Ultrasensitive wearable pressure sensors based on Silver nanowire-coated fabrics

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Abstract

Flexible pressure sensors have attracted increasing attention due to their potential applications in wearable human health monitoring and care systems. Herein, we present a facile approach for fabricating all-textile-based piezoresistive pressure sensor with integrated Ag nanowire-coated fabrics. It fully takes advantage of the synergistic effect of the fiber/yarn/fabric multi-level contacts, leading to the ultrahigh sensitivity of $3.24 \times 10^5 \text{ kPa}^{-1}$ at 0–10 kPa and $2.16 \times 10^4 \text{ kPa}^{-1}$ at 10–100 kPa, respectively. Furthermore, the device achieved a fast response/relaxation time (32/24 ms), and a high stability (>1000 loading/unloading cycles). Thus, such all-textile pressure sensor with high performance is expected to be applicable in the fields of smart cloths, activity monitoring and healthcare device.

Introduction

In recent years, flexible pressure sensors, as one of the critical components in wearable electronics, are developed to obtain real-time mechanical feedback for a multitude of applications such as E-skin devices, health monitoring systems, and smart robots.^{1–7} In order to be viably employed in these applications, pressure sensors must exhibit excellent sensitivity performance, thus providing exhaustive information for accurate diagnosis or analysis.

Various studies have focused on using nanomaterials to improve the sensor performance, including CNTs,¹ graphene nanosheets,⁸ metal nanowires,^{9–17} conductive polymers,¹⁸ and their composite materials.^{19–21} Particularly, AgNW has been extensively used as the sensing elements or conductive fillers in pressure sensors due to its outstanding electrical and mechanical properties. For example, Wang et al. fabricated a flexible pressure sensor with a AgNW-filled PU film as the dielectric interlayer, achieving a sensitivity of 5.54 kPa^{-1} for pressure below 30 Pa and 0.88 kPa^{-1} for pressure above 30 Pa.²² Ho et al. reported a transparent crack-enhanced capacitive sensor consisting of two laminated PDMS films bearing AgNW-embedded microfluidic channels.²³ Zhong et al. developed an ultrasensitive piezoresistive sensor with high flexible, which is composed of POE nanofibers and AgNWs by a facile filtration method.¹¹ However, most of these sensors were fabricated using airproof elastic substrates, which are unbreathable and uncomfortable to wear, thus limiting their practical applications.

More recently, textile-based pressure sensors have attracted increasing attention because of its softness, breathable and biocompatibility, which makes it durable and wearable for long term. AgNWs have been used in the textile-based pressure sensors. For instance, Wei et al. demonstrated a useful wearable pressure sensor with the structure of two conductive cotton sheets coated with AgNWs.²⁴ Zhou et al. designed a pressure sensor with a printed textile electrode and AgNW-coated cotton fabric.²⁵ Despite this progress, an all textile-based pressure sensor with ultrahigh sensitivity is seldom reported by far.

Here, we demonstrate a facile and approach for fabricating all-textile-based pressure sensors. The AgNWs solution was synthesized and then the conductive fabric can be fabricated using a dip-coating method, which was done by dipping cotton pieces into the AgNW dispersion. The active sensing element

contained double-layered AgNW-coated cottons with a cotton mesh spacer to secure the initial contact between them. The pressure sensing is based on changes in the electrical current due to the contact between the facing layers upon external pressure. This all-textile-based piezoresistive pressure sensor fully takes advantage of the synergistic effect of the fiber/yarn/fabric multi-level contacts, leading to the ultrahigh sensitivity of $3.24 \times 10^5 \text{ kPa}^{-1}$ at 0–10 kPa and $2.16 \times 10^4 \text{ kPa}^{-1}$ at 10–100 kPa, respectively. Meanwhile, the pressure sensor achieved a fast response/relaxation time (32/24 ms), and a high stability (> 1000 loading/unloading cycles). Such devices have wide applications in smart cloths, activity monitoring and healthcare device.

Experimental Section

Materials And Methods

The AgNWs solution was synthesized by hydrothermal method. First, the solution of PVP was added into EG, then the mixture was stirring for 20 min to fabricate the solution of PVP/EG. Subsequently, the solution of AgNO_3/EG and NaCl/EG were prepared with the similar method. Second, the solutions of AgNO_3/EG and NaCl/EG were added into PVP/EG and the mixture was stirred and transferred into a reaction kettle. Third, the kettle was heated to 140 °C for 2 h and then to 160 °C for 30 min. Subsequently, the kettle was naturally cooled down to room temperature. The obtained precipitates were washed and centrifugal filtered with acetone and deionized water for several times to form white powder. Lastly, the obtained AgNWs were ultrasonically dispersed in ethanol.

Fabrication of Pressure Sensor

The all-textile-based pressure sensor was fabricated using “dipping and drying” process²⁶ (Fig. 1). First, the cotton fabrics were cleaned with DI and anhydrous ethanol each for 15 min. Second, the fabrics was dipped into the obtained solution of AgNWs for 20 min and followed by drying at 90 °C for 10 min (Fig. 1a). Then the copper electrodes were attached to the surface of the AgNW-coated fabrics with silver paste and dried at 90 °C for 1 h. Meanwhile, the cotton mesh spacers with different hole diameters were fabricated by a laser etcher process (Fig. 1b). Finally, the double-layered sensing fabric with an inserted cotton mesh spacer was assembled by a face-to-face package process (Fig. 1c).

Characterization

The scanning electron microscopy (SEM) images of the AgNW-coated fabric surfaces were taken via a GeminiSEM 500 (ZEISS, New York, America) at 5 kV. The current response of the pressure sensors was recorded using a digital source meter (Keithley 4200, America) and measured using a digital force gauge (SJS-500V, China).

Results And Discussion

Fig. 2a shows the morphology of the AgNWs-coated fabric observed from SEM images. It can be seen that the average diameter of AgNWs is about 55 nm. The density of the AgNWs on the surface of the fabrics was adjusted by the times of dip-coating cycles. The SEM images showed that the AgNWs were distributed on the surface of the individual fibers (Fig. 2b). With increasing dip-coating cycles, the density of AgNWs coated on the fibers is higher. Meanwhile, the nanowire mesh spacings was decreased from 2–4 μm to below 1 μm accordingly. For the fibers with 5 dip-coating cycles, the AgNWs conductive networks were completely coated on the fibers.

The composition of the AgNWs-coated fabric was also investigated by the EDS, as illustrated in the inset of Fig. 2b. In addition to the C and O contents which mainly attributed from cotton, Ag element was also observed, indicating the distribution of AgNWs on the cotton.

The sensing principle of the pressure sensor is shown in Fig. 3a. In the unloading state, the initial resistance is large, which is caused by the non-contact AgNWs on the fabrics. Once pressure was applied, the increasing fiber-scale contacts of nanowires on the adjacent fabrics contributed to a decrease in the resistance. Furthermore, when the nanowires on the fabrics were contacted completely, the continued pressure loaded on the fibers then increased the yarn-scale contacts. With loading pressure increasing, fabric-scale contacts further reduced the resistance of the sensor due to the increased contact area between the facing fabrics. Therefore, the pressure sensing of the sensors was determined by the synergistic effect of the fiber/yarn/fabric multi-scale contact.

Figure 3b shows the current-voltage curves of the pressure sensor under different pressures. When the applied pressure increased from 0 kPa to 100 kPa, the resistance of the sensor was decreased. Furthermore, the response of sensor was steady and fell in line under Ohm's law.²⁷ The current of pressure sensor is shown in Fig. 3c, which is relatively constant under different applied pressure, revealing that the response of the sensor is stable for different pressures. Therefore, the results provide the excellent electrical stability for the potential application of the pressure sensor.

To investigate the performance of pressure sensors, the relative current changes ($\Delta I/I_0$) versus pressure with the different AgNWs dip-coating cycles and mesh hole diameters were shown in Fig. 3d and e. Here, the sensitivity of the pressure sensor was defined as $S = (\Delta I/I_0)/P$, where P denotes the applied pressure. At a mesh hole diameter of 0.25 mm, the sensitivity of the pressure sensor was strongly dependent on the AgNWs dip-coating cycles. The sensitivity of the sensors was improved from $2.12 \times 10^3 \text{ kPa}^{-1}$ to $1.98 \times 10^5 \text{ kPa}^{-1}$ within the range of 0–10 kPa when the dip-coating cycles increased from 1 to 5. In addition, the sensitivity improved from 764 to $1.12 \times 10^3 \text{ kPa}^{-1}$ at 10–100 kPa. The improvement of sensitivity with high dip-coating cycles is mainly attributed to the increase of the AgNWs densities.

Furthermore, the dependence of hole diameter was subsequently characterized. The pressure sensors with 5 dip-coating cycles exhibited enhancing sensitivities with increasing diameters, which were increased from 1.12×10^3 , 9.88×10^3 , to $2.16 \times 10^4 \text{ kPa}^{-1}$ within the pressure range of 10–100 kPa, respectively. The enhancement in the sensitivity was mainly attributed to the increased contact area

through the larger holes. Notably, the pressure sensor clearly exhibited two linear current segments, the sensitivity increases sharply in the low-pressure range and increases gradually in the high-pressure range. According to the sensing principle as we mentioned above, in the low-pressure range, the adjacent AgNWs contact plays an important role in increased current. Furthermore, when the pressure is increased to 10–15 kPa, the AgNWs on the interface were contact completely. The current changes were mainly determined by the contact resistance between the yarns and fabrics, which was relatively stable. Contact between the yarn- and fabric-scales played a more significant role in the sensing mechanism at a dip-coating cycles of 5 times and diameter of 0.75 mm by enhancing the sensitivity and linear range. Therefore, the diameter of 0.75 mm (Fig. 3e) exhibited a higher sensitivity and larger linear range due to increased contact.^{28,29}

The dynamic response of the device was studied under loading/unloading pressure cycles. The sensor exhibited an immediate response to the cyclic pressures. The time-resolved response was analyzed to quantify the response and relaxation times (Fig. 4a). The measured response and relaxation times were 32 and 24 ms, respectively. The $\Delta I/I_0$ with an applied pressure of 10 kPa with 1,000 loading cycles was used to verify the repeatability of the device (Fig. 4b). The results show the excellent stability of the pressure sensors.

Due to the natural flexibility of fabrics and high sensitivity of sensors, the pressure sensor was wearable and able to detect mechanical signals such as physiological pulse and respiratory rate. First, the device was attached at the wrist using an adhesive bandage to monitor the pulse pressure. Figure 4c presents the real-time recorded data, in which the pulse rates were measured to be $\approx 72 \text{ beats min}^{-1}$. In addition, the sensor was also attached on a mask to detect respiration states. Figure 4d indicates that the normal respiratory rate of 10 breaths per minute of an adult and a square-like wave for normal breathing. Furthermore, the width of the waveband indicated the maintained time of breathing. These results suggest that the pressure sensor with high sensitivity and superiority has great potential in wearable healthcare device applications.

Conclusion

In this work, the AgNWs was fabricated by hydrothermal method and the morphology was characterized and analyzed. An all-textile-based pressure sensor was fabricated by inserting a cotton mesh spacer between the double-layered AgNW-coated cottons. Owing to the collective effect of the fiber/yarn/fabric multi-scale contacts, the sensor has extremely high sensitivity ($3.24 \times 10^5 \text{ kPa}^{-1}$ at 0–10 kPa, and $2.16 \times 10^4 \text{ kPa}^{-1}$ at 10–100 kPa, respectively), fast response/recovery time (32/24 ms), high stability (1000 cycles), and wide pressure range (0–100 kPa). The physiological signals monitoring such as pulse pressure has been successfully demonstrated. With a facile and efficient method for fabrication, such ultrasensitive pressure sensor will promote a wide application in next-generation development of smart cloths, activity monitoring and healthcare device.

Abbreviations

CNTs: carbon nanotubes; AgNW: Ag nanowire; PVP: polyvinyl pyrrolidone; EG: ethylene glycol; NaCl: dium chloride; DI: deionized water; SEM: scanning electron microscope; EDS: energy dispersive X-ray spectroscopy.

Declarations

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Authors' Contributions

YL, MW and XY designed and carried out the experiments. HZ participated in the work to analyse the data. YL prepared the manuscript initially. HY polished the English. All authors read and approved the final manuscript.

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Availability of Data and Materials

The authors declare that the materials and data are available to the readers, and all conclusions made in this manuscript are based on the data which are all presented and shown in this paper.

Competing Interests

The authors declare that they have no competing interests.

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Figures

Figure 1

Fabrication process of the all-textile-based pressure sensor. a The preparation process of AgNW-coated cotton. b The fabrication process of mesh spacer cotton. c The assembling process of pressure sensor

Figure 2

The morphology of the AgNWs-coated fabric. a SEM images of AgNWs-coated fabrics of 5 dip-coating cycles with different magnification, b is focusing on the different cycle dip-coated AgNWs that attached on a single yarn, in which the EDS analysis is included.

Figure 3

Performances of the pressure sensors. a Schematic illustration of pressure sensing. b I-V curves of the pressure sensor with different applied pressures. c The current response of the sensor under different pressures. d, e The performance comparison of the pressure sensors with different dip-coating cycles and mesh hole diameters

Figure 4

a Response/release times of the device. b The cycling test of the device under a pressure of 10 kPa. c Wrist pulse signal of the human user. d The current signal responds to respiration under normal breathing