PIEZORESISTIVITY OF AG NWS-PDMS NANOCOMPOSITE

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ABSTRACT

In this work, we developed a conductive silver nanowire (AgNW)-PDMS composite thin film for a flexible strain sensing application. The piezoresistivity of AgNWs-PDMS nanocomposite thin film was experimentally investigated and analyzed by a computational model. The strain sensor shows a strong piezoresistivity with an average gauge factor in the ranges of 1.6 to 14 and a high stretchability up to 70 %. We found excellent agreement between our experiment and simulation results. Finally, a finger motion detection device was developed by using the AgNWs-PDMS nanocomposite thin film as a highly stretchable, flexible and sensitive strain sensor.

INTRODUCTION

Human motion recognition has stimulated much interest due to its potential applications such as rehabilitation and personal health monitoring [1-3], sport performance monitoring [4-5], and entertainment fields (e.g. motion capture for games and animation) [6]. Despite of numerous efforts for the human motion capturing by using vision based techniques (i.e. motion detection by set of cameras and image processing) [7, 8], vision based approaches are not widely applicable due to their space requirement, high cost and low resolution for a small movements (e.g. fingers' movement detection). Toward these objectives, demands are increasing for flexible, stretchable and wearable electronic devices due to their facile interactions with the human body, small size and higher accuracy [8-10]. For instance, flexible, wearable and stretchable strain sensors (i.e. devices that respond to the mechanical deformations by change in the resistance or capacitance) can be attached to the human body for the human motion detection. However, both high sensitivity (i.e. gauge factor (GF)) and high stretchability ($\varepsilon > 50\%$) are the minimum requirements of desired strain sensors for the human activity recognition; compare with that in the commercial strain gauges with stretchability (up to 5% maximum strain) and GFs~2 [10]. Several approaches have been reported to develop strain sensors with desirable properties (i.e. high stretchability coupled with sensitivity) by using nanomaterials and nanostructures. Among them carbon nanomaterial based sensors have shown outstanding performances due to the superior mechanical and electrical properties of carbon nanomaterials. Even though graphene based strain sensors pose a good sensitivity, they have very low stretchability due to brittleness of the graphene sheets [11, 12]. On the other hand, highly stretchable (up to 40%) strain sensors were developed by using single-walled carbon nanotubes (SWCNTs) on the elastomer substrate [10]; but, the strain sensors were suffering from approximately low GFs (~0.82). Although there have been numerous efforts to develop strain sensors with a high stretchability and sensitivity using carbon based nanomaterials, mostly reported strain sensors have high sensitivity coupled with approximately low stretchability and vice versa. Furthermore, strain sensors with desired characteristics particularly for the human motion detection are still remaining challenge.

Herein, we report a highly flexible and stretchable thin film based on the nanocomposite of PDMS with AgNWs as fillers. The thin film shows a strong piezoresistivity by external stimulus so that AgNW network with a sandwich structure (i.e. the AgNW network-PDMS nanocomposite layer laminated between two layers of PDMS (PDMS/AgNWs-PDMS nanocomposite thin film/PDMS)) was utilized as a highly stretchable and sensitive strain sensor. The characteristics of the sensors such as stretchability and response to both dynamic and static loads have been investigated. In addition, piezoresistivity of AgNW network was studied computationally using a 3D resistor network. We found an excellent agreement between our experiment and simulation. Finally, an artificial finger was developed to investigate the applicability of our strain sensor for the human fingers' gesture recognition. The resistance changes caused by the bending of strain sensors on the finger was measured and then positions of fingers were calculated based on the resistance changes, all in real-time.

MATERIAL AND SAMPLE FABRICATION

AgNWs were synthesized by polyol method according to Korte et al. [13] (see the reference for more details). AgNWs were stored in isopropyl alcohol (IPA) for further experiments. The average diameter and length of AgNWs were 150-200 nm and 10-20 μm, respectively.

The thin films were fabricated by drop-casting of the AgNW solution onto a glass slide which was patterned with a polyimide tape and cleaned (with acetone, ethanol, and DI water) beforehand. The uniformity of AgNW thin film is an important parameter for stable and predictable response of the strain sensors. Here, instead of using a hot plate or a vacuum oven, light heating has been employed as heating source. After drop-casting of the AgNW solution, the glass slide was exposed to a lamp light (OSRAM DR 51 50W 12V with Luminous intensity of 1450 cd) to dry AgNW solution and deposit the AgNWs onto the glass slide. Light heating provided uniform and gradual heating throughout deposited AgNW thin film and made it more uniform and homogenous. After drying the solution, polyimide tape was removed on the glass slide and patterned AgNW thin film was annealed at 200 °C for 20 min to increase the conductance of thin film. Furthermore, thermal annealing can reduce the resistance between AgNW junctions and improve the conductivity of film by removing the PVP surfactant and allowing fusion between AgNWs [14-15]. Sandwich structured samples were prepared by casting 0.5 mm layer of the liquid PDSM onto the patterned and annealed AgNW thin film. After partially curing the PDMS layer at 70 ºC for 20 min, it was peeled-off and flipped. Then copper wires were attached to the ends of the AgNW thin film by silver paste. Finally, another layer of the liquid PDMS with a same thickness (~ 0.5 mm) was poured on the AgNW embedded PDMS film and cured at 70 ºC for 2 hours. The fabrication process, photographs and SEM image of the sandwich structured sample are shown in Figure 1.

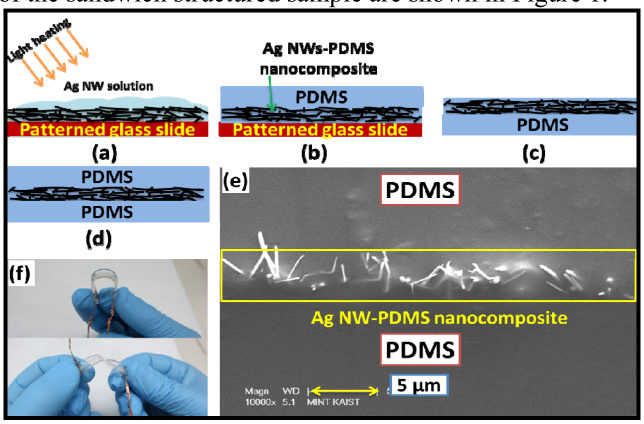

Figure 1: a-d) Fabrication processes of the sandwich type of AgNW thin films. a) Deposition of AgNWs on a glass slide under light heating and further annealing at 200 ℃ for 20 min. b) Casting the liquid PDMS onto the AgNW thin film and partially curing it at 70 ℃ for 30 min. c) Peeling-off and flipping the AgNWs embedded PDMS. d) Pouring another layer of PDMS and curing it at 70 ℃ for 2 hours. e) The cross-sectional SEM image on the sample; the AgNW nanocomposite layer is embedded between two layers of PDMS. f) Photographs of the fabricated sandwich structured sample when it is bended and twisted.

RESULTS AND DISCUSSION

Figure 1e shows the cross-sectional SEM image of the sandwich structured sample. As the figure shows, PDMS penetrated into the AgNW thin film network and filled the gaps between NWs, forming a composite of PDMS and AgNWs. The penetration of PDMS enhanced the contact of jointed NWs and made the total sparse network of AgNWs mechanically robust. The penetration enhanced the adhesion between the AgNW network and PDMS layers as well.

Figure 1f shows the photographs of sandwiched thin film which is bended and twisted without any damage to the AgNWs-PDMS nanocomposite thin film. The sample is very flexible and stretchable and it can be easily mounted onto the complex surfaces or directly attached to the human body.

To test the stretchability, samples were attached to a motorized moving stage. Strain/release cycles were applied to the conductive AgNW thin films while the current changes were measured with a potentiometer. Figure 2 shows the response of a sample to the cyclic loading (from □=0 to □=70 %). As figure illustrates the current of sample was recovered very well after releasing it from strain, indicating the applicability of the thin film as a highly stretchable strain sensor. Moreover, the position and orientation of NWs in the AgNW network-PDMS nanocomposite are changed by the applied strain. As strain increases, the numbers of disconnected NWs increase due to the PDMS elongation. Disconnection reduces the number of electrical passways, thereby causing the current to reduce and resistance to increase, accordingly. When the strain sensor is released from strain, all NWs slide back to their initial positions and the current of the strain sensor recovers to its original value.

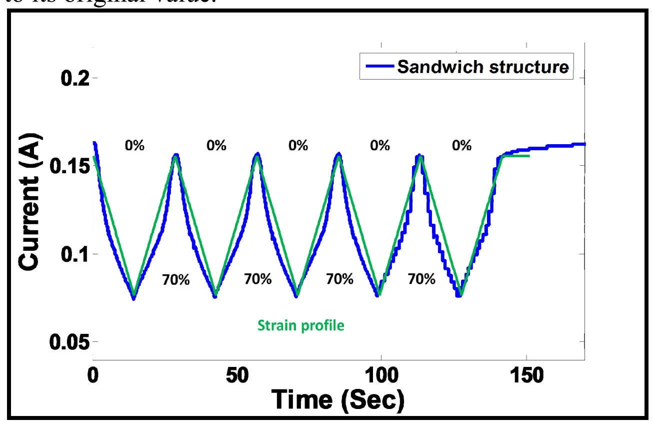

Figure 2: Response of the AgNWs-PDMS nanocomposite under 70% of stretch/release cycles.

The piezoresistivity of the AgNW network-PDMS nanocomposite is further investigated by a computational model. AgNWs with a constant diameter (D=150 nm) and length (L=20 µm) were randomly orientated in the PDMS matrix, as shown in Figure 3. The position and orientation of each NW can be determined by the coordinates of NW in the 3D space. Since the Young's modules of the AgNWs are much higher than that of the PDMS medium, the NWs can be assumed as rigid element [16, 17]. Therefore, the re-position and re-orientation of NWs by the applied strain can be calculated using the 3D equilibrium equation for the PDMS matrix.

We considered three electrical configurations for the two neighboring NWs including, (I) Complete connection without contact resistance; when the distance between centerlines of the adjacent NWs are less than the diameter of single NW, (II) Disconnected NWs; when the distance between the centerlines of NWs surpasses a cut-off distance (C), and (III) Tunneling junction; if the centerline distance of the two neighboring NWs is between diameter and cut-off distance so that electrons can tunnel through the PDMS matrix. We assign the cut-off distance as a distance between the two adjacent NWs whereby the resistance between NWs is 30 larger than the resistance of single NW (C~150.58 nm). The tunneling current can be estimated as [18]:

$$R_{Tunnel} = \frac{V}{AJ} = \frac{h^2 d}{Ae^2\sqrt{2m\lambda}} \exp\left(\frac{4\pi d}{h}\sqrt{2m\lambda}\right) \qquad (1)$$

where J is tunneling current density, V is the electrical potential difference, e is the single electron charge, m is the mass of electron, h is Planck's constant, d is the distance between NWs, λ is the height of the energy barrier (1 eV for PDMS), and A is the cross-sectional area of the tunnel, which is assumed to be the same as the cross-sectional area of single NW.

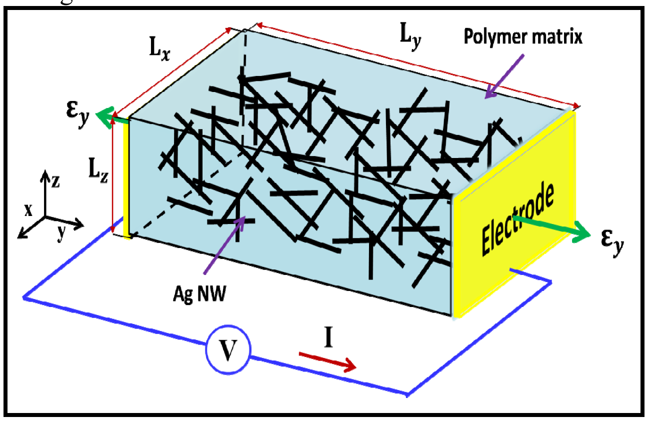

Figure 3: 3D random orientation of AgNWs in the PDMS medium.

A network resistor model was then constructed by the junction identification between all pairs of NWs in the network and the resistance of total network was calculated by using Kirchhoff's current law and Ohm's law. To obtain the total conductance change under strain, the positions and orientations of all NWs were re-calculated and the conductivity of thin film was analyzed again.

Figure 4 shows the relative change of resistance against the applied strain (up to 50%) for the nanocomposite, both experiment and simulation. As the figure demonstrates, there is an excellent agreement between our experiment and simulation results. Furthermore, the relative resistance of sensor gradually increases by the applied strain with almost linear manner.

Gauge factor (GF) showing the sensitivity of sensor to applied strain can be calculated by the following equation:

$$GF = (\Delta R / R_0) / \varepsilon \quad (2)$$

where R_0 is the initial resistance at the zero strain, ΔR is the change of resistance caused by the applied strain, and ε is the applied strain. The GFs of all tested samples are in the ranges of 1.6 to 14; in comparison with conventional strain sensors (GF~2 with stretchability of 5%), these sensors have higher gauge factor and stretchability (□=70%).

The effects of the aspect ratio (L/D) of NWs on the sensitivity and stretchability of the strain sensor were investigated by our computational model. NWs with the aspect ratios of 115, 85.7, and 61.3 were randomly signed into the PDMS matrix. Size of the samples and volume fractions of NWs are assumed to be all the same. The relative change of resistance against the applied strain for the different aspect ratios is illustrated in Figure 5. As the figure shows, the sensitivity of sensor gains by the decrease of aspect ratio. On the other hand, both linearity and stretchability of the sensor enhance by the increase of aspect ratio. Furthermore, stretchability improvement by the higher aspect ratios could be due to the better connection of long NWs in the network for larger strains. Since the NW-NW disconnection rates for longer NWs are slower than that of short NWs, reasonably the sensors possess lower sensitivity.

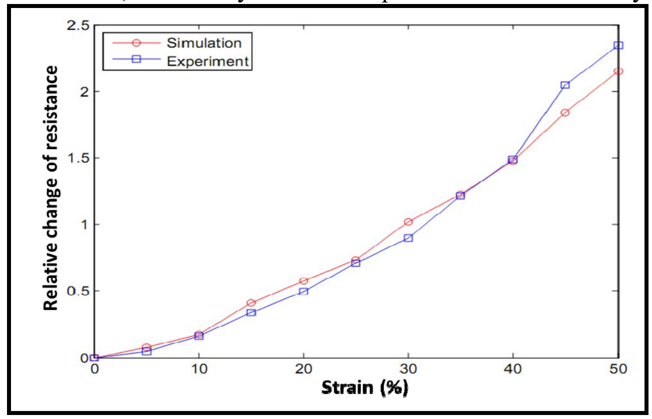

Figure 4: Relative change of resistance versus applied strain-both experiemnt and simulation.

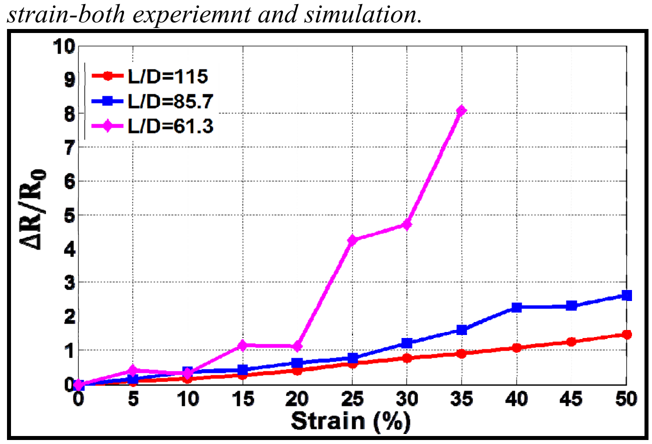

Figure 5: Relative change of the resistance versus strain for the different aspect ratios.

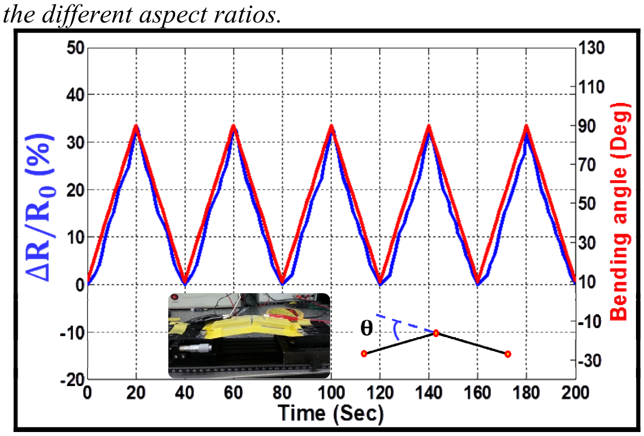

Figure 6: Response of the strain sensor to the bending/relaxation cycles; bottom inset, a photograph of the artificial finger device.

As an application of highly stretchable and sensitive Ag NWs-PDMS nanocomposite strain sensor, we constructed an artificial finger for the detection of human joints' angle, bottom inset of Figure 6. The strain sensor was attached on the artificial finger joint and then cyclic bending/relaxation loads (from 10º to 90º) were applied to the sensor while the current was measured. The more bending accommodates the more strain to the sensor, causing the resistance of sensor to increase accordingly. As Figure 6 shows, there is an excellent overlap between the response of sensor and loading profile. The strain sensor responds to cyclic loads very fast without considerable hysteresis and drift.

CONCLUSIONS

In this paper, a highly stretchable and sensitive strain sensor based on the Ag NW network-PDMS nanocomposite was fabricated. Stretchability and GFs of the sensors are 70% and in the ranges of 1.6 to 14, respectively. The Ag NWs-PDMS nanocomposite strain sensors exhibit a good bendability performance and they can be easily mounted on the body for the applications such as joint angle measurement and skin movement monitoring. Piezoresistivity of Ag NW network-PDMS nanocomposite was investigated by a computational model based on the network resistor. We found an excellent agreement between our experimental and computational results. Finally, an artificial finger was developed by assembling the stretchable strain sensor in the finger joint. The angle of joint can be calculated by the response of the strain sensor.

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