, high transparency, good elasticity, and biocompatibility. In a flexible device, fabrication of electrode on its flexible substrate is one of the key processes because cracks are likely to appear when using metal in this process. Given the high mechanical flexibility, high conductivity, and low weight of CNTs [10, 14], some researchers have fabricated flexible pressure sensor by using CNTs as conducting electrode on PDMS substrate [15]. For example, Lipomi *et al.* proposed that spraying single-walled CNTs (SWNTs) could form transparent and conducting films that were used to fabricate a skin-like pressure and strain sensors on PDMS substrate. Another research group has reported a flexible resistive pressure sensor, which used SWNT as electrode and PDMS with silk microstructure as substrate. In their work, the pressure sensor could be used in various sensing applications, such as voice recognition and wrist pulse detection [5].

Although these flexible sensitive pressure sensors demonstrate great performances, fabricating these devices by using a simple and low cost method remains challenging. Multi-walled CNTs (MWNTs) are not only cheaper by over 100 times than SWNTs [16], but also display good conductivity and mechanical flexibility. This Letter proposed a simple and low cost method to fabricate flexible capacitive pressure sensor that consisted of PDMS substrate, MWNT electrode layer, and parylene C dielectric layer. In particular, MWNT films not only can be used to prepare electrodes, but also naturally form numerous micro–nano structures that help increase the sensitivity of sensors.

2. Experiment: Fig. 1 shows the structure of the flexible capacitive pressure sensor. The dielectric layer, which had the advantages of low stiffness (Young's modulus 4 GPa), biocompatibility, and CMOS/MEMS process compatibility [17], was a thin layer of parylene C deposited through chemical vapour deposition (CVD). In this sensor, the top and the bottom sides of the dielectric layer were symmetrical, which were composed of flexible PDMS substrates and MWNT electrodes. The PDMS substrates were used to transfer force, and the electrodes consisted of MWNT films with metal deposition. MWNT films were not only used as conducting layer, but also naturally created numerous micro–nano structures on the surface of the flexible substrate. In addition, the metal layer deposited on the MWNT film could further improve the conductivity of the electrodes. Fig. 2 illustrates the fabrication process of the flexible capacitive pressure sensor.

2.1. Preparation of PDMS substrate: First, silicon wafer was used to prepare the PDMS substrate (Fig. 2*a*). A 10:1 mixture of PDMS elastomer and cross-linker (Sylgard 184, Dow Corning) was stirred for at least 15 min and then degassed in vacuum for 15 min to discharge the bubbles. Second, the PDMS mixture was spin-coated on the silicon wafer at 480 rpm (~250 μm thick) and then they were put in an oven at 70°C for 2 h. Last, the PDMS was carefully peeled off from the silicon wafer after the PDMS solidified (Fig. 2*b*).

2.2. Fabrication of the electrode layer: After preparing the PDMS substrates, we used MWNTs to fabricate the electrode layer (length: 10–50 μm, diameter: 8–15 nm, Time NANO Cheng Du). The concentration of MWNT in the alcohol solution was 0.1 mg/ml. First, MWNT solution need be dispersed by ultrasound for 30 min, and free standing MWNTs were floating in the solution. Second, the PDMS substrate was inserted into the solution containing MWNTs. The PDMS substrate attached to the MWNT films was removed from the solution and was put in the oven at 200 °C for 30 min to improve their adhesion (Fig. 2*c*). To

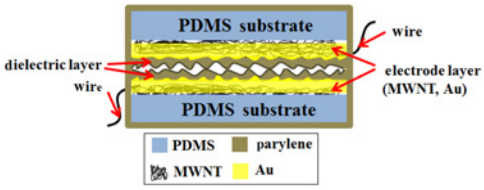

Fig. 1 *Schematic structure of the flexible capacitive pressure sensor*

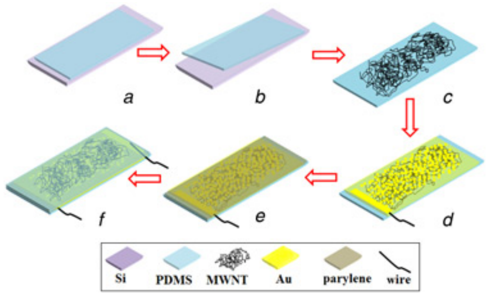

Fig. 2 *Schematic illustration of the fabrication process of the flexible capacitive pressure sensor*
a Preparation of the PDMS substrate on a silicon wafer
b Peeling off the PDMS from the silicon wafer
c Coating the MWNT film on the PDMS substrate
d Au deposition on the MWNT film
e Preparation of the parylene C dielectric layer
f Assembly and completion of fabrication of the flexible capacitive pressure sensor

improve the conductivity of the electrodes, we sputtered 20-nm-thick Au on the MWNT layer. Finally, leading wires were subsequently led out from the electrodes by using Ag paste (Fig. 2*d*). Through the process above, the PDMS substrate and the electrode layer were combined together. Fig. 3 shows the scanning electron microscopic (SEM) images of the surface of MWNT films deposited with metal on the PDMS substrate. The results showed that the MWNT films were randomly distributed on the PDMS substrate and formed numerous micro–nano structures on the surface of the PDMS substrate.

2.3. Preparation of the dielectric layer and encapsulation: 1-μm-thick parylene C was initially deposited on the surface of MWNT electrodes through CVD (Fig. 2*e*). Fig. 4 shows the SEM images of the parylene C deposited on the surface of the electrode layer. The results showed that parylene C coatings demonstrated good coverage property and were uniformly deposited on the surface of the electrode layer that exhibits micro–nano structure. In addition to the benefits mentioned above, the parylene C demonstrated good shape retention that maintains the micro–nano structure of the electrode layer. Finally, the two pieces of PDMS substrates with MWNT electrode and

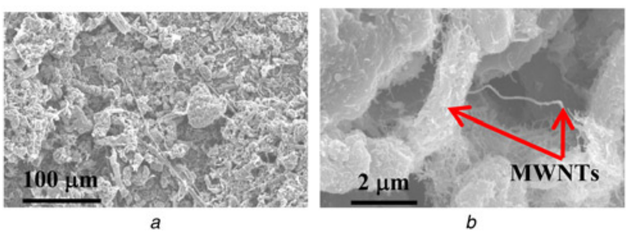

Fig. 3 *SEM images of MWNT films with metal deposition on the surface of the PDMS substrate*
a Large-scale view
b Small-scale view

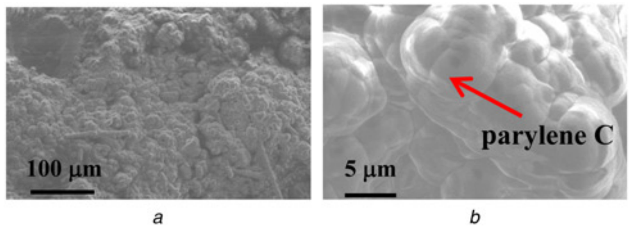

Fig. 4 *SEM images of the parylene C deposited on the electrode layers*
a Large-scale view
b Small-scale view

parylene C dielectric layer were overlapped together and encapsulated by parylene C through CVD (Fig. 2*f*).

3. Results and discussion: Fig. 5 illustrates the schematic of the pressure sensor performance test. The pressure was applied by a pressurising device (Digital force gauge, HP2), and the capacitance was measured using an LCR meter. Fig. 6*a* shows the curves of capacitance against the pressure. In this work, the initial capacitance of the pressure sensor was 8.87 pF, and it increased to 15.23 pF when the applied pressure reached 758 Pa. The relative change in capacitance of the sensor was calculated under the pressure range of 0–758 Pa (Fig. 6*b*), and the capacitance and pressure were positively correlated. Moreover, the pressure sensor displayed a relatively high sensitivity, and the average value could reach up to 1.33 kPa^{-1}, which was calculated by (2). In addition, we measured the response of the pressure sensor with loading and unloading. The proposed pressure sensor demonstrated a satisfactory response and could detect low weight, such as vitamin C tablets or petals, which were as light as 10 mg (Fig. 6*c*). Besides, we have gotten the details of the response in the partial enlarge drawing (Fig. 6*d*). It could be clearly seen that the pressure sensor had a rapid response and the response time could reach to the millisecond level.

The capacitive pressure sensor exhibits a simple structure, which is similar to that of a parallel plate capacitor, and is defined by the following equation

$$C = \varepsilon_1 \varepsilon_2 \frac{A}{d} \tag{1}$$

where ε_1 and ε_2 are the vacuum dielectric constant and relative dielectric constant, respectively, A is the effective area of the parallel plate electrodes, and d is the distance between the two electrode plates. Pressure sensitivity is one of the most important parameters of capacitive pressure sensor and is defined as

$$S = \frac{(\Delta C / C_0)}{\Delta P} \tag{2}$$

where P is the applied pressure, ΔP is the change in pressure, C_0 is

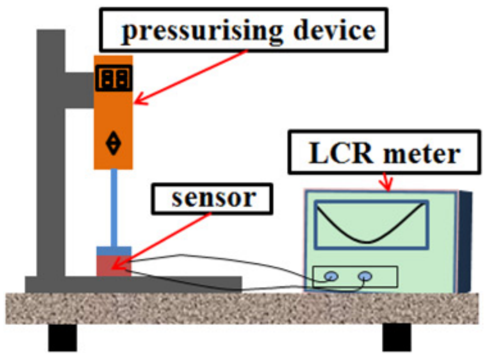

Fig. 5 *Schematic of the experimental setup equipped with pressure sensor*

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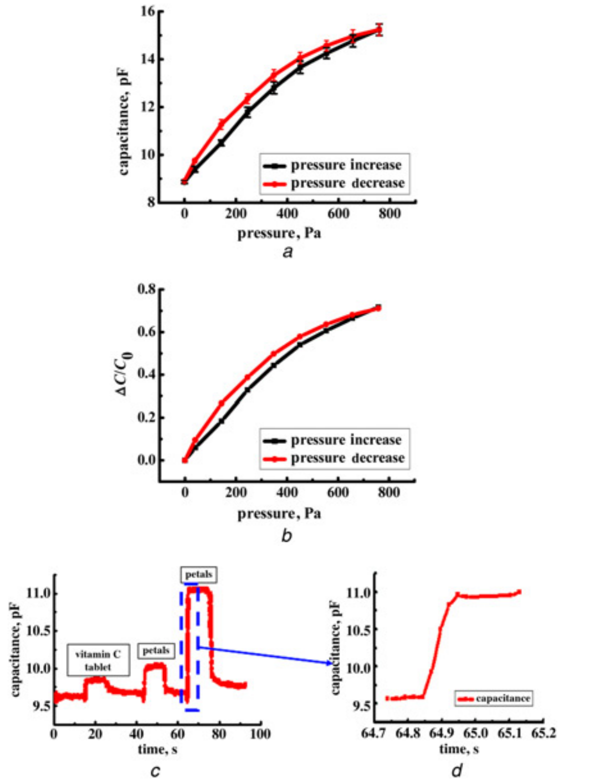

Fig. 6 *Performances of the flexible capacitive pressure sensor*
a Curves of the capacitance against applied pressure
b Curves of the capacitance relative change against applied pressure
c Curve of the capacitance-time for detecting small weights
d Partial enlarge drawing of the curve of the capacitance–time for detecting small weights

the initial capacitance of the capacitive pressure sensor without applied pressure, and ΔC is the change in capacitance. Table 1 lists other related research works using various electrode materials, which showed that the sensitivity of proposed pressure sensor using MWNT/Au electrode was higher than that of other reported results.

The results of the test above and the SEM photos (Figs. 3 and 4) further demonstrate the mechanism and good performance of the sensor. MWNT films with metal deposition were used as conducting electrode, and they virtually created numerous micro–nano structures with air voids because they were irregularly distributed on the PDMS substrate. When the sensor is compressed by applied pressure, the air voids will be replaced and ε_2 will increase. At the same time, the distance between the two electrodes easily changes because flexible materials are used. Considering the factors above and according to (1) and (2), the proposed capacitive pressure sensor could achieve relatively high sensitivity. Besides, according to experiments, it was found that our device has less dependence on temperature and humidity, which was in accordance with other researchers' results [18].

Table 1 Comparison of pressure sensor performance of various electrode materials

Dielectric material	Electrode	Sensitivity, kPa^{-1}	Reference
PDMS	Au	4.0×10^{-4}	[19]
PDMS	Au	3.6×10^{-3}	[20]
PDMS	Cu	1.8×10^{-3}	[21]
PDMS	ITO	2.0×10^{-2}	[4]
PDMS	Al	4.0×10^{-2}	[22]
PDMS	AgNW	0.124	[22]
PDMS	MWNT/Au	1.33	this work

4. Conclusion: We proposed a simple and low cost method to fabricate flexible capacitive pressure sensor, which exhibited a sandwich-liked structure and was composed of flexible MWNT electrode, PDMS substrate, and parylene C layer. The experimental results demonstrated the flexible capacitive pressure sensor had a good property and a positively correlated between the capacitance and pressure. In addition, the pressure sensor demonstrated a rapid response with loading and unloading, which could reach down to the millisecond level. The proposed flexible pressure sensor based on MWNT electrodes will have wide application prospects in artificial skins, health monitoring devices, and other electronic products.

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