STRETCHABLE, TRANSPARENT AND WEARABLE SENSOR FOR MULTIFUNCTIONAL SMART SKINS

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ABSTRACT

This paper reports a novel active body motion sensor with PDMS-AgNWs structure, which is not only highly sensitive to detect body static gestures by strain-resistance response, but also self-powered to recognize both body and prosthesis motion based on triboelectrification and electrostatic induction synchronously for the first time. By attaching the sensor on human skin or robot surface directly, the motion of the relative surface could be reconstructed simultaneously. Particularly, the sensor could work as functional part of smart skins and wearable devices for its great stretchability and transparency.

INTRODUCTION

Recently, stretchable electronics have attracted much attention due to their abilities to sustain complex deformation and conformal contact with irregular surfaces, which meets the demand generated by the rapid development of electronic skins and wearable devices [1-3]. In order to make the devices stretchable, new materials synthesis and special structure design are two important areas of development [4]. Many nanomaterials, such as carbon nanotubes [5], graphene [6] and metal nanowires [6-9], have been used to fabricate stretchable electronics with polymers [4,10]. Some novel structures, including wave, mesh and textile, are applied in the device designs [4]. There is a spectrum of promising applications for stretchable electronics, for example, sensors, energy harvesters, displays, smart skins, health monitors and wearable electronics, which would facilitate our lives in many ways [1-10].

Human or robotic motion detection is indispensable for human-machine interfaces, next-generation prosthetics and healthcare monitor [3,11]. Some strain sensors based on nanomaterials have been developed to achieve wearable detection [5,7,9]. However, one weakness of majority of current wearable sensors is need for external power source, which means indispensable wire connections, limited usage time and the need to be recharged very often and makes the sensing system bulky [11,12]. The other is that the transparency of the sensor has been severely weakened in some cases [5-9], which is inconvenient to integrate with other sensors.

Ag has the highest electrical conductivity among all the metal materials, and silver nanowires (AgNWs) networks shows a high transmittance for a wide range of wavelengths [4], which make AgNWs attach much attention for potential applications as transparent, flexible and stretchable electrodes [6-9]. Here, through pre-stretching and spin-coating, AgNWs are distributed on the polydimethylsiloxane (PDMS) membrane surface uniformly and form a conductive and transparent network, which is still stable and recoverable even after thousands of stretches. When attached on human skin or prosthesis directly, the sensor could catch the motion signal based on triboelectrification and electrostatic induction in real time [11-14], and detect static gestures by strain-resistance response of the AgNWs network. PDMS-AgNWs structure makes the sensor stretchable, transparent, wearable and self-powered.

FABRICATION

The fabrication process of the sensor is schematically illustrated in Figure 1. The mixture of PDMS base and cross-linker is dropped on the smooth glass surface, spin-coated at 400 rpm for 120 seconds and then heated on the hot plate at 100 degrees Celsius for 10 minutes to solidify. After peeled off carefully, the PDMS membrane is stretched in one direction (50%) or two vertical directions (20% for each direction). Then 5 minutes oxygen plasma treatment is carried out to make the PDMS membrane surface hydrophilic by the inductively coupled plasma (ICP) etching process [15], for which the alcohol solution of silver nanowires (2 mg/ml) could disperse on the surface uniformly. After repeating dropping the solution on the membrane surface and then spin-coating at 1000 rpm for 25 seconds ten times, the membrane is placed on the hot plate at 150 degrees Celsius for 15 minutes to anneal, through which the electrode becomes more conductive and stable. Finally, the sensor is completed via releasing the strains. Here we use the pre-stretching strategy and spin-

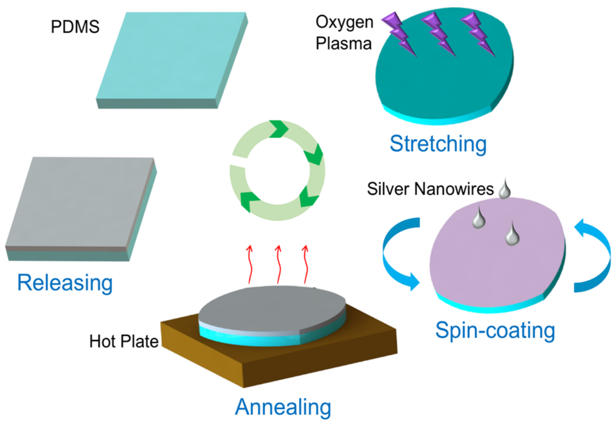

Figure 1: Schematic of the fabrication process of the PDMS-AgNWs sensor.

coating method to make the electrode stretchable and transparent.

CONCEPT AND PRINCIPLE

When attached on human skin or prosthesis, the sensor could supply static gestures and dynamic motion detection at the same time. Figure 2a shows the working principles of the sensor.

For static detection, with the strain increases, on the one hand, the cross-sectional area of the silver nanowire network reduces, in other words, the conductive layer thins; on the other hand, the contact area and the number of contact points of the silver nanowire also reduce, as shown in Figure 2b, causing the resistance of the sensor to increase.

For dynamic detection, the sensor could work as a single-electrode triboelectric nanogenerator [13,14]. As shown in Figure 2c, when PDMS layer contacts with human skin, the electrons will be transferred to PDMS, which has a better ability to attract electrons according to triboelectric series. When motion happens, the PDMS layer contacts or detaches from the skin and the contact area changes, the charges on the surface will redistribute because skin can be seen as ground for its conductive nature and large area. Then, there is a potential generated at the AgNWs layer because of the electric field created by triboelectric surface charges. Electrons will flow into (from) AgNWs layer through load equipment from (into) ground when potential is higher (lower) than ground. Therefore, dynamic detection is achieved without batteries.

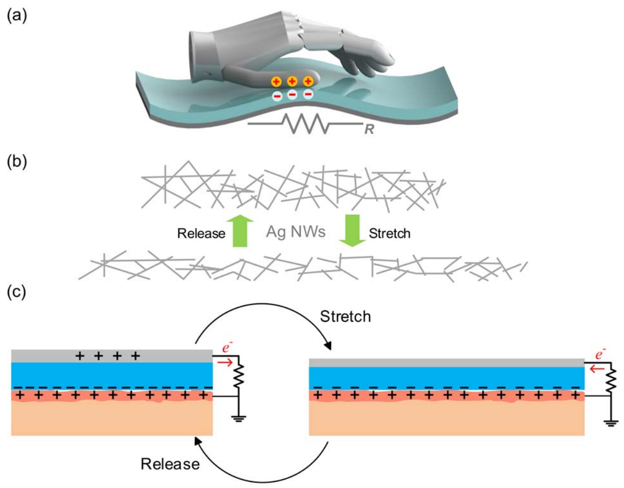

Figure 2: (a) Structure and the working principles to supply static and dynamic monitoring of the sensor. Schematics of (b) the AgNWs network structure and (c) charges transfer when sensor stretched and released.

RESULTS AND DISCUSSION

The distribution of the AgNWs on the PDMS membrane surface are displayed in Figure 3 with the help of the scanning electron microscopy (SEM). As shown in the SEM images, AgNWs build a uniform interconnected conductive network on the PDMS surface. The diameter of the silver nanowire used here is about 30 ~ 50 nm and the length is about several microns. After oxygen plasma treatment, the Young’s modulus of the PDMS surface increase. After releasing the strain, periodic microstructures and cracks appeared for the difference of Young’s modulus between PDMS surface and inside.

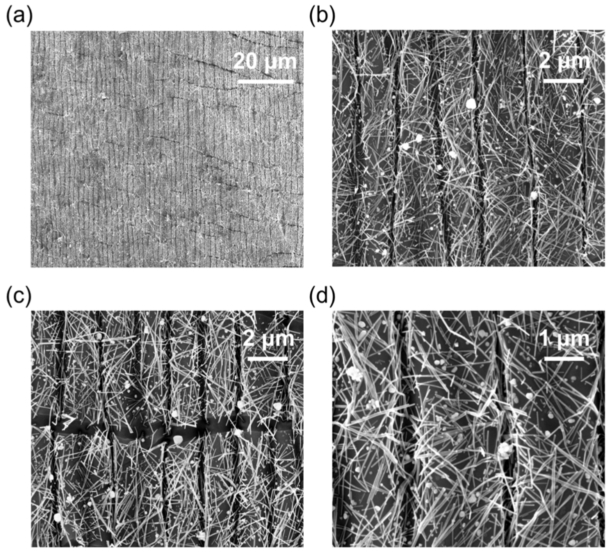

Figure 3: SEM images of the sensor surface, which shows AgNWs distributed on the PDMS surface with periodic microstructures and cracks uniformly.

In order to study the effect of stretching on the performance of the sensor, we first tailor the samples pre-stretched in one direction (50%) in their fabrication process into rectangles (2 cm × 0.5 cm) and then record the changes in resistance when the samples are stretched along their length. Figure 4a displays the relative resistance (R/R_0) response when the sensor is stretched in different elongation. With the increase of the elongation, the relative resistance approximately linearly increases, which makes

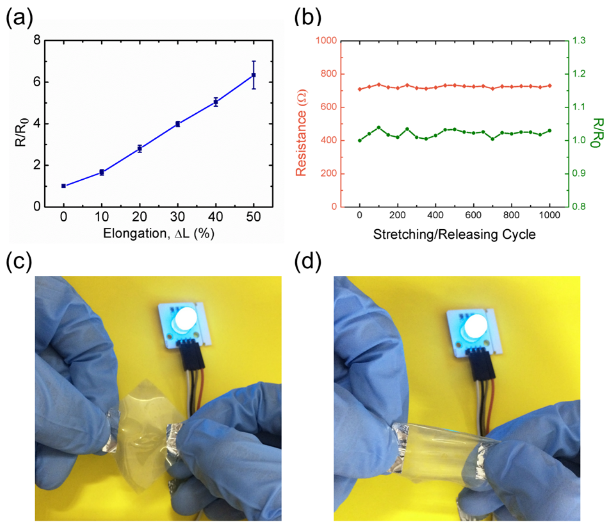

Figure 4: Resistance responses of the sensor to (a) the strain and (b) 1000 cycles of repeated stretching to 50% elongation and releasing. Photographs of the sensor (c) released and (d) stretched working as a part of a conductive loop.

it suitable for the sensor to work as a strain sensor. After released, the silver nanowire network will reconstruct slowly, and the resistance of the electrode will go back to the initial value approximately after some time. As shown in Figure 4b, after 1000 cycles of repeated stretching to 50% elongation and then relaxing, the resistance remains almost constant. Figure 4c-d shows the photographs of the sample pre-stretched in two vertical directions (20% for each direction) in its fabrication process working as a part of a conductive loop, the small bulb is bright regardless of whether the sample is released or stretched, which displays the stretchability and conductivity of the sensor.

When attached on the finger knuckle, the sensor can supply static and dynamic monitors. Figure 5a displays the triboelectric output voltages when finger bends 30°, 60°, 90° and 120° and restores. With the increase in bending angles, the voltage increases obviously. Therefore, the sensor could work as a self-powered body motion sensor to monitor the dynamic change of not only the fingers, but also neck, elbows, knees and other joints. In addition to the dynamic monitor, the sensor also supports static monitor for the approximately linear relative resistance (R/R_0) response to the strain. The dynamic (maximum voltage of the triboelectric output) and static (relative resistance) responses to the bending angles are demonstrated together in Figure 5b. When finger is static, there would not be the friction signals, we could also know the bending angles by measuring the resistance change. The monitor process could be seen in the Figure 5c-g.

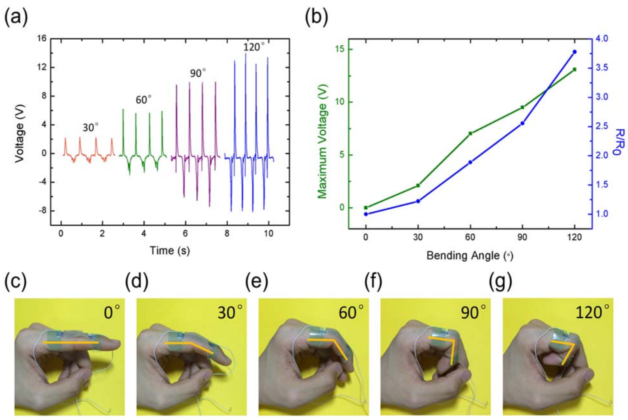

Figure 5: (a) Output voltage waveforms and (c-g) photographs of the sensor when finger bends 30°, 60°, 90° and 120°. (b) Maximum voltage and relative resistance (R/R_0) responses of the sensor to the bending angle.

Except for human skin, the dynamic and static responses of the sensor attached on a wooden manipulator are displayed in Figure 6a. The initial state of the finger is reconstructed through relative resistance (R/R_0) responses to strain of two sensors placed on joint A and joint B, as shown in Figure 6c. Figure 6b displays the maximum voltage of the triboelectric outputs of two sensors after an uncertain motion. Compared with the data in Figure 6a, the bending angles and directions of two joints can be calculated, which are about 55° and 75° respectively. And then the final state of the finger is reconstructed in Figure 6d according to the results calculated above, which shows a process of self-powered motion recognition and reconstruction. The remarkable sensing ability makes the sensor have huge potential applications in health monitors, wearable devices and smart skins.

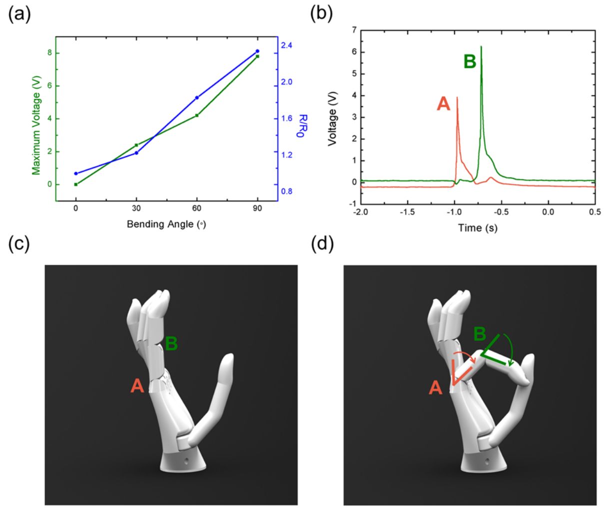

Figure 6: (a) Maximum voltage and relative resistance (R/R_0) responses of the sensor attached on the manipulator to the bending angle. (b) Output voltages generated by an uncertain motion. Schematics of the reconstructed (c) initial state and (d) final state of the manipulator's index finger after the motion.

CONCLUSIONS

In summary, a novel stretchable, transparent and wearable body gesture and motion sensor has been developed. AgNWs are deposited on the PDMS layer with the help of pre-stretching strategy, oxygen plasma treatment and spin-coating process. The relative resistance (R/R_0) response of the sensor to strain is approximately linear, which makes it suitable to be a strain sensor. The resistance of the sensor remains almost constant even after 1000 cycles of repeated stretching to 50% elongation and relaxing. When attached on the human skin or prosthesis, the sensor can monitor not only static gestures by resistance response to strain, but also dynamic motions based on triboelectrification and electrostatic induction at the same time. Then the gestures and motions could be restructured according to the results output above in real time. All of the excellent properties makes the sensor have much potentials in the development of multifunctional smart skins and wearable devices.

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