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Study on the Ag Nanowire/PDMS Pressure Sensors with Three-Layer and Back-to-Back Structures

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Abstract. Ag nanowire (NW)/polydimethylsiloxane (PDMS) pressure sensors with the three-layer and back-to-back structures were fabricated by a coating-peeling method. The bending and pressing responses of the sensors were comparably investigated. The results reveal that two kinds of pressure sensors show similar response linearity in the bending test with a bending angle of 0-180°. However, the response sensitivity of the three-layer structured pressure sensor is superior to that of the back-to-back structural one, which exhibits that the relationship between the capacitance value (Y) and the bending angle (X) is: $Y = 0.01244X + 2.9763$. On the contrary, in the pressing test, the response sensitivity of the back-to-back structural sensor is better than that of the three-layer structural one. The relationship between capacitance value (Y) and the number of paper clips (pressure, X_2) is $Y = 0.09241X_2 + 88.03597$.

1. Introduction

In recent years, people pay increasing attention to their health with the development of science and technology. Thus, the wearable sensors with real-time monitoring of human activities have been caught extensive research interest[1], which have tremendous potential for use in rehabilitation medicine and play an active role in personal health monitoring [2], sports monitoring and human motion capture interactive entertainment systems, *etc*[3-6]. In order to meet these application requirements, the pressure sensor should have the characteristics of high sensitivity and durability, fast response and recovery [7, 8].

Usually, the pressure sensors with resistive or capacitive structure are based on an elastomer and embedding conductive materials, such as metal NWs (for example, Ag and Au NWs), carbon nanotubes, *etc*[9-13]. These structures can convert the mechanical deformation caused by the applied strain into a change in the electrical characteristics (resistance or capacitance). Due to its excellent elasticity, good transparency, biomedical adherence to human tissues, and simple and low-temperature manufacturing process, PDMS is one of the most popular elastomeric materials for strain sensors [7-8].Considering the excellent conductivity of Ag NWs, a very simple and low-temperature preparation process [14-16], and the advantages of adding Ag NWs into PDMS that not only can enhance the electrical properties of PDMS, but also greatly improve mechanical properties, Ag NW/PDMS pressure sensors are a hot research topic of wearable sensor [8, 17, 18].

The pressure sensors are normally fabricated with three-layer and back-to-back structures [13, 18]. In this work, we comparably investigated the properties of the Ag NW/PDMS pressure sensors with two structures. Firstly, Ag NWs were prepared by a hydrothermal method and then the Ag NWs were transferred to the PDMS surface by a coating method. Following that, the Ag NW/PDMS sensors with

three-layer and back-to-back structures are fabricated. Finally, the device performance is comparatively studied under the bending and pressing condition.

2. Experiments

2.1. Preparation of Ag NWs

Firstly, 0.1 mol/L glucose solution, 0.15 mol/L $AgNO_3$ solution, and 0.015 mol/L $Fe_2(SO_4)_3$ solution were prepared with 40 mL, 20 mL, and 40 mL, respectively. The $AgNO_3$ solution was dropped into the glucose solution slowly with the dropper under magnetic stirring, and the following was the $Fe_2(SO_4)_3$ solution. And then, 4.5g polyvinyl pyrrolidone (PVP, K30) was added into the mixture solution with 30 min stirring. After that, the mixture solution with 40 mL was put into a Teflon autoclave of 100 mL capacity, and heated to 180 ^oC for 6 h reaction. After reaction, the Ag NWs with gray-green color were obtained by centrifugation.

2.2. Configuration of PDMS Solution

2g of PDMS original solution (Dow Corning 184) was weighed in a beaker, 0.2g of curing agent was added and stirred with a magnetic stirrer until the solution was clear, and then the mixture solution was exposed to air for 15 min until the bubbles were completely escaped from the solution.

2.3. Fabrication of Ag NW/PDMS Pressure Sensor

Figure 1 shows the schematic illustration of the fabrication process of Ag NW/PDMS composite film, the detail chart was as follows: firstly, a uniform Ag NW film was coated on a cleaned bare glass/polyethylene terephthalate (PET) substrate by pulling a glass rod over the Ag NW ethanol dispersion. Next, in order to improve the conductivity of the Ag NW film, the film on the glass substrate was heated at 250 °C for 2 h, or the film on the PET substrate was laminated at a pressure of 10 MPa for 3 min. PDMS solution was dropped on the surface of Ag NWs film. After the solution was freely diffused, it was uniformly covered on the film surface and cured at 60 ^oC for 4 h. After cooling, the PDMS layer and the substrate were separated, and the Ag NW networks could be transferred onto the surface of the PDMS layer to obtain the Ag NW/PDMS composite film. Finally, the composite films were packaged into a 5×5 cm^2 size sensor with three-layer or back-to-back structure. The structures of the devices are shown in Figure 2.

The Ag NW distribution, diameter, and crystal quality were characterized by transmission electron microscopy (TEM, JEOL-2100F). The morphologies of the Ag NW/PDMS composite films and the crystal quality of the Ag NWs were characterized by SEM (FEI Nova nano SEM430) and X-ray diffraction (XRD, X'Pert Pro), respectively. The electrical properties of the Ag NW/PDMS composite films and pressure sensors were tested using a four-probe (SZ-82, SX) and a digital source meter (Keithley 2400).

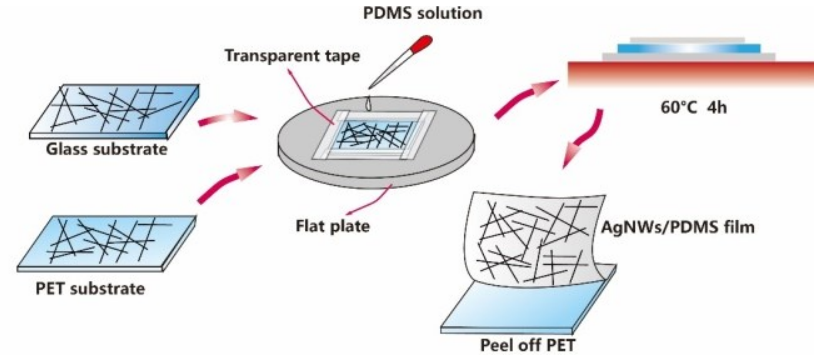

Figure 1. The fabrication illustration of the Ag NW/PDMS composite film

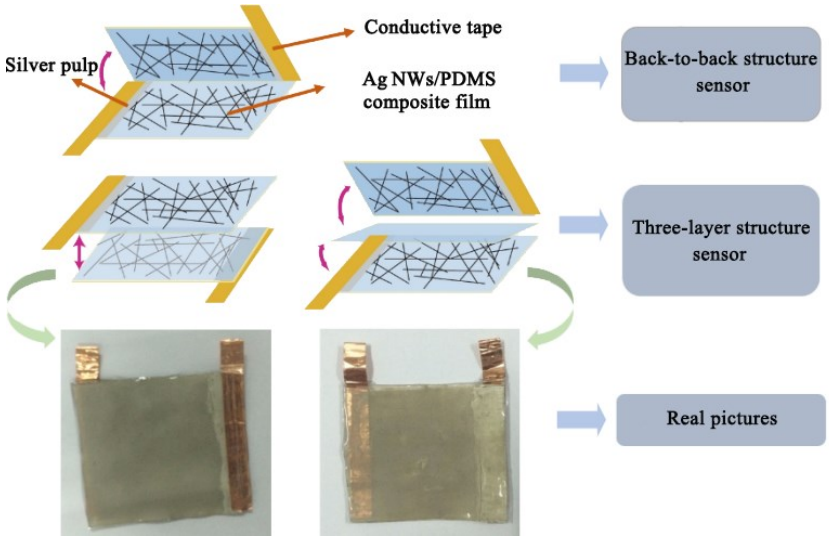

Figure 2. The fabrication illustration of the Ag NW/PDMS pressure sensors and the corresponding real pictures: (a) back-to-back structure and (b) three-layer structure

3. Results and Discussion

Figures 3(a) and (b) are the optical micrographs of the Ag NW solution after centrifugation. As shown in Figure 3(a), the diameter distribution of the AgNWs in the upper layer solution is relatively uniform and is easily distributed uniformly on the substrate. In addition, many small particles are observed in the solution, and there are no apparent large particles. Instead, many large Ag particles exist in the underlying solution (as shown by the dark spots in Figure 3(b)). The large silver particles would cause an uneven distribution of Ag NWs on the substrate and reduce the transparency and stability of the sensor. Therefore, we choose the upper AgNW solution to prepare the conductive films. Moreover, most of the small Ag particles can be removed by suction filtration to improve the uniformity of AgNWs distribution and decrease the scattering **[15]**.

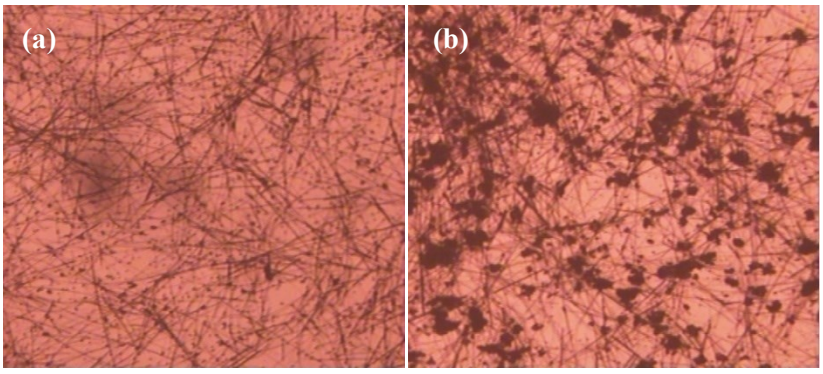

Figure 3. The optical micrographs of the Ag NWs in the upper of the solution (a) and the bottom solution (b) after centrifugation

In order to characterize the microstructure of the Ag NWs, TEM was used to analyze the size, the uniformity of size distribution and crystal quality of the NWs. As shown in Figure 4(a), the diameter of the Ag NWs is relatively uniform with a range from 70 to 90 nm. This creates a favourable condition for the preparation of the conductive percolation networks [15]. Further study by high-resolution TEM reveals that the Ag NWs have good crystalline quality/atomic arrangement periodicity, and seldom defects, as shown in Figure 4(b). The electrical properties of the Ag NWs are directly dependent on their crystalline properties. The better the crystalline quality is, the higher the electrical

conductivity is. Therefore, the prepared Ag NWs in this work exhibit good electrical properties, which can provide strong support for the signal acquisition of the pressure sensor [16].

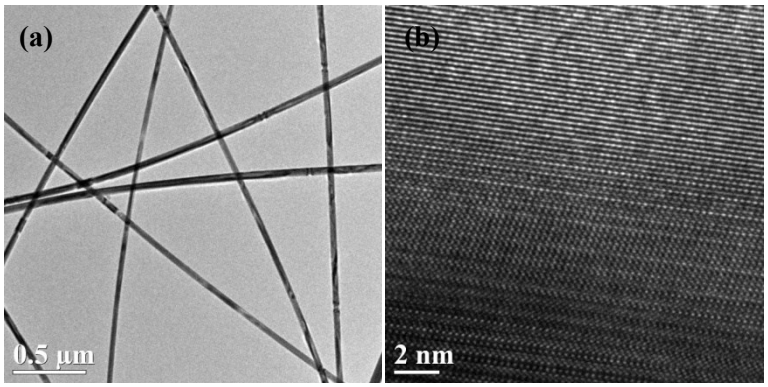

Figure 4. (a) TEM image and (b) high-resolution TEM image of the Ag NWs

Figure 5 is a SEM image of the Ag NW/PDMS composite film. The Ag NWs are uniformly distributed on the film surface after being transferred to the PDMS layer. The length of each single Ag NW exceeds dozens of micrometers, and the Ag NWs are cross-linked with each other to form the conductive networks. The Ag NW/PDMS composite films have good electrical properties and outstanding advantages in the electrical signal acquisition and response [19].

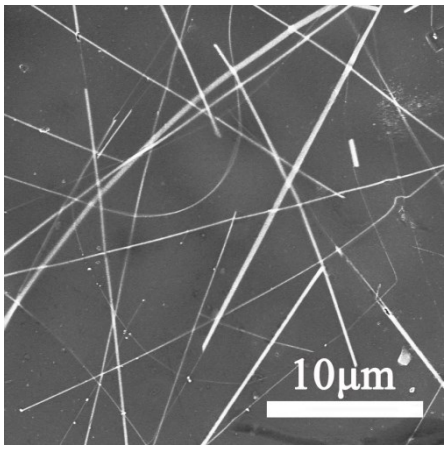

Figure 5. Typical SEM image of the Ag NW/PDMS composite film

XRD is employed to investigate the structure of the Ag NWs. Figure 6 shows the XRD pattern of the Ag NW/PDMS composite film. Four strong diffraction peaks at 38.09°, 44.41°, 64.49° and 73.33° are observed respectively, which correspond to the (111), (200), (220) and (311) characteristic diffraction peaks of metallic Ag (JCPDF No. 01-087-0597). In addition, no other peaks are observed, especially the characteristic peaks of silver oxide, which indicates that the Ag NWs maintain good stability during the transfer process. Furthermore, the Ag NW film has a sheet resistance of 4.40 Ω/sq and 4.45Ω/sq before and after transferring, respectively. It can be seen that the resistance of Ag NW networks remains basically unchanged. This paves the way for the subsequent manufacture of high-quality pressure sensors.

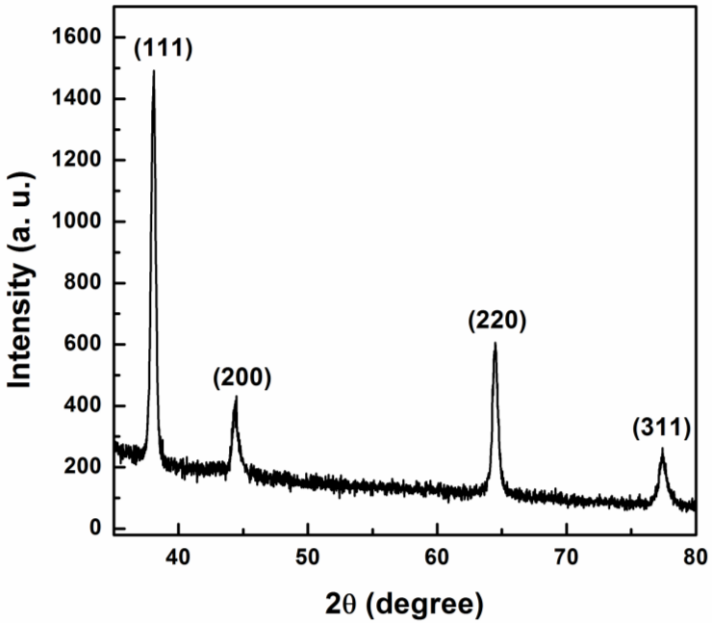

Figure 6. XRD pattern of Ag NW/PDMS composite films

We study the bending characteristic of two structural pressure sensors. Figures 7(a) and (b) are bending-capacitance value characteristic patterns of the Ag NW/PDMS pressure sensors with three-layer and back-to-back structures. As shown in Figure 7(a), the Ag NW/PDMS pressure sensor with a three-layer structure shows better linearity with the bending range of 0-180°. After fitting, it is found that the capacitance value (Y) is proportional to the bending angle (X), and their relation is: Y = 0.01244X + 2.97563. Similarly, the Ag NW/PDMS pressure sensor with a back-to-back structure also reveals a good linear response with the bending range of 0-180°, as shown in Figure 7(b), and the relationship is Y = 0.00656 X + 87.73579. The slope in the equation is related to the response sensitivity of devices: the slope is greater, the response is more sensitive. Thus, the response sensitivity of the Ag NW/PDMS pressure sensor with the three-layer structure is better than that of the back-to-back structure in the bending performance.

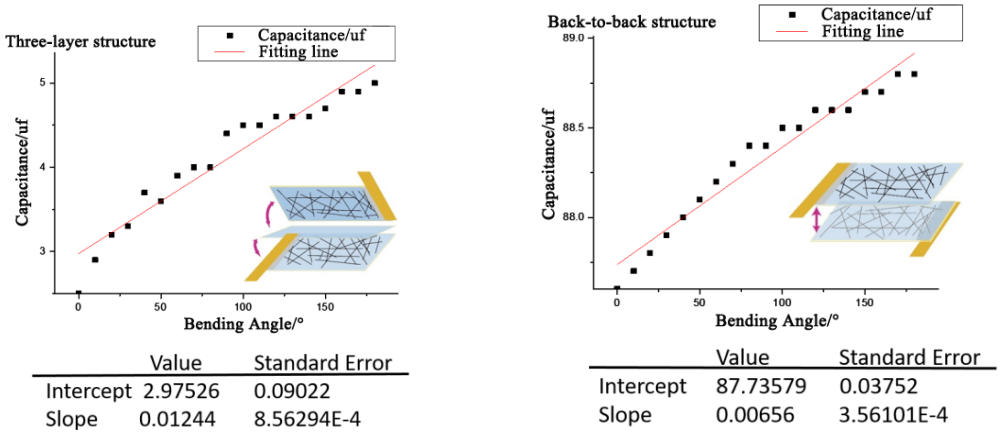

Figure 7. Bending-capacitance value characteristic patterns: (a) three-layer structure and (b) back-to-back structure Ag NW/PDMS pressure sensors

In addition, we also investigate the pressure response of the pressure sensors with two structures by applying pressure with an additional amount of paper clips (0.4670g/pcs). Figures 8(a) and (b) exhibit the numbers of the paperclips (pressure)-capacitance value characteristic patterns of the Ag NW/PDMS pressure sensors with the three-layer and back-to-back structures. As shown in Figure 8 (a), the Ag NW/PDMS pressure sensor with the three-layer structure exhibits a linear response in the range of 1-36 clips: in the range of 1-20 clips, the device presents good linear response, when the numbers of paper clips exceeds 20; the device's linear response is decreased. The relationship between the capacitance value (Y) and the numbers of the paperclips (X_2) is obtained by mathematical fitting: $Y = 0.10151X_2 + 3.04714$. Significantly different from the former, as shown in Figure 8 (b), the Ag NW/PDMS pressure sensor with the back-to-back structure displays a very good linear response under the pressure of 50 paper clips, and the linear growth can still be maintained. The fitting relation is $Y = 0.09241X_2 + 88.03597$.

To sum up, in the pressing test, the sensitivity of the back-to-back structure is higher than that of the three-layer structure. Better linearity can make the sensor close to the real change and have a broader test range. In the three-layer structure package, the pressure of the paperclips is applied on the PDMS layer, and then the PDMS compresses the Ag NWs deformation to produce the change of the electric signal. When the applied pressure exceeds the elastic deformation range of the PDMS, the signal response will deviate from the linear change. In the back-to-back structure package, the paper clips are directly applied on the Ag NW networks, the change of the electrical signal is easily received by the test instrument, and this reception can be sustained.

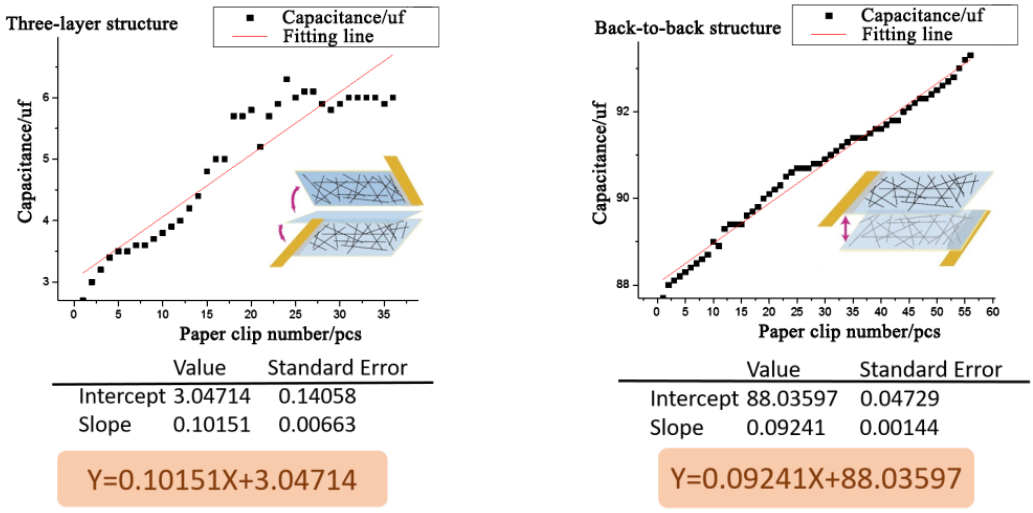

Figure 8. Paperclip numbers (pressure)-capacitance value characteristic patterns: the Ag NWs/PDMS pressure sensor with (a) three-layer structure and (b) back-to-back structure

4. Conclusion

In this work, the Ag NW/PDMS composite films were prepared by the coating method, and the pressure sensors with a three-layer structure and a back-to-back structure based on the composite film were fabricated. The result reveals that in the bending test, the linear response of the two kinds of pressure sensors is basically equivalent, and the response sensitivity of the sensor with the three-layer structure is better than that of the back-to-back structure. In the stressing test, the sensitivity, the linearity and testing range of the sensor with the back-to-back structure are better than that of the three-layer structure. Therefore, the Ag NW/PDMS pressure sensor with the back-to-back structure exhibits a better overall performance.

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6. References

[1] Rus Dand Tolley MT2015*Nature* **521** 467-475
[2] Park YL, Chen BR, Pérez-Arancibia NO, Young D, Stirling L, Wood RJ, Goldfield EC, and Nagpal R2014 *Bisinspir. Biomim.***9**016007
[3] Giorgino T, Tormene P, Lorussi F, De Rossi D, and Quaglini S 2009*IEEE Trans. Neural Syst. Rehabil. Eng.***17** 409-415
[4] Wang Y, Wang L, Yang T, Li X, Zang X, Zhu M, Wang K, Wu D, and Zhu H 2014*Adv.Funct.Mater.***24** 4666-4670
[5] Ryu S, Lee P, Chou JB, Xu R, Zhao R, Hart AJ, and Kim S-G 2015*ACS Nano***9** 5929-5936
[6] Lee J, Kim S, Lee J, Yang D, Park BC, Ryu S, and Park I 2014 *Nanoscale***6**11932-11939
[7] Lin L, Liu S, Zhang Q, Li X, Ji M,Deng H, and Fu Q2013 *ACS Appl.Mater.Interfaces***5** 5815-5824
[8] Mannsfeld SCB, Tee BC-K, Stoltenberg RM, Chen CVH-H, Barman S, Muir BVO, Sokolov AN, Reese C, and Bao Z2010 *Nature Mater.***9**859-864
[9] Yamada T, Hayamizu Y, Yamamoto Y, Yomogida Y, Izadi-Najafabadi A, Futaba DN and Hata K2011 *Nature Technol.***6**296-301
[10] Park Y, Bormann L, Müller-Meskamp L, Vandewal K, LeoK2016 *Organic Electron.***36**68-72
[11] Kim KK, Hong S, Cho HM, Lee J, Suh YD, Ham J, and Ko SH 2015 *Nano Lett.***15(8)**5240-5247
[12] Becerril BHA, Roberts ME, Liu Z, Locklin J, and Bao Z 2008 *Adv.Mater.***20**2588-2594
[13] Wan Y, Wang Y, Guo CF 2017 *Mater. Today Phys.***1** 61-73
[14] Wang C, Cheng B, Zhang H, Wan P, Luo L, Kuang Y, and Sun X2016 *Nano Res.***9(5)**1532-1542
[15] Moon H, Won P, Lee J and Ko SH 2016 *Nanotechnology***27**295201
[16] Akter T and Kim WS 2012 *ACS Appl.Mater.Interfaces***4**1855-1859
[17] JWang, CYan, WKang and PSLee 2014 *Nanoscale***6**10734-10739
[18] Quan Y, Wei X, Xiao L, Wu T, Pang H, Liu T, Huang W, Wu S, Li S, Chen Z2017 *J.Alloys Compd.***699**824-831
[19] Lee H, Hong S, Lee J, Suh YD, Kwon J, Moon H, Kim H, Yeo J, and KoSH2016 *ACS Appl.Mater.Interfaces***8**15449-15458