FLEXIBLE STRAIN SENSOR BASED ON CNS/SILICONE COMPOSITE FOR HUMAN HEALTH AND MOTION DETECTION

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ABSTRACT

Melamine sponge, also named as nano-sponge, is widely used as abrasive cleaner in our daily life. In this work, the fabrication of wearable strain sensor for human motion detection is first demonstrated with commercial available nano-sponge as starting material. The key resistance sensitive material in the wearable strain sensor is obtained by encapsulation of carbonized nano-sponge (CNS) with silicone resin. The as-fabricated CNS/silicone sensor is highly sensitive to strain with a maximum gauge factor of 18.42. The CNS/silicone sensor as wearable device for human motion detection including joint motion, eye blinking, blood pulse and breathing is demonstrated by attaching the sensor to corresponding part of human body. In consideration of the simple fabrication technique, low material cost and excellent strain sensing performance, the CNS/silicone sensor is believed to have great potential in the next-generation of wearable devices for human motion detection.

INTRODUCTION

In recent years, the demands for wearable electronics have exponentially risen [1, 2]. For example, flexible strain sensors play a significant role in the areas of sport, fitness tracking, e-skins, personal health monitoring and etc [3]. It is known that conventional strain sensors based on metal and semiconductors cannot meet the need in wearable devices due to their fragile, rigid and low sensing range nature [4]. Large-scale fabrication of highly sensitive and flexible strain sensors with low-cost and facile techniques is significant to meet the need in the next-generation of wearable electronics. To enhance the wear-ability, various flexible strain sensors based on capacitors [5], triboelectric nanogenerators [6], field-effect transistors [7], and piezo-resistive materials [8] have been successfully demonstrated. Among them, strain sensors based on flexible piezo-resistive polymer composites are highly attractive due to their relatively simple structure and fabrication techniques, as well as low energy consumption in operation. Moreover, the strain or stress can be simply measured by monitoring the resistance change of the polymer composites.

In early years, the resistive-type flexible strain sensor is generally based on carbon black filled polymer composites, but their sensitivities are very low [9]. Recently, to achieve high sensitivity, flexible strain sensors based on three dimensional (3D) conductive network constructed within elastomeric matrix have been reported [10, 11]. In general, expensive nanomaterials such as silicon nanoribbons [12], metal nanoparticles and nanowires [13], carbon nanotubes [14, 15] and grapheme [16, 17], and complicated fabrication techniques such as freeze-drying plus pyrolysiss [8], template based technique combined with a chemical vapor deposition process or a dip coating process [18] are essential to construct those 3D conductive networks, which drastically hamper their large-scale production for massive market penetration.

Melamine sponge, also named as nano-sponge, is widely used as abrasive cleaner in our daily life. Herein, we demonstrate the fabrication of wearable strain sensor with nano-sponge as starting material. Firstly, carbonized nano-sponge (CNS), the key strain sensing material for the wearable sensor, was obtained by simple high temperature pyrolysis of commercial available nano-sponge. In comparison with those 3D conductive networks constructed with nanomaterials, CNS as strain sensing material has the advantages of 1) mechanically stable 3D network with high compressibility, 2) low cost with commercial available sponge as raw materials and 3) easy large-scale production with simple one-step carbonization process. By simple infusion of CNS with silicone resin, a highly sensitive and flexible strain sensor was achieved, which shows excellent piezo-resistive behavior with fast and stable response. Moreover, human motions including joint motion, eye blinking, blood pulse and breathing were successfully monitored with CNS/silicone sensor, which indicates its great potential in the next-generation of wearable devices.

Experiment

Preparation of CNS and CNS/silicone Sensor

Nano-sponge (Outlook Company, Chengdu, China) for cleaning was diced into desired shape and size and then washed with ethanol and deionized water. CNSs with different shape and size were obtained by carbonization of the as-prepared nano-sponge pieces in a tubular furnace at 1000 ºC for 2 h in N_2 atmosphere. Then, the CNSs obtained were washed with ethanol and deionized water to remove impurities. The CNS strain sensors were fabricated by simple encapsulation of CNSs with silicone resin. Two pieces of aluminum foil as electrodes were soldered with silver paste at the two ends of CNS sheet prior to encapsulation. Silicone resin (Ecoflex supersoft 00-30, Smooth-On, Inc.) was prepared by homogenously mixing the base agent and curing agent in a mass ratio of 1: 1. The mixed silicone resin was poured on the surface of the CNSs with electrodes inside a mold, which was degassed in a vacuum chamber for 10 min and then cured in an oven at 40 ºC for 30 min. The CNS/silicone composites without electrodes were prepared with similar procedure.

Characterization

All optical images were taken by a digital camera (Canon EOS 70D). The scanning electron microscope with an energy-dispersive x-ray spectroscope (SEM-EDS, Phenom XL) was used to image the microstructure and morphology of CNSs and CNS/silicone composite and analyze their element composition. The electrical conductivity of CNSs and CNS/silicone composite were measured with a two-probe method using a digital multimeter (VICTOR 86E). The compressive behavior of CNSs, silicone resin, and CNS/silicone composite was studied with a universal testing machine (SHIMADZU AGS-X) at a loading rate of 5 mm/min. To investigate the performance of CNS/silicone sensor, CNS/silicone sensor was fixed between two fixtures of the universal testing machine, while each electrode of the sensor was connected with the electrode of a digital multimeter (KEYSIGHT 34465A). When strain was applied to the sensor, the resistance change of sensor was recorded by the digital multimeter. The relative change of the resistance (RCR) was calculated on the basis of the resistance recorded: $\Delta R/R_0 = (R_s - R_0)/R_0$, where R_0 and R_s are the resistance without and with applied strain, respectively. The gauge factor (GF) defined as $\delta(\Delta R/R_0)/\delta S$, where S denotes the applied strain, was calculated to reflect the sensitivity of strain sensor.

Results and Discussion

The commercial available nano-sponge for cleaning has a typical 3D network structure composed of numerous branched fibers. Via a simple high temperature pyrolysis process in N_2 atmosphere, as indicated in Fig. 1a, the white nano-sponge is transferred into one black and porous CNS. CNSs with different complex geometries are fabricated (Fig. 1b), which retain the shape of original nano-sponge. As shown in Fig. 1c, the CNS obtained has a 3D network structure with pores in the scale of several tens of micrometers in diameter. The network structure of CNSs is composed of jointed fibers with a diameter close to nanoscale. EDS analysis reveals that the CNSs prepared mainly contain C (83.3 wt%) and N (16.7 wt%) elements, which confirms that carbon is the dominated element. Although with an extremely low density of 0.01g/cm^3, the CNSs prepared exhibit a moderate electrical conductivity of 1.60 S/m attributing to the well-connected 3D network structure.

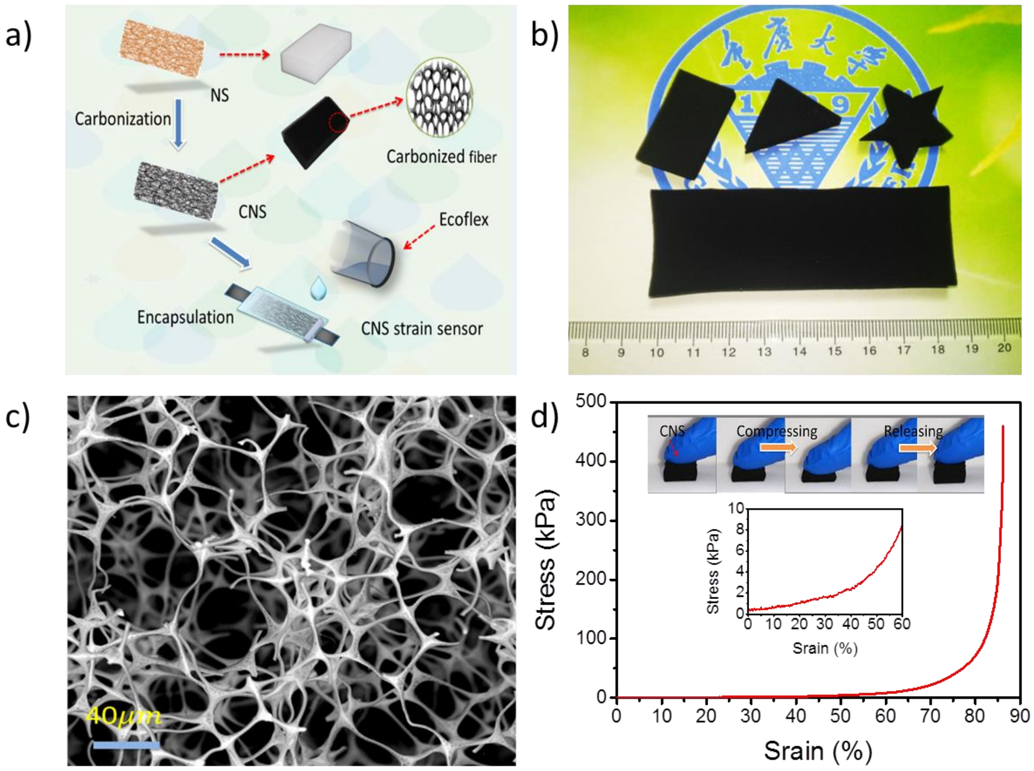

Figure 1**:** (a) Schematics for the fabrication of CNS and CNS strain sensor, (b) photograph of CNSs with different shape and size, (c) SEM image of CNS, (d) the typical compressive stress-strain curve of the CNS, and the insets show its reversible compression behavior.

The CNS fabricated exhibits remarkable mechanical stability; namely, the CNS is not only freestanding but also compressible. As indicated in the insets of Fig. 1d, the CNS can bear a maximum compressive strain of 80%, which can completely recover to its original state due to its high porosity and well-connected 3D network structure. The typical stress-strain curve of the CNS is displayed in Fig. 1d. Under compression, a linear relationship between stress and strain is seen when the strain is less than 60%. Further increase in the compressive strain leads to a sharp increase of stress, which also results in permanent structure collapse.

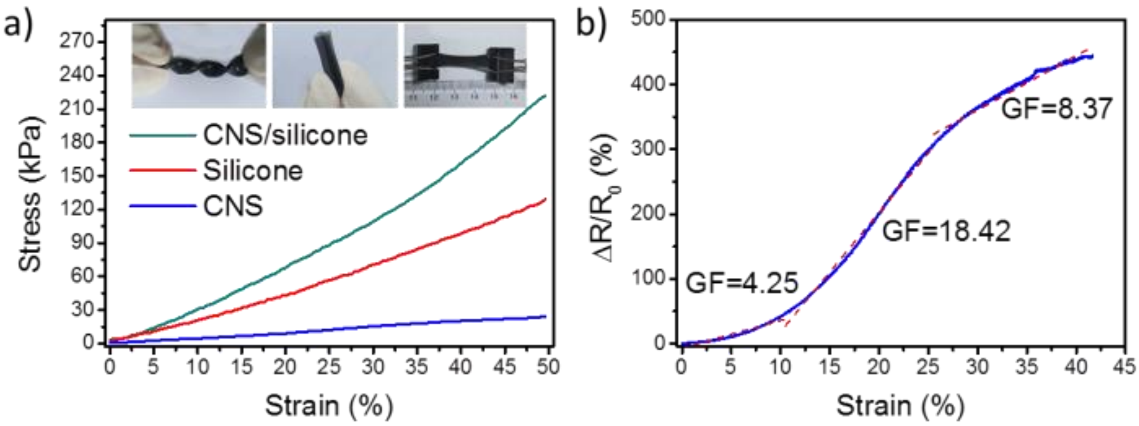

Figure 2: (a) Typical compressive stress-strain curves of CNS, silicone resin and CNS/silicone composite, the insets show the flexibility of CNS/silicone composite; (b) the RCR response of the CNS/silicone composite with applied compressive strain.

Owing to its 3D network structure, excellent mechanical stability and piezo-resistive behavior, the

CNS prepared has great potential in fabrication of wearable strain sensor. To improve its flexibility, stability and wear-ability, Ecoflex®, a widely used silicone resin in wearable devices, was employed to encapsulate the as-prepared CNS with a vacuum infusion process. The typical compressive stress-strain curves of CNS, silicone resin, and CNS/silicone composite are shown in Fig. 2a. It can be seen that the stress of the CNS/silicone composite at a strain of 50% is 225 kPa, which is 8 and 1.5 times higher than that of the CNS and silicone resin, respectively. The higher slope of the CNS/silicone composite over the CNS and silicone is due to penetration of silicone into the networks of CNS to be shown in Fig. 3. In addition, as indicated by the insets of Fig. 2a, the CNS/silicone composite can be easily twisted, bended and stretched multiple times without any visible damage. Tensile test shows that the elongation at break of the CNS/silicone composite is up to 600%, indicating a good stretch-ability.

It is exhibited that the resistance of the CNS/silicone composite changes dramatically under external stimulus such as compressive loading. As shown in Fig. 2b, the RCR of the CNS/silicone composite monotonically increases with the augment of compressive strain up to 40%, which can be divided into three regions according to the variation of slope. The GF of the CNS/silicone composite in the strain range of 0-10%, 10-25% and 25-40% calculated is 4.3, 18.4 and 8.4, respectively. The sensitivity of the CNS/silicone composite at middle strain range (10-25%) is around 4 and 2 times larger than that at low (0-10%) and high (25-40%) strain range. It is known that the GF of conventional strain gauge is around 2 [19], thus the sensitivity of the CNS/silicone composite outperforms it in the whole strain range.

It is known that the piezo-resistive behavior of CNS/silicone composite mainly relies on the change of its conductive network under loading. The fracture surface of the CNS/silicone composite is shown in Fig. 3a, jointed carbon fibers and uniformly spread silicone resin are clearly observed. In addition, the electrical conductivity of the CNS/silicone composite measured is 1.65 S/m, which is close to that of the CNS, indicating that the 3D network structure of the CNS is well preserved after the infusion of silicone resin. However, after a compressive loading is applied on the CNS/silicone composite, some cracks, holes, and carbon fiber/silicone interface separations in the CNS/silicone composite are observed (Fig. 3b), which results in the breakage of the conductive paths and leads to the piezo-resistive behavior of the CNS/silicone composite. After unloading, the cracks, holes and interface separations in the composite disappear and the most of disconnected conductive paths recover to its initial states due to the reversing deformation of the silicone resin and CNS.

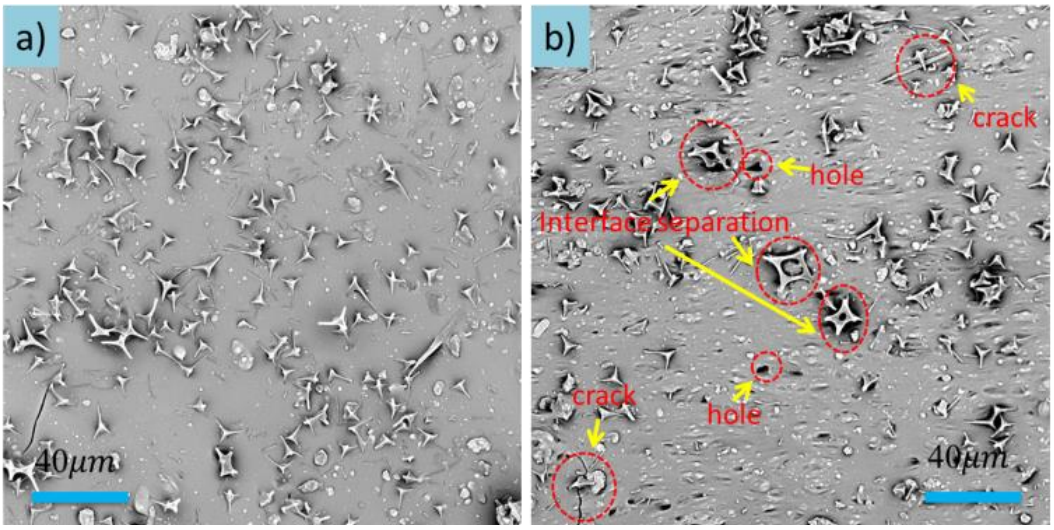

Figure 3: SEM images of the CNS/silicone composite without (a) and with (b) pre-applied compressive loading.

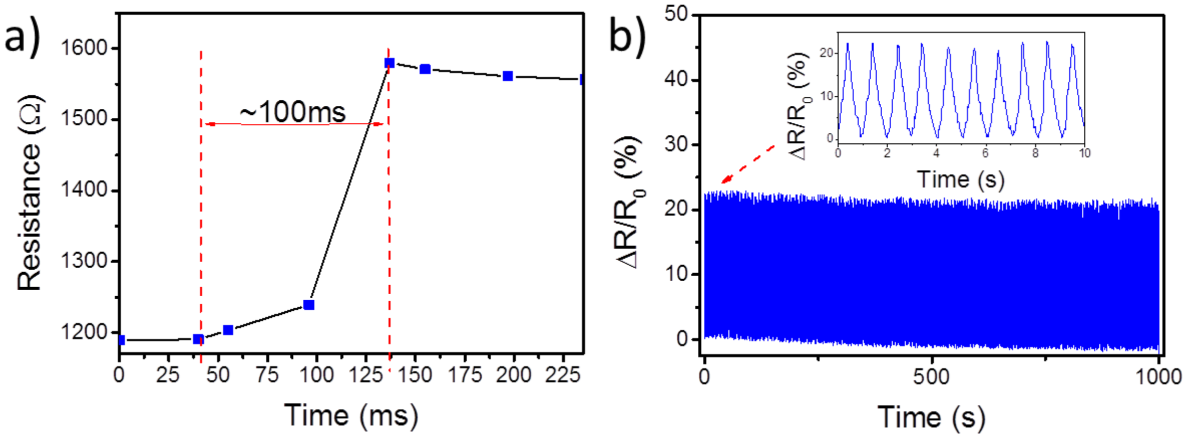

Figure 4: RCR response of the CNS/silicone composite to compressive loading: (a) resistance with responsive time, (b) the durability test at a frequency of 1 Hz with the 5% strain peak for 1000 cycles.

To reveal the response time, a strain of 5% is applied on the CNS/silicone composite with a compressive speed of 900 mm/min. Because the CNS/silicone composite sample has a thickness of 2.4 mm, the time duration of 8 ms is needed to apply the strain. The real-time resistance change of the CNS/silicone composite is monitored with a high resolution multimeter. As shown in Fig. 4a, the resistance change is completed within about 100 ms, indicating that the response time of the CNS/silicone composite is about 92 ms. The durability of the CNS/silicone composite is another important feature for its practical application in sensors. As shown in Fig. 4b, the RCR of the CNS/silicone composite exhibits a high stability within 1000 loading cycles at a frequency of 1 Hz with 5% strain and no significant change is observed, indicating the high reliability of the CNS/silicone composite as strain sensing material. The above results approve that the CNS/silicone composite possesses a merit of high strain sensitivity, fast response, and excellent durability, which is ideal for wearable strain sensors.

To demonstrate the potential of the CNS/silicone composite in wearable devices, a strain sensor prototype is fabricated by encapsulation of the CNS sheet with two electrodes. Various subtle human motions are successfully monitored with the CNS/silicone strain sensor fabricated. As shown in Fig. 5a, the wrist motions of a volunteer are tracked with the CNS/silicone strain sensor attached on the wrist. The wrist bending motions are well recognized with a dramatically RCR increase of 50%, which reverted to its original state after relaxing. As shown in Fig. 5b, the facial muscle stretching induced by eye blinking is precisely recorded by the CNS/silicone strain sensor, indicating its outstanding ability in subtle human body motion detection.

It is known that blood pulse and breathing are two important physiological signals related with the health condition of human. The real-time wrist blood pulses of a testee in relaxation and after exercise are detected with the CNS/silicone strain sensor. The RCR responses of the sensor recorded within 10 s are presented in Fig. 5c. Two pulse beat modes in relaxation and after exercise are easily identified, both of them show good repeatability. The pulse rate calculated is about 78 times per minute in relaxation. After exercise, the pulse rate is increased to 126 times per minute, and the shape becomes irregular, demonstrating the high sensitivity of the CNS/silicone strain sensor. As shown in Fig. 5d, the real-time breathing of a healthy adult volunteer in relaxation and after exercise are monitored by the CNS/silicone strain sensor assembled on the waist. It is observed that the breathing frequency of the testee in relaxation is about 0.32 Hz, which is increased to 0.59 Hz after exercise. The above results indicate that the CNS/silicone strain sensor as wearable device has great potential in detection of human body motions and health.

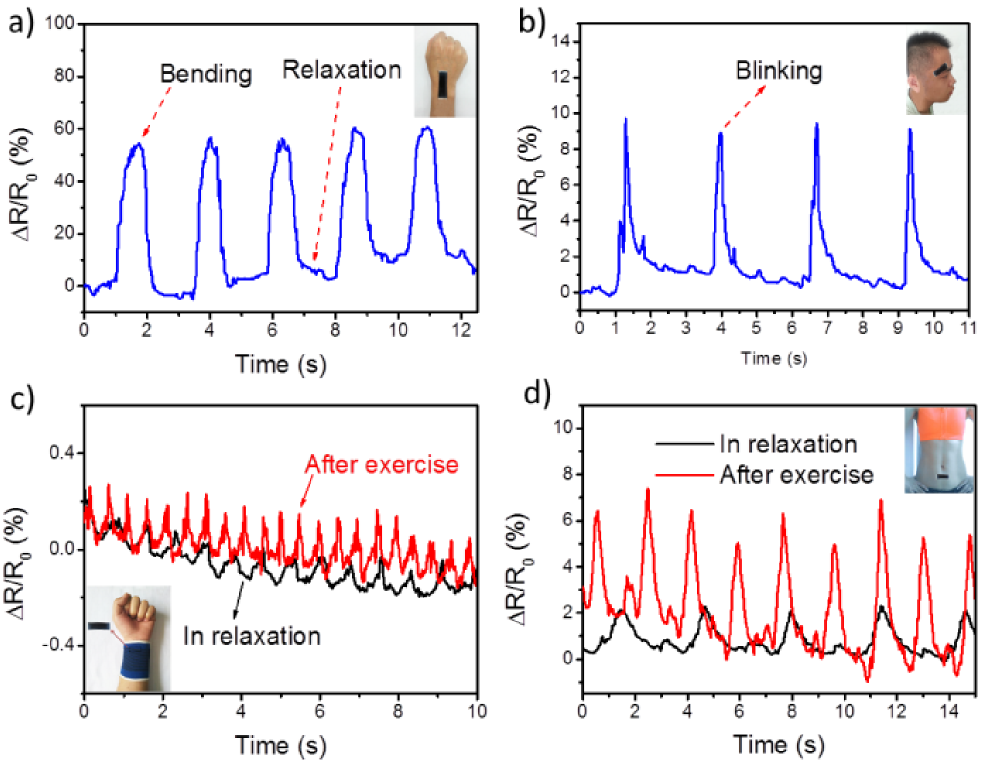

Figure 5: RCR responses of the CNS/silicone strain sensor to various human motion: (a) wrist bending, (b) eye blinking, (c) wrist blood pulse and (d) breathing.

Conclusions

In summary, a piezo-resistive strain sensor with high flexibility, sensitivity and stability has been fabricated with commercial available nano-sponge as starting material. The CNS obtained via high temperature carbonization of nano-sponge has a well-connected 3D network structure with moderate electrical conductivity and excellent mechanical stability, which enables it as an ideal material for flexible strain sensor. The strain sensitivity, flexibility, wear-ability and stability of the CNS are significantly enhanced by the incorporation of silicone resin. The CNS/silicone composite prepared shows a high GF of 4.3, 18.4, and 8.4 within the compressive strain range of 0-10%, 10%-25% and 25-40%, respectively. Furthermore, the CNS/silicone composite has fast response (92 ms) and high stability (1000 cycles). Finally, subtle human motions including wrist bending, eye blinking, blood pulse and breathing are successfully monitored with the CNS/silicone strain sensor fabricated. Importantly, attributed to the simple fabrication technique, low-cost with commercial available raw material, large-scale production ability and excellent performance, the CNS/silicone composite paves a new way for the fabrication of wearable strain sensors and will be primed for the commercialization in future.

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