ULTRA-SENSITIVE TRANSPARENT AND STRETCHABLE PRESSURE SENSOR WITH SINGLE ELECTRODE

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ABSTRACT

This paper reports a novel ultra-sensitive pressure sensor with single electrode PDMS-PEDOT-Parylene 3-layers structure, which is not only super thin, but also transparent and stretchable. Therefore, it can be utilized as an important part for electronic skins or wearable devices. Thanks to the sensitive deformation of the microstructures when external pressure applied, it reaches the high sensitivity of 14.15 kPa^{-1} and excellent linearity in the low pressure region, and distinguishes a pressure about 0.212 Pa for the first time. Moreover, the distinctive single electrode design greatly simplifies the fabrication process and enhances the transparency of the device.

INTRODUCTION

Recently, multitudinous flexible and stretchable electronics have been proposed to meet the increasing demand generated by the rapid development of electronic skins and wearable devices. Especially, for the ability to sustain complex deformation, stretchable electronics can be used on almost all the objects' surfaces, such as our skins and irregular geometries, having attracted much attention [1, 2]. Pressure sensors, featuring highly sensitive, flexible, stretchable and transparent have many promising applications in the field of electronic skins, smart robots and wearable health devices [3-8]. Since these applications require pressure sensors to be not only sensitive enough to perceive subtle change of pressure, such as the landing of a small insect or human pulse, but also stretchable to conformal contact with the curved surface. Additionally, transparency is also important and indispensable to reduce the impact of the sensors on the users and facilitate the integration of the sensors and other devices.

Various sensing mechanisms have been adopted to achieve the high sensitivity, including piezoresistive, piezoelectric, triboelectric and capacitive sensing [13]. Pressure sensors based on piezoresistive sensing have been widely used in electronic skins for their low operating voltage and high sensitivity [5-7]. Piezoelectric sensors should choose piezoelectric materials as functional materials, like poly(vinylidene fluoride) (PVDF) [8], which could generate an electrical charge when pressure applied. Triboelectric sensors have little restriction on the materials and could "feel" pressure through triboelectrification and electrostatic induction [9, 10]. Both piezoelectric sensors and triboelectric sensors could be self-powered, which is a huge advantage for the application in wearable devices. However, as a coin has two sides, the main drawback of the triboelectric sensors is that it can only measure the change in the pressure but difficult to get the absolute value. Due to the high stability, simple design and mechanical stretchability, capacitive effect also have been widely chosen as the working mechanism of the pressure sensors [3, 4, 11-13]. Some elastic composites and nanomaterials, such as carbon nanotubes and metal nanowires are used to make pressure sensors stretchable, but in some cases, the transparence of the sensors have been severely weakened [2-5, 12, 13].

To enhance the sensitivity of the pressure sensors based on capacitive effect, microstructures have been introduced. A variety of microstructures, including pyramids, lines, pillars [4, 6, 7, 9] regular and irregular wrinkles [10, 13], have been fabricated on the elastomeric dielectric materials, such as polydimethylsiloxane (PDMS), to increase the deformation when external pressure is applied on the sensor. PDMS has good elastic properties, biomedical compliance with human tissue and high performance as a dielectric material [4]. Previous work has demonstrated that PDMS layer with micro-pyramid showed higher sensitivity. Under the same weight, the pyramids are more easily to deform than the pillars of the same height and width [4, 7].

In this work, we present an ultra-sensitive, stretchable and transparent pressure sensor based on capacitive effect, which employs PDMS layer with micropyramid arrays as the elastomeric substrate. A conductive layer consisting of poly(3,4-ethylenedioxythiophene–poly(styrenesulfonate) (PEDOT:PSS) and a dielectric layer made of parylene are deposited on the microstructured PDMS surface. Unlike the previous works [2, 12, 13], the PDMS used here is not made conductive by mixing with other conductive nanomaterials, which improves the transparency of the whole device. Considering that human skins and other conductive surfaces could work as an electrode, we use the single electrode design to simplify the structure of the sensor and the fabrication process, reduce production cost and enhance the transparency.

FABRICATION

The fabrication process of the pressure sensor is shown in Figure 1 schematically. The mixture of PDMS base and cross-linker is dropped on the Si mold with textured structure, spin-coated at 400 rpm for 120 seconds and then heated on the hot plate at 100 °C for 10 minutes. After peeled off carefully, the microstructured PDMS film with pyramid arrays is obtained as the first layer, the thickness of this layer is about 110 μm. Then about one-micrometer-thick PEDOT:PSS is spin-coated on top of the microstructured PDMS surface as the second layer and the single electrode. Finally, about one-micrometer-thick parylene is deposited on the PEDOT:PSS layer with CVD method for its good shape preserving property as the third layer. After that, the sensor has been fabricated successfully.

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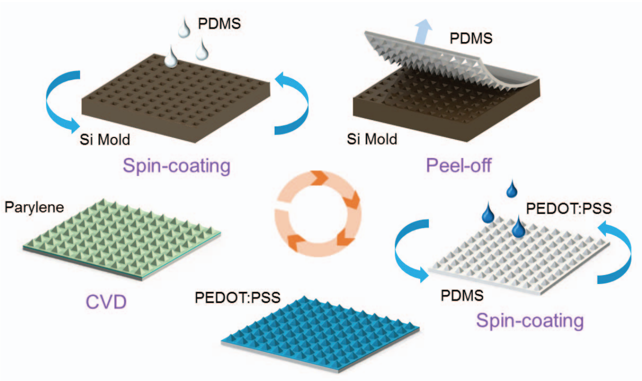

Figure 1: Schematic of the fabrication process of the PDMS-PEDOT-Parylene 3-layers pressure sensor.

RESULTS

Figure 2a shows the PDMS-PEDOT-Parylene three layers structure schematically. Microstructured PDMS works as an elastic substrate for its good elastic properties; PEDOT:PSS serves as the electrode for its good electrical conductivity, transparence and tensile properties to a lesser degree; Parylene acts as the dielectric layers for its good dielectric properties, conformal shape preserving properties, and transparence. When the sensor is put on the skins or other conductive surfaces, PEDOT:PSS layer and the conductive surface work as two electrodes of the capacitor, meanwhile, the parylene layer and air work as the dielectric layer, as shown in Figure 2b. Because of the sensitive deformation of the micropyramid arrays on PDMS surface when external pressure applied, the three layers deform synchronously, which leads to the distance between two electrodes shorten and the capacitance increase. The area of the sensor used in the test is 9 cm^2 (3 cm × 3 cm), and the size of the sensor could be adjusted to applications. Figure 2c shows the photograph of the sensor on the skin, which could contact with the skin conformably.

The sensor is flexible and stretchable to a lesser degree, which are displayed in Figure 3a and Figure 3b. Because the PEDOT:PSS membrane is susceptible to cracking, with cracks observed when deformation reaches 5%, the resistance of the electrode will increase rapidly [7, 14]. However, the requirement of the electrode resistance of the capacitor sensor is not very strict, which makes the sensor stretchable to a lesser degree. Figure 3c displays the side view scanning electron microscopy (SEM) image of the whole sensor, from which we could see the thickness of the sensor is about 110 μm, the ratio of the height of the micropyramid and the thickness of the PDMS substrate is about 1:10. Figure 3d shows enlarged side view SEM images of the microstructure. Figure 3e and Figure 3f show the top view SEM images of the PEDOT:PSS deposited on the PDMS layer and parylene grown on the PEDOT:PSS layer, which both cover the microstructure conformably.

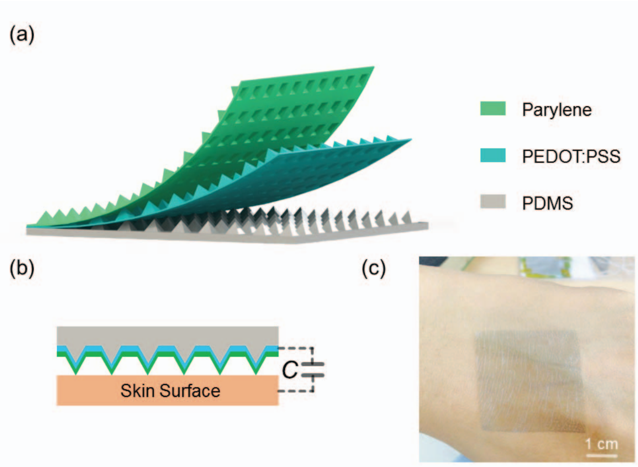

Figure 2: (a) Schematic of the PDMS-PEDOT-Parylene 3-layers pressure sensor. (b) Schematic of the working mechanism. (c) Photograph of the sensor on the skin.

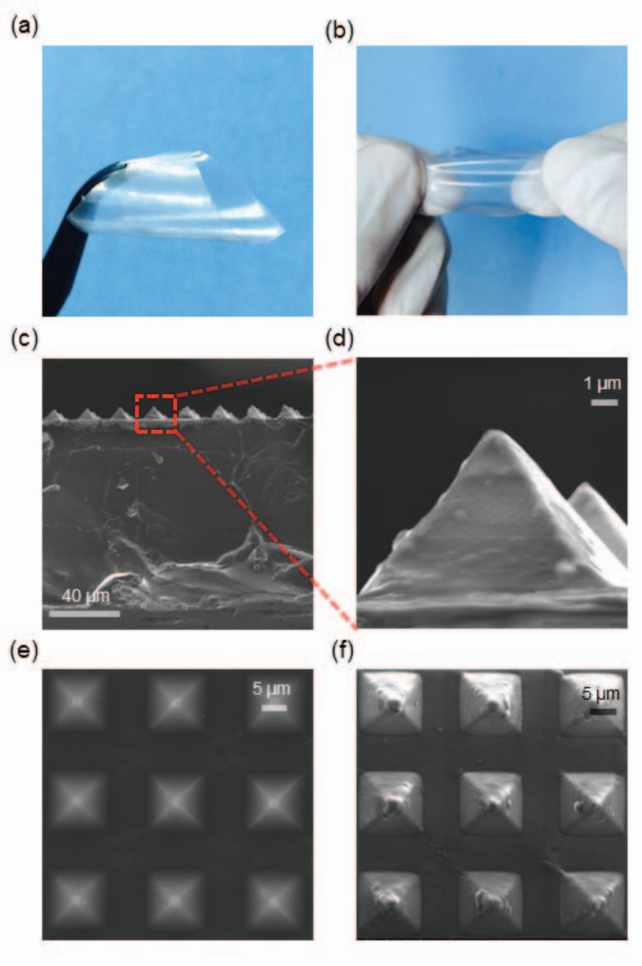

Figure 3: Photographs of the sensor to display its (a) flexibility and (b) stretchability. (c) Side view and (d) enlarged side view SEM images of the sensor and microstructure. Top view SEM images of the (e) PEDOT:PSS on the microstructured PDMS layer and (f) Parylene on the PEDOT:PSS layer.

To study the relationship between the external pressures applied on the sensor and the changes in capacitance, we conduct the finite element simulation (FES) to study the effect of pressure on deformation first. The model we used to calculate has the same ratio of the height of micropyramid and the thickness of the PDMS substrate as the actual sensor. Figure 4a shows the theoretical stress distribution when an external pressure is applied, which illustrates that stress concentrates near the microtips [15]. We also calculate the shape variable of all dots in the bottom margin (the zigzag edge) in different pressure situations, and the results are displayed in Figure 4b. The abscissa in this figure means the distance between each dot in the bottom margin and the leftmost dot in the bottom margin, we assume that the length of the base and the height of the triangle are 10 units. Additionally, for each dot in the bottom margin, the FES results demonstrate that the relationship between pressure and shape variable is linear, as shown in Figure 4c. Each dot could be seen as a small capacitor, and the whole capacitor could be seen as numerous small capacitor paralleled. For each small capacitor, the initial capacitance is defined by:

$$C_0 = \frac{\varepsilon S}{4\pi k d} \tag{1}$$

Using "*x*" to represent the shape variable of the dot, the capacitance change could be written as:

$$\Delta C = \frac{\varepsilon S}{4\pi k}\left(\frac{1}{d-x} - \frac{1}{d}\right) \tag{2}$$

So, the capacitance change rate could be written as:

$$\frac{\Delta C}{C_0} = \frac{d}{d-x} - 1 = \frac{x}{d-x} \tag{3}$$

For the relationship between pressure and shape variable is linear, the capacitance change rate response of pressure should be hyperbolic approximately, which has been verified by experimental results.

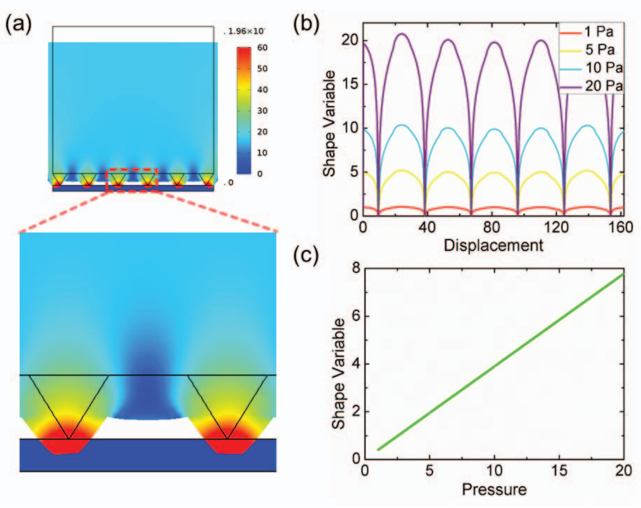

Figure 4: Finite element simulation results of the sensor. (a) Image of the stress distribution when an external pressure is applied on the sensor. (b) The shape variable of all the dots in the bottom margin under different pressure situations. (c) Relationship between deformation and pressure of a bottom margin dot.

As shown in Figure 5, the curve of the relationship between capacitance change rate and pressure could be seen as a part of a hyperbola approximately, and could be divided into two regions. In the low pressure region (0 – 20 Pa), the result shows excellent linearity (the goodness of fit, $R^2 = 0.99784$) and super high sensitivity of 14.15 kPa^{-1}, which has surpassed that of previously reported capacitive pressure sensor [3, 4, 11-13] and is high enough to detect the minor change of acoustic wave and air flow, such as our breathing. The sensitivity will decrease with the increase of pressure, and there would be a limit of pressure measurement because the electrode is on the microstructure surface and the deformation of the micropyramid arrays is limited.

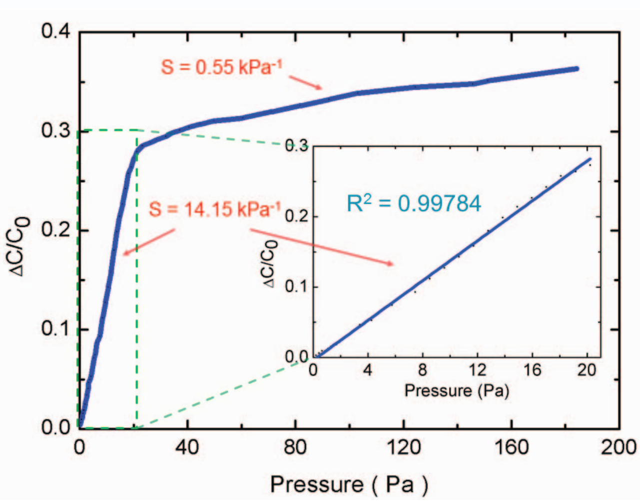

Figure 5: Characterization of the capacitive pressure response of the sensor.

Particularly, a significant change in capacitance (about 0.15 pF) is observed when a piece of paper (1 cm × 1 cm) whose pressure is about 0.212 Pa is put on and then removed from the sensor hundreds of times, as shown in Figure 6, which gives a good description of the sensor's sensitivity and stability. It's the first time for capacitive pressure sensors to detect so tiny pressure change. The detection of a bee is shown in Figure 6 together.

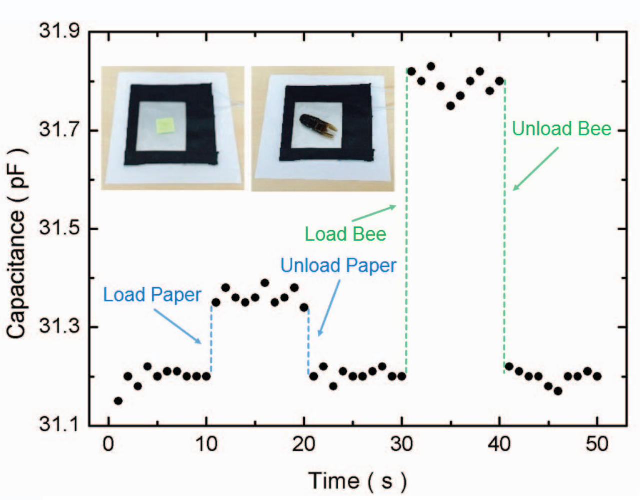

Figure 6: Experimental images and the capacitance-time curve for detecting small paper (0.212 Pa) and bee.

Moreover, for the super high sensitivity and excellent transparency, the ultrathin and stretchable pressure sensor shows huge potential applications in electronic skins, wearable health monitors, etc.

CONCLUSIONS

In summary, a novel ultra-sensitive stretchable and transparent pressure sensor has been developed. The sensor has distinctive PDMS-PEDOT-Parylene three layers structure, and the micropyramid arrays on the sensor surface give it super high sensitivity. Compared to traditional capacitive pressure sensors, this device has only one electrode, which not only simplifies the sensor structure and the fabrication process and reduces cost, but also enhances the transparency of the sensor. For the stretchability, the sensor could fit on the skin conformally and can be used on irregular conductive geometrical surfaces. The super high sensitivity of 14.15 kPa^{-1} in low pressure region and excellent linearity, and distinguishes a pressure of a tiny piece of paper (about 0.212 Pa), help the device to be applied in many areas.

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