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Fully flexible strain sensor from core-spun elastic threads with integrated electrode and sensing cell based on conductive nanocomposite

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A B S T R A C T

A fully flexible strain sensor from core-spun elastic threads with integrated electrode and sensing cell based on conductive nanocomposite is successfully prepared by a simple coating-drying process. It not only avoids mechanical failure at the junction between the sensing cell and electrode during the stretching process but also easily connect with external equipment or circuit. The conductive nanocomposite used for electrode and sensing cell is manufactured by carbon black/sliver paste/poly (sodium-p-styrenesulfonate) and single-walled carbon nanotubes/carbon black, respectively. The integrated strain sensor shows a typical resistive behavior and the gauge factor calculated at 0–50% strain is 2.18, which is close to that of the traditional metallic strain sensor. The integration sensor exhibits fast response (~125 ms), excellent stability and durability. The integrated strain sensor could be fabricated into various ideal shapes and located in different places. This new strain sensor is applicable to many situations such as monitoring the liquid level in the container, detecting the density of the solution, measuring acceleration and monitoring human movement.

1. Introduction

In recent years, researchers have became increasingly interested in developing flexible and stretchable sensor which can capture and monitor various human motion by their facile interaction with the human body [1–3]. Conventional strain sensors which composed of metals and semiconductors are incompatible with the human body because of the limited stretchability ($\varepsilon<5\%$) [4,5]. In order to develop such a high performance stretchable strain sensor, conductive stretchable fabric was usually be used because of their high surface-to-volume ratios, good stability, lightweight, suitability for integration into textiles and large stretchability against external deformation [6–8].

Recently, various nanomaterials with high conductive including conducting polymers [9,10], Ag nanowires [7,11–13], graphene [14–17], or carbon nanotubes (CNTs) [6,18,19] have been used to obtain conductive fiber which used for fiber-based electrode and fiber-based strain sensor. There are extensive reports on stretchable electrode with excellent conductive and wearable strain sensor used in human monitoring. For example, Lee et al. fabric highly stretchable conductive fibers composed of silver nanowires and silver nanoparticles embedded in a elastomeric matrix that can recognize gestures [7]. Park et al. created a conducting fiber based silver nanoparticles with highly stretchable and electrical conductivity [13]. However, there is still a big challenge to monitor human daily activities because the predecessors just fabricated the sensing cells which are inconvenience to measurement or connecting to external circuits. Moreover, it may cause the mechanical failure at the junction between the stretchable sensing cell and metal wire [4]. In summary, although flexible stretchable fiber strain sensors and electrode have been studied extensively, there is still no full flexibility strain sensor with integrated electrode and sensing cell has been reported.

In this paper, a strain sensor integrated with electrode and sensing cell was developed. This strain sensor is full flexibility and stretchability, also, it could be measured and connect with external

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circuits easily. The integrated strain sensor was prepared by a simple and low-cost method of the coating-drying assembly technique. We used the integrated strain sensor to make a few simple devices to measure the level of liquid, the density of the liquid and the acceleration of object. Furthermore, there are several wearable applications were created by using the integrated strain sensors. Plus, their performance has been characterized. The experimental results show that the integrated strain sensor exhibits the excellent flexibility, superior stability and reproducibility. The integrated strain sensor's simple structure combined with electrode and sensing cell has wire-like shape enabled exceptional properties, including small dimension, light weight, and high flexibility. The unique architecture makes it highly promising as wearable sensor for human health and motion monitoring, since it can be fabricated into various desired shapes and located in different places.

2. Experimental

2.1. Materials

Core-spun elastic threads were purchased from Shanghai textile CO., Ltd. The cotton thread is wound around the polyurethane fiber to form a single core-spun elastic thread, and three single core-spun elastic threads twisted together form the core-spun elastic threads which used in this work. Single-walled carbon nanotubes (SWCNTs) powder was purchased from Chengdu Organic Chemicals CO., Ltd. The mean length and diameter of SWCNTs are 20 μm and 2 nm, respectively. Carbon black (CB) was provided by SPC Chemical Company (Sweden). Poly (sodium-p-styrenesulfonate) (PSS) was purchased from Shanghai Mackin Biochemical CO., Ltd. The molecular weight of PSS is 80000. Conductive sliver (YC-02) paste was purchased from Nanjing Hangshuo Electronic Technology CO., Ltd. Silicon rubber (SR) (GD401) was purchased from Sichuan Chenguang Engineering Design Institute, China.

2.2. Fabrication of the integrated strain sensor

In order to make the fiber electrode, electrode suspension should be prepared firstly. Above all, make 0.08 g CB dissolved in 20 ml dimethyl dispersion solution. Then, 2 g conductive sliver paste on it and 0.15 g PSS add to the above solution followed by sonication for 1 h and magnetic stirring for 30 min, respectively. At last, after adding 0.4 g SR to the above solution with magnetic stirring for 20 min, the electrode suspension was prepared. Secondly, sensing cell suspension was prepared for fabricating the sensing cell. 0.05 g SWCNTs and 0.1 g CB was dissolved in 20 ml dimethyl dispersion solution followed by sonication for 1.5 h and magnetic stirring for 30 min, respectively. After that, 1.35 g SR was homogeneously added to the above solution with magnetic stirring for 40 min. The sensing cell suspension was prepared.

The core-spun elastic threads was cleaned in deionized water for 10 min and dried in air. After that, both ends of the core-spun elastic threads were stretched to 80% strain in order to enhance the amount of the electrode suspension immersed in the core-spun elastic threads that leads to the good conductivity of the electrode. The electrode suspension was coated on the ends of the core-spun elastic threads in order to obtain stretchable electrode for integrated strain sensor. After the stretchable electrode was dried in air, the core-spun elastic thread was release to the original state. Then, made it coated with sensing cell suspension in order to obtain sensing cell for integrated strain sensor. Also, the sensing cell suspension should connect with the dried electrode. After the sensing cell dried in air, a fully flexible strain sensor from core-spun elastic threads with integrated electrode and sensing cell was obtained.

2.3. Characterization

Tensile test was carried out in pulling force testing machine (T2002, Shenzhen Lishen Technology Co., Ltd) which can record strain (ε) and tension (F) at the same time. The micro-structure was examined by a scanning electron microscope (Sirion 200, JEOL Ltd., Akishima, Japan). Resistance of samples was measured by DC a digital multimeter (HP-3458A, Agilent, California, US). The voltage data was recorded through a LabVIEW program in a real-time manner by acquisition card (USB-6211, National Instruments, Austin, US). The temperature experiment was provided by the Temp & Humi Programmable Chamber (BE-TH-80, Bell Experiment Equipment Co., Ltd, Dongguan, China) with the precision of 0.5 °C, within the temperature range from room temperature (25 °C) to 120 °C.

3. Results and discussion

3.1. Structural characterization of the integrated strain sensor

Fig. 1a schematically illustrates the fabrication processes of the strain sensor integrated with electrode and sensing cell. The SEM image of pristine core-spun elastic threads was shown in Fig. 1b, which exhibits all the threads are loosely and individual thread shows no physical bonding with each other. This design improves the conductivity of the core spun elastic thread, where the loose structure facilitates the penetration of the conductive filler into the core spun elastic thread. Fig. 1c shows the core-spun elastic threads coated with conductive nanocomposites. Fig. 1d shows the cross section of the junction between the electrode and sensing cell, which exhibit the good combination of electrode and sensing cell. The integrated strain sensor can be stretched to 50% of tensile strain and deformed into different shapes as it shown in Fig. 1e. Fig. 1f shows that integrated strain sensor can be mass-produced because of its simple and convenient manufacturing process.

Fig. 2a shows obvious adhesions caused by the CB/Ag/PSS/SR conductive nanocomposites between individual threads. Fig. 2b shows connect between Ag and CB, the sliver was surrounding by a large amount of CB, when the fiber was stretched the CB become the conductive bridge between Ag particle. As shown in Fig. 2c, there are obvious adhesions caused by the CB/SWCNTs/SR conductive nanocomposites between individual threads. Fig. 2d shows the sensing mechanism of the CB/SWCNTs/SR conductive nanocomposites. Owing to the continual contact between SWCNTs and CB, the conductive network of CB/SWCNTs couples with SR is able to maintain electrical conductivity even under high strain.

3.2. Electrical and mechanical properties of the electrode

In order to obtain a stretchable, flexible and high conductivity electrode, the influence of different conductive fillers has been investigated. Comparisons of the electrode to those coating different conductive fillers reveal that the electrode added PSS keep the excellent shape (Fig. 3a). Fig. 3a also shows the resistance of different conductive fillers based fiber electrode, and the electrode based on CB/Ag/PSS/SR has the minimum resistance, which caused by CB/Ag synergistic conductive network. Adding PSS to the conductive fillers is necessary because the PSS plays an important role in enhance conductivity [20], physical and mechanical properties [21,22] of fiber electrode. It caused by π-π interactions of aromatic rings of PSS, CB [8,23] and surface-initiated atom of CB transfer polymerization [24].

In order to demonstrate the good adhesion between CB/Ag/PSS/SR conductive nanocomposites and core-spun elastic threads, during the experiment, one hand hold one end of the fiber, the other hand press on the fiber electrode to slide from top to bottom