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Research Article

PDMS-Based Capacitive Pressure Sensor for Flexible Transparent Electronics

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We propose a flexible pressure sensor based on polydimethylsiloxane (PDMS) and transparent electrodes. The transmittance of the total device is 82% and the minimum bending radius is 18 mm. Besides, the effect of annealing temperature on the mechanical properties of PDMS is reported here. The results show that the PDMS film under lower annealing temperature of 80°C has good compression property but poor dynamic response. While for higher temperatures, the compression property of PDMS films significantly reduced. The best compromise of annealing temperature between compression property and dynamic response is found for PDMS film of about 110°C. The pressure sensor under 110°C curing temperature shows a good sensitivity of 0.025 kPa^{-1} and robust response property. The device shows a promising route for future intelligent transparent sensing applications.

1. Introduction

In the last few years, various flexible electronics have been extensively researched for application in portable and wearable electronic devices [1, 2]. Among them, transparent sensors have received widespread attention in recent years, due to their wide applications, such as displays [3], optoelectronic devices, smart system [4], health-care services [5], and electronic skins [6, 7].

Nowadays, elastomer polydimethylsiloxane (PDMS) as functional material has been widely used in flexible sensing field due to their low Young's modulus, superior mechanical flexibility, and high transparency [8–11]. Bao et al. have reported a PDMS-based pressure sensor using in electronic skins showing a good sensitivity of 0.55 kPa^{-1} [12]. Tie Li et al. have proposed a high sensitive and stable capacitive tactile sensor using PDMS as dielectric layer, which has been successfully applied in wearable electronics [13]. The common up electrode materials used in PDMS are carbon nanotubes, graphene [14], and other metal nanowires [15]. However, the transmittance of carbon nanotubes and metal nanowires is not good, while the fabrication process of graphene is complicated and expensive. In comparison, poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS), which has high flexibility, relatively low material cost, and simple process, such as spin coating, has been considered as a promising candidate for transparent electrode [16]. In addition, the electrical conductivity of PEDOT:PSS films has been greatly improved to 4000S/cm through various postprocessing methods [17]. In the visible range, the transparency of PEDOT:PSS films can reach 97%. However, it is still difficult to prepare transparent electrode on dielectric layer for highly transparent pressure sensors.

In this work, we present a study of a transparent and reliable capacitive sensor based on the elastomer polydimethylsiloxane (PDMS) film and PEDOT:PSS electrodes. To further improve the mechanical properties of PDMS film, the performance of PDMS film under different annealing temperatures has been studied. The total device is fabricated on PET substrate showing good flexibility which can be used for wearable electronics and electronic skins.

2. Experimental

2.1. Sensor Fabrication. The flexible substrates are chosen among the commercially available products: an optically transparent PET (polyethylene terephthalate) substrate covered with an indium tin oxide- (ITO-)coating. The substrate

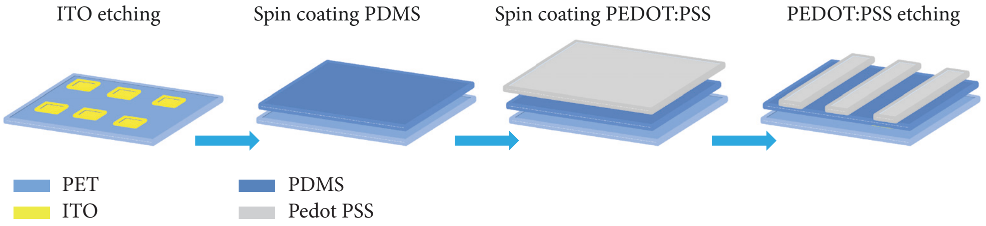


Figure 1: The flow chart of transparent sensor manufacturing.

is composed of 5×5 cm^2 squares of ITO/PET. The ITO film is 100 nm thick and has a sheet resistivity of 50 Ω/□. The fabrication process of the transparent pressure sensor is shown in Figure 1. The transparent ITO electrode is patterned by photolithography development and etched by oxalic acid solution for 2 minute. The PDMS (Sylgard 184 Elastomer) is purchased from Dow Corning Corporation. The PDMS base and curing agent are mixed in a weight of 10:1 and then put into a vacuum drying oven for 20 min to remove air bubbles. After that, the PDMS dielectric layer is fabricated by spin coating on the ITO electrode. The curing process of PDMS film is studied in the next part to improve sensor's sensitivity and response performance. In order to improve the transmittance and flexibility of the device, PEDOT:PSS is used as the electrode, since it has the advantages of low cost [18], being bendable [19], high transmittance [20], and good electrical conductivity [21]. The PEDOT:PSS solution and isopropanol are mixed according to the volume ratio of 3:1. Before preparing the top electrode, the PDMS film was cured by oxygen plasma treatment and ultraviolet irradiation for 10 min to enhance the hydrophilicity of PDMS surface. Finally, the PEDOT:PSS electrodes are patterned and wiped by ethanol.

2.2. PDMS Curing Process. The PDMS mixture is made by mixing PDMS base and curing agent in a weight of 10:1. Then 50 μm thick PDMS film is coated on glass substrate by spin coating and then cured at 60°C for 1 hour. The PDMS film is cut into a 5 mm × 50 mm rectangle to test its storage modulus by Dynamic Mechanical Analysis (DMA) technology. The whole test condition from 60°C to 300°C is under a temperature rise ratio of 3-degree centigrade per minute. Figure 2 shows the relationship between storage modulus and temperature of PDMS film. The PDMS shows lower storage modulus at the temperature of 75°C to 220°C. So, we further study the characteristic of PDMS film at this temperature range. To exclude the influence of PDMS thickness and other factors on PDMS film, the samples are fabricated on one glass substrate by spin-coating and then cut into five parts, and both side electrodes of the samples are fabricated. Then five samples are annealing at 80°C, 110°C, 140°C, 170°C, and 200°C for 1 hour, respectively.

The PDMS capacitors are characterized by the experimental setup represented in Figure 3. A sweep signal generator (DH-1301) is collected to acquisition analyzer (DH5922N) to provide voltage signal which is transferred to vibration exciter (DH40020) to control output pressures. The output pressure and the output PDMS capacitance can be measured and collected by acquisition analyzer and C-V characteristic analyzer (WAYNE KERR 6500B), respectively. Corresponding software are used to present datum on computer.

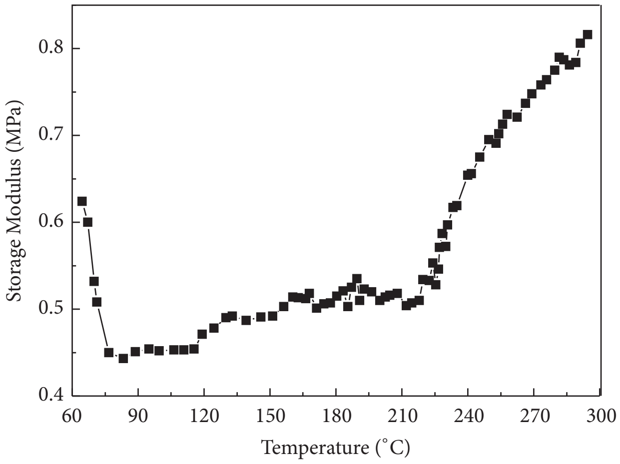


Figure 2: The relationship between storage modulus and temperatures of PDMS thin film.

3. Results and Discussion

The measurements are conducted by applying 0.1 Hz sinusoidal pressure on the PDMS capacitors through the vibration exciter by moving in the direction of Z axis. The waveform of applied sinusoidal pressure is shown in Supplementary Figure S1(a). Several pressures are applied on the PDMS capacitors. The distance between two parallel electrodes changed which led to the change of the measured capacitance. Therefore, the capacitance of PDMS capacitor increased when the pressure is applied on the PDMS capacitor and gradually restored when the pressure is revoked. The corresponding capacitance changing characteristics of PDMS capacitors under 80°C, 110°C, 140°C, 170°C, and 200°C annealing temperatures are shown in Supplementary Figure S1(b-f). We studied the characteristics of PDMS capacitors including compression property and dynamic response property by comparing the variation ratio of PDMS capacitance value.

The initial capacitance of PDMS capacitor is recorded as C_0. Cmax is the capacitance value when the pressure reaches the maximum and Cmin is the minimum capacitance when the pressure is revoked. The compression properties of PDMS

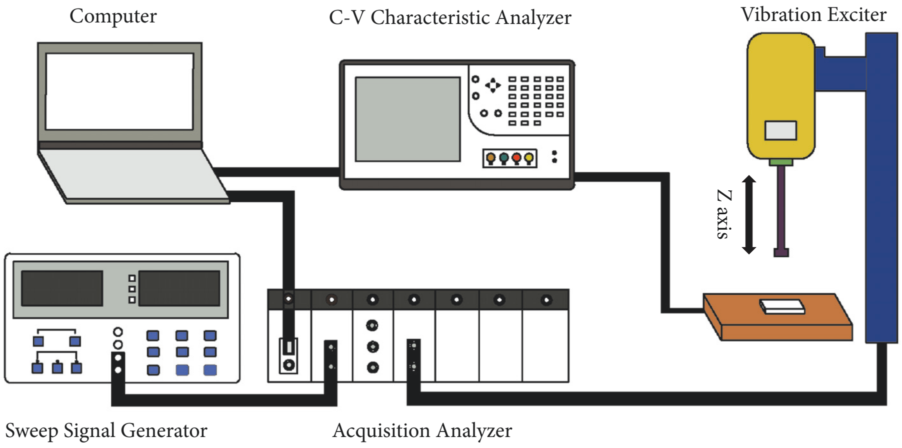
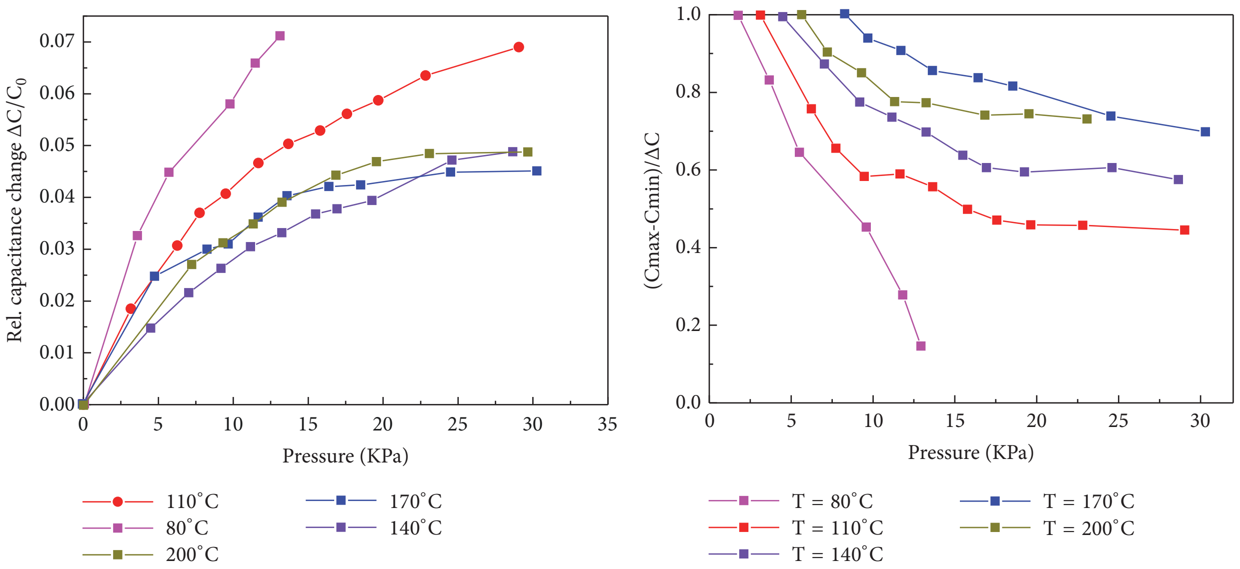


Figure 3: The schematic of experimental setup for PDMS capacitor.



(a)

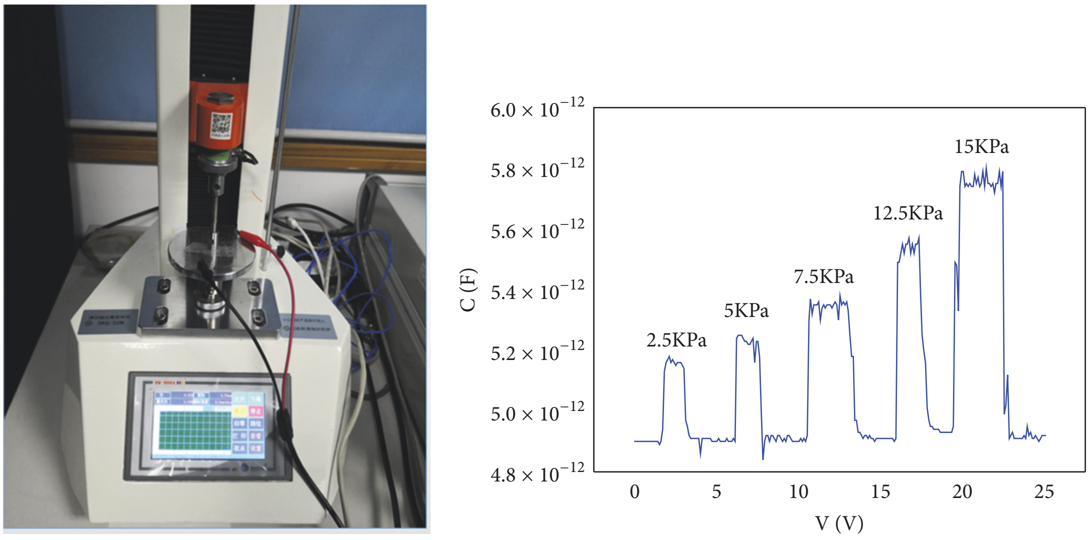
(b)

Figure 4: (a) The relative capacitance change $\Delta C/C_0$ of PDMS samples, (b) the dynamic response of PDMS samples.

capacitors are calculated according to the relative capacitance change $\Delta C/C_0$ ($\Delta C = C_{max} - C_0$). As shown in Figure 4(a), as the pressure increases, the PDMS becomes more difficult to deform, resulting in a smaller relative capacitance change. Comparing PDMS capacitors under curing conditions of 80°C, 110°C and 140°C, the relative capacitance change $\Delta C/C_0$ of PDMS capacitance decreases obviously with the annealing temperature rising. The fabrication of PDMS film is the reaction of PDMS base and curing agent. Since the ambient temperature contributes to the curing of the PDMS film, the higher temperature makes the PDMS film harder and more difficult to deform. However, this trend begins to reverse when the annealing temperature reaches 170°C. The relative capacitance change $\Delta C/C_0$ of PDMS capacitors has a small rise under 170°C and 200°C.

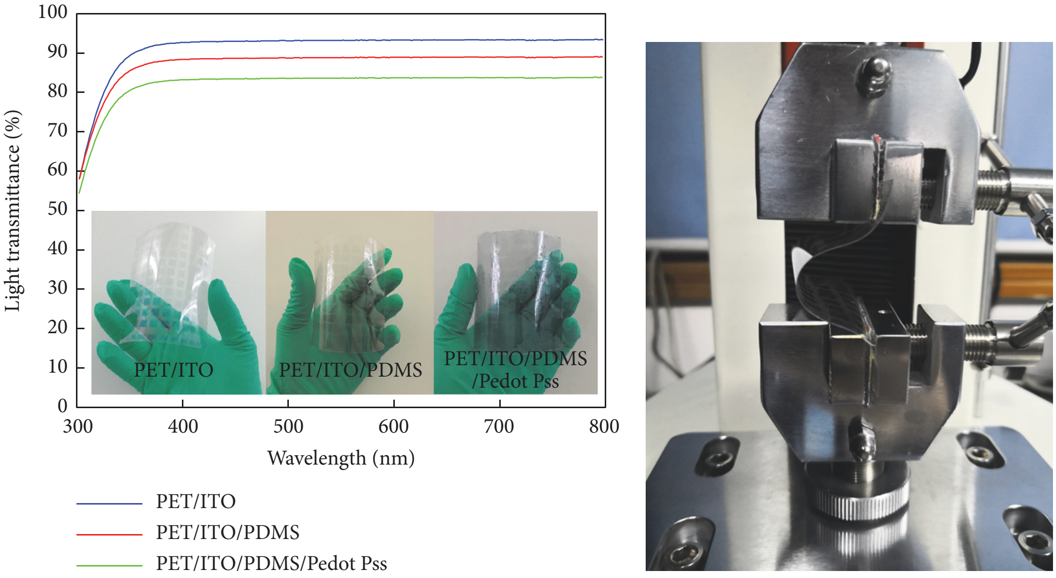
Figure 4(b) shows the dynamic response of PDMS film which is characterized by $(C_{max} - C_{min})/\Delta C$. The dynamic response of PDMS films gradually decreases with the pressure increasing, since the deformation of PDMS film becomes deeper while the pressure increases, and it needs more time to restore. Comparing annealing temperature under 80°C, 110°C, 140°C, and 170°C, the annealing temperature has also influenced the dynamic response of PDMS film. The PDMS film curing at 80°C is hard to restore when the applied pressure is higher than 13 kPa, since it only recovered 0.2 of the total deformation at the pressure of 13 kPa. However, the PDMS films cured at 110°C, 110°C, 140°C, 170°C, and 200°C show the response property of 0.6, 0.7, 0.9, and 0.79 at the same pressure of 13 kPa. This demonstrates that increasing the curing temperature properly can improve the dynamic response property of PDMS film.

To conclude, although the PDMS thin film curing at 80°C shows excellent compression deformation property, the dynamic response is poor, which greatly restricts the



(a) (b)

FIGURE 5: (a) The sensitivity of pressure senor is tested by lectric tensile testing machine. (b) The performance of pressure sensor under pressures of 2.5 kPa, 5 kPa, 7.5 kPa, 12.5kPa, and 15 kPa.



(a) (b)

FIGURE 6: (a) The light transmittance of PDMS and Pdeot Pss based pressure sensor. (b) The bending characteristic of pressure sensor tested by tensile test machine.

measurement range of the PDMS capacitor. In order to fabricate a pressure sensor with both good compression property and good dynamic response property, PDMS film under annealing temperature 110°C is a compromise.

The sensitivity of fabricated flexible pressure sensor is tested by electric tensile testing machine (ZQ-990A), as shown in Figure 5(a). The performances of pressure sensor under 2.5 kPa, 5 kPa, 7.5 kPa, 12.5kPa, and 15 kPa are tested, as shown in Figure 5(b). The pressure sensor shows an average sensitivity of 0.025 kPa^{-1} and robust response property.

To evaluate the light transmission of the device, the light transmittance of PDMS and PEDOT:PSS based pressure sensor are tested within wavelength from 300 nm to 800 nm, as shown in Figure 6(a). Surprisingly, the total pressure sensor device achieves 82% transmittance, thanks to the excellent light transmission of PET/ITO substrate, PDMS film, and PEDOT:PSS electrode. This provides a promising way for transparent intelligent display and future smart system. The fabricated pressure sensor also shows good bending properties, as shown in Figure 6(b), the bending characteristic of the flexible pressure sensor is tested by tensile test machine, and the minimum bending radius of the device is 18 mm, which means it can be applied to the curved applications.

4. Conclusion

We successfully fabricated a highly transparent and flexible pressure sensor by using transparent substrate PET, transparent pressure sensitive layer PDMS, and transparent electrodes PEDOT:PSS. The light transmittance of the device reaches 82%, and the minimum bending radius is 18 mm. This provides a new way for pressure sensing system applied to future smart system and intelligent transparent display. Besides, we have prepared different PDMS films by varying the annealing temperatures and successfully studied the characteristics of these films. A compromise annealing temperature of 110°C has been demonstrated to have both good compression property and good dynamic response property. Our work shows that the proposed flexible transparent pressure sensor can be a good candidate for use in future flexible touch displays and electronic skins.

Data Availability

The data used to support the findings of this study are included within the article and the supplementary information file.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Supplementary Materials

Supplementary Figure S1. (a) The waveform of 0.1 Hz sinusoidal pressure generated by vibration exciter. The corresponding capacitance changing characteristics of PDMS capacitor under (b) 80°C, (c) 110°C, (d) 140°C, (e) 170°C, and (f) 200°C. *(Supplementary Materials)*

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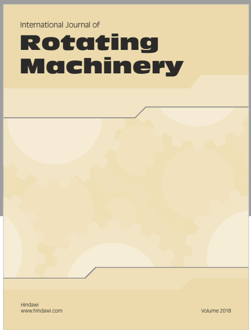
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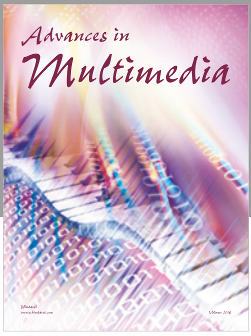
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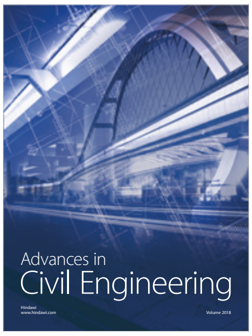
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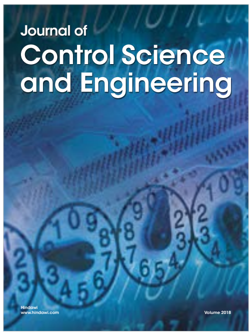
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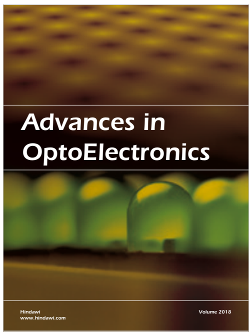
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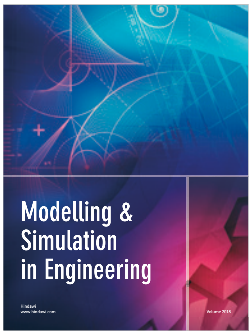
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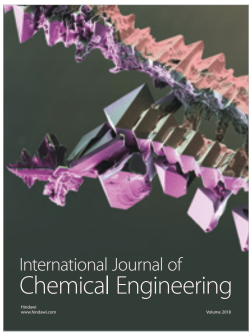
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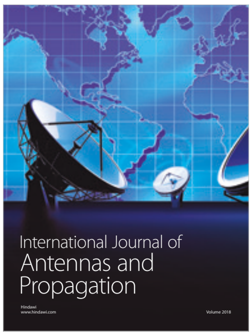
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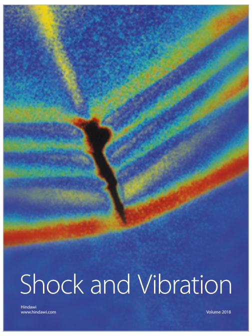
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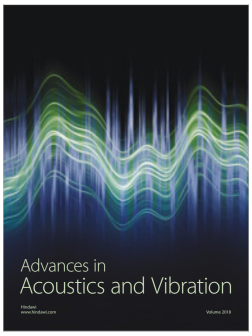
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