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Preparation of washable, highly sensitive and durable strain sensor based conductive double rib knitted fabric

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A strain sensor based nylon/spandex double rib elastic knitted fabric has been fabricated by coating graphene and adhesive. The morphology, conductivity and sensing property of treated fabric are investigated. The coated knit fabric exhibits a good conductivity of 15.65 S/m and the resulting strain sensors could detect the small strains of about 0.2% with gauge factor of 29.15. Within a strain range of 0-20%, the gauge factor is found as 28.64. It also shows excellent performance in terms of sensitivity, stability and durability over 5000 wash cycles, and could monitor small external deformations with a response time of 0.24s. Moreover, it has good washability.

Keywords: Conductive fabric, Knitted fabric, Nylon, Spandex, Strain sensor, Washable fabric

1 Introduction

At present, the study of flexible fabric sensors has globally attracted much attention[1-3]. Many textile-based strain sensors have been used in woven fabric, as flexible substrates[4-8]. However, the research on elastic knitted fabric with flexible sensors is in the initial stage of exploration. Deng *et al.*[9] prepared a strain sensor fabricated by sandwiching a carbonized cotton cloth between two polydimethylsiloxane films. The presence of carbon fibres in cloth helps in changing the resistance of sensor under strain. Wang *et al.*[10] utilized carbonized silk fabrics as sensing elements, due to their chemical structures and woven structures for applications in strain sensors. Ren *et al.*[11] fabricated a flexible conductive cotton fabric by deposition of graphene oxide onto a cotton fabric by vacuum filtration. The sheet resistance of the conductive cotton fabric increased from 0.9 $k\Omega/cm^2$ to 1.2 $k\Omega/cm^2$ after 10 wash cycles, exhibiting good wash ability. The conductive cotton fabric showed viability as a strain sensor. Lee *et al.*[12] fabricated a stretchable and wearable grapheme-based fabric strain sensor by a simple and scalable dipping-reduce method using commercial spandex/nylon fabrics as a starting material. In the development of woven sensors, there was still a conflict between high resistance and feasibility, high conductivity but poor mechanical properties, and detecting ultrafine deformations but lack of stretchability. In addition, woven fabrics usually have the disadvantages of poor skin contact and limited elastic recovery, while the knitted fabric has advantages of soft hand-feel, well dimensional stability, not easy to detach, strong fastness and wear resistance, excellent elasticity and extensibility, and productibility[13-15]. Li *et al.*[16] designed and fabricated a knitted strain sensor using technology of weft-knitting a nylon/nylon-wrapped spandex/silver-coated yarn into a knitted garment, and demonstrated that three-dimensional surface testing method could be effectively applied for the sensing performance evaluation of fabric strain sensors. Hong *et al.*[17] fabricated a smart strain sensing RGO/PET fabric via a facile and safe dip-dry reduce method. They endowed fabric with high sensitivity, broad sensing range, remarkable long-term durability and stability, and exhibited resistance strain anisotropy. Sun *et al.*[18] prepared a flexible and wearable GnPs/cellulose strain sensor with a special double rib knitted fabric structure by a simple dip-coating method. It exhibited dual-sensing performance with high sensitivity of 25.32 kPa^{-1} at 3 kPa pressure, 32.62 gauge factor, 25% tensile strain, stretchability and dynamic stability. Its potential application prospects were also predicted by the monitoring of human movement and physical parameters through a wireless bluetooth connection. Knitted fabric can meet the human body's requirements for wearing comfort, close-fitting, and sense without

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restriction. It is easier to create a flexible structure that fits closely with the human body, which is more suitable for strain sensor applications.

Graphene is a two-dimensional carbon nanomaterial, which is formed by sp^2 hybridization carbon atoms. Thanks to its electrical conductivity, biocompatibility, excellent thermal and mechanical stability and strong adhesion with the textile surface via van der Waals interaction due to its large specific surface ($2630 cm^2/g$) (refs 19,20). Graphene is considered as a strong candidate material for the high-performance wearable strain sensor. Especially, it is the material that has the best conductivity at room temperature till now. The excellent conductivity of graphene makes it widely used in flexible sensor products. Lee *et al.*[21] reported the piezo-resistance response of graphene and the grapheme-based strain sensor with a gauge factor of 6.1. Fu *et al.*[22] also demonstrated a monolayer grapheme-based strain sensor with high sensitivity. Furthermore, Wang *et al.*[23] showed that graphene could be used under high strain over 30% using fully reversible structural geometry.

In this study, nylon/spandex double rib elastic knitted fabric has been chosen to prepare the strain sensor using graphene coating method. The morphology, conductivity and sensing property of treated fabric are also characterized.

2 Materials and Methods

Nylon/spandex double rib knitted fabric [nylon/spandex (65/35), 160 g/m^2, 12×26] was purchased from Qingdao Xu Teng Textile Co., Ltd. Graphene solution (solid content 1.2%, thickness 200nm, size 15μm) was kindly provided by Beijing Zhong Lun Co., Ltd. Adhesive was produced from BASF Company.

Parameter analyzer (2601B, Keithley), scanning electron microscope (ZEISS-EVO18) and stepping motor controller (RiKo DKC-1B) were used.

2.1 Preparing of Modified Nylon/Spandex Knitted Fabric

The fabric was coated with graphene by screen printing method and then dried at 90°C for 30 min. The aqueous adhesive was diluted to 0.05g/mL and then ultrasonic treatment was done for 60 min. The coated fabric was then dipped in the adhesive diluent and dried in the dryer.

2.2 Characterization and Measurement

The surface morphology of the fabrics was observed by scanning electron microscope to study the dispersion of graphene and the change of morphology before and after coating treatment.

The sheet resistance of the specimen was measured by a parameter analyzer to consider the influence factors of graphene coating on the conductivity of the knitted fabric. The parameter analyzer reflected the sensitivity, resilience and hysteresis of the sensor. In addition, bending application tests of the different parts of the body were judged. The wash-ability was tested according to ISO105-C10 standard, and the washing process was repeated eight times.

3 Results and Discussion

3.1 Analysis of Surface Morphology

Figures 1 (a) & (b) reflect the smooth surface of the original fabric and Figs 1(c) & (d) show the fibre morphology after treatment, at 500 times and 2000 times magnification. Compared to original fabric, it is found that the fibre surface has formed functional layers and it is rough in case of treated fabric.

3.2 Conductivity and Sensitivity

The current-voltage curve of strain sensor under different concentrations of graphene coating is shown in Fig. 2 (a). The samples are treated with 0.3%, 0.6%, 0.9% and 1.2% graphene concentrations. Each sample is tested using 2601B Keithley Parameter analyzer at five different points and the mean of conductivity is taken as the conductivity value. The fabric treated with 1.2% graphene shows the best conductivity (15.65 S/m).

The high sensitivity of the sensor is reflected through its ability to detect different strains. To confirm the relationship between conductivity and

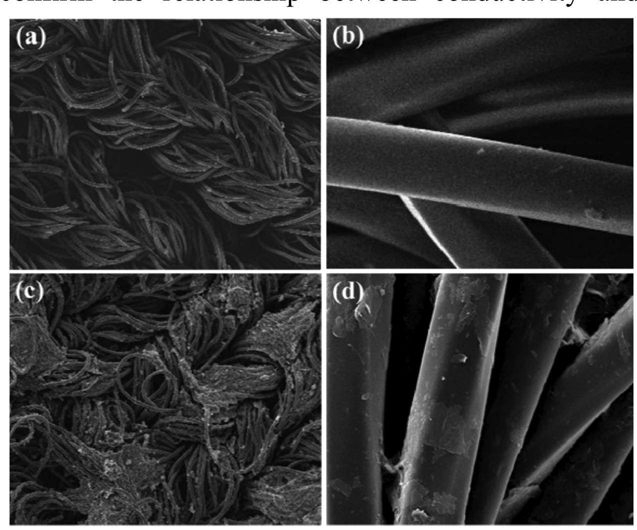

Fig. 1 — SEM images of original fabric at (a) ×100 & (b) ×5000; and treated fabric (c) × 100 & (d) ×5000 magnifications

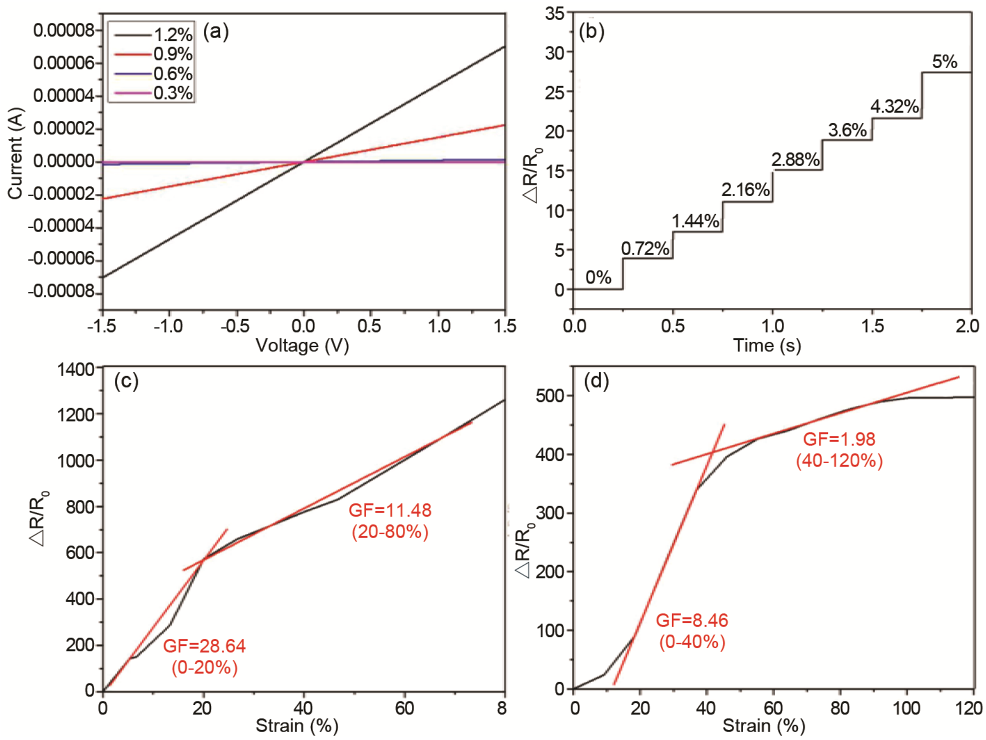

Fig.2 — C-V Curves of sensor (a), resistance change within the low strain range of 0-5% (b), and at different tension in the wale direction (c) and course direction (d)

strain further, a parameter analyzer is selected to determine the change in resistance of the sensor when it is stretched under different tensile strain states. The tests are repeated to observe the resistance change.

Treated fabric of the size 3 × 11 cm is used as the sample and the clamping distance is kept 10cm. Pull the fabric sample along the wale direction from 10cm to 18cm at a constant speed (maximum strain is 80%). Then organize the data and draw the wale strain resistance curve. According to Figs 2(b)-(d), the conductivity of the sensor increases linearly within the strain range of 0-80%. The sensing coefficient [GF =($\Delta R/R_0$)/ε] is used to calculate the sensitivity of the sensor; where ΔR is the change in resistance when strain is loaded, R_0 is the resistance when strain is not applied, and ε is the strain applied. By multiple calculations, the gauge factor is found 29.15, indicating that the sensor can detect the small strains down to 0.2%. Within a strain range of 0-20%, GF is found 28.64, which has a high sensitivity, while GF is found 11.48 within a strain range of 20-80%.

3.3 Stability and Repeatability

To obtain a more durable and stable flexible substrate, the dynamic characteristics of the fabric sensor are used to verify whether the sensor has good stability. The fabric with a sensing area size of 3 cm×10 cm is stretched from the original length to 0.2% strain along the wale direction. The fabric is stretched repeatedly 5000 times and the resistance change rate is recorded simultaneously. The results are shown in Fig. 3. The relative change in electrical resistance of the fabric when it is stretched repeatedly in the wale direction is found more stable than the

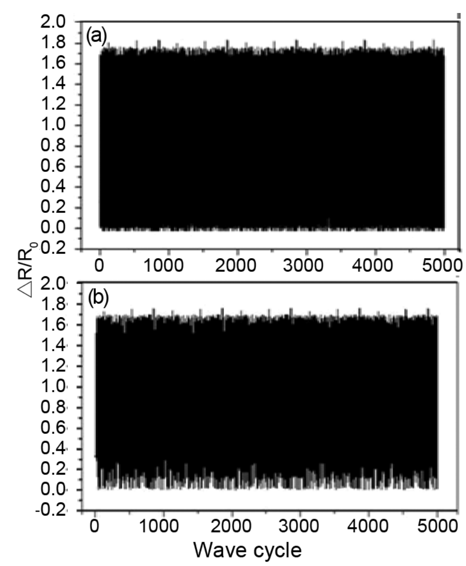

Fig. 3 — Stability stretched from 0% to 0.2% after 5000 times in wale direction (a), and course direction (b)

change in the course direction. And the fabric shows better stability and repeatability in the wale direction.

3.4 About Hysteresis

Hysteresis could be defined as the relative difference in the area beneath the $\Delta R/R_0$-strain curves under stretching and releasing; and it is evaluated by a formula $\gamma_H = \pm \Delta H_{max}/y_{FS} \times 100\%$; where ΔH_{max} is the maximum output value between the forward and reverse travel, and y_{FS} is the full-scale output value. According to the characteristic curve of the strain sensor (Fig. 4), the γ_H is found 8.16%. It indicates that the fabric is not suitable for large-strain applications.

3.5 Analysis of Wash-ability

The response of these sensors (1.2% GO and 0.05g/mL BASF adhesive dilute) after being washed is also researched. The sensitivity and repeatability of the strain sensor are tested after each washing and drying cycle. As shown in Fig. 5(a), the curves of resistance at different tension demonstrate that there are no distinct changes at different tension and also the stability has no significant difference before and after washing [Fig.5 (b)], which attributes to the graphene coating and excellent adhesion.

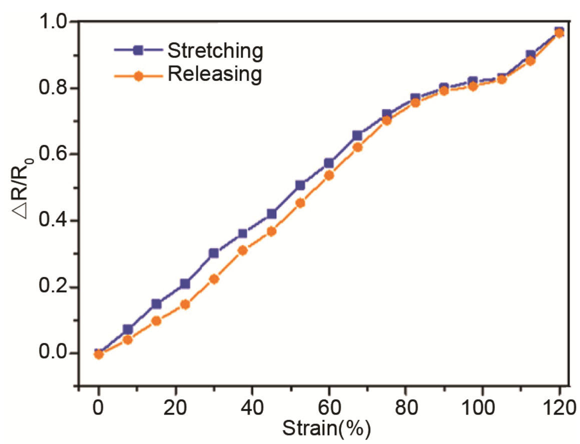

Fig. 4 — Relative resistance under a 120% strain stretching-releasing cycle (strain rate 10%/s)

3.6 Human Body Application Test

To further detect the ability of the sensor to perceive more subtle physiological signals, the sensor is fixed on the throat to test the vibration of the vocal cord (cough). As shown in Fig. 6(a), modes of light cough, holding and severe cough are tested. The signal frequency of severe cough is significantly faster than that of light cough. And the peak value of $\Delta R/R_0$ for severe cough is higher than that of light cough, which shows that the sensor could well recognize different modes of cough through the signal of $\Delta R/R_0$.

The sensor is also used to detect the vibration of the vocal cords during vocalization. The sensor with a breathing mask is used to detect changes in respiratory airflow as shown in Fig. 6(b). $\Delta R/R_0$ could reflect each exhalation and inhalation in time.

In order to evaluate the bending recognition of the tip of the finger by the sensor more accurately, the $\Delta R/R_0$ value of the sensor under different bending angles (30°, 60°, 90°) is tested and the $\Delta R/R_0$ change in curve is shown in Fig. 6(c). The illustrations are actual pictures corresponding to different finger bending states. Through curve analysis, $\Delta R/R_0$ value of the sensor is found to increase with the increase in bending angle of the finger. When the finger is bent 90°, it

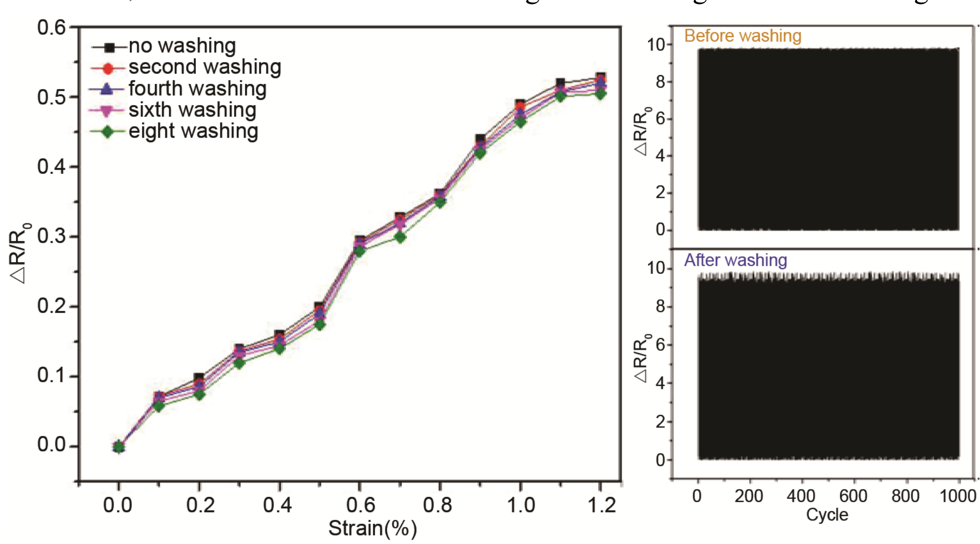

Fig. 5 — Changes before and after washing (a) resistance at different tension and (b) stability when stretched from 0% to 0.2% after 1000 times

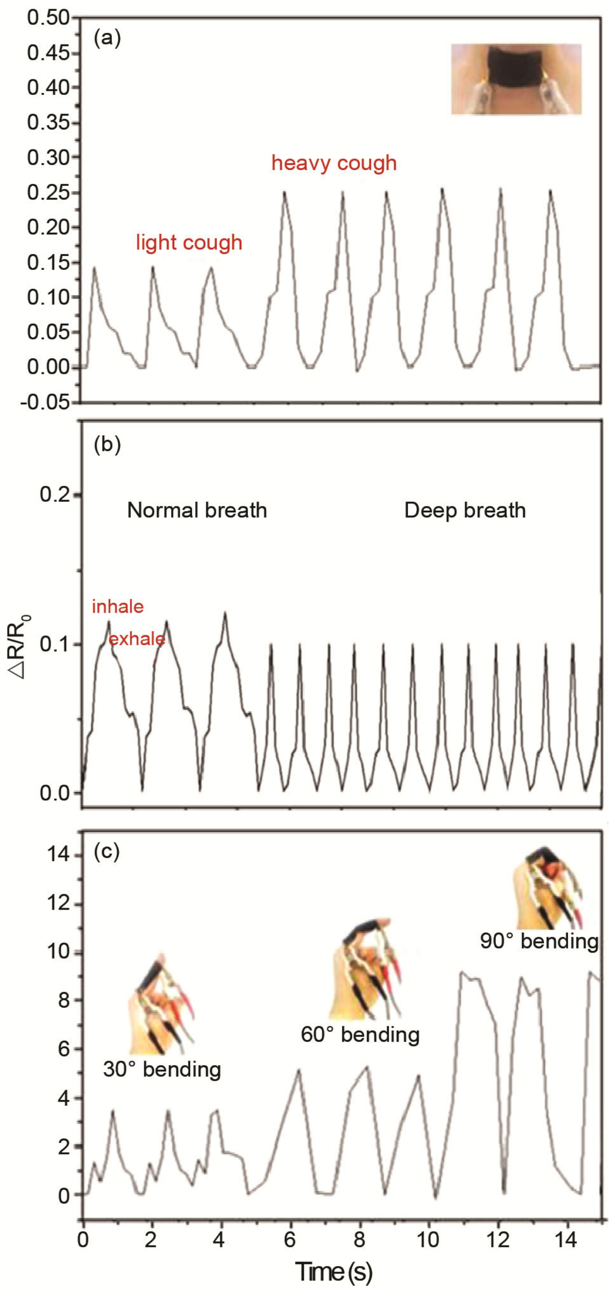

Fig. 6 — Response curves of fabric sensor at different positions (a) light cough and heavy cough, (b) normal breath and rapid breath and (c) bending finger and leg in different angles

attains the maximum value of about 9.1 and then the value is returned to the initial state bending 0° (or 180°). It indicates that the sensor could accurately detect the bending angle of different fingers and has extremely low hysteresis. When the human body is moved back to the initial state, the current is also returned to the initial state, confirming the sensing ability of the sensor when wearing on the human body.

4 Conclusion

In this work, the elastic knitted fabric is treated with conductive material (graphene and adhesive) to create the washable and wearable strain sensor. The result shows that the dense graphene layer is more evenly distributed on the surface of the fabric. The graphene coating and adhesive dipping gives the elastic fabric high sensitivity and better washing durability. The nylon/spandex double rib knitted fabric sensor shows excellent elasticity and conductive properties. The produced sensor could monitor the smaller external strain quickly and sensitively, which is suitable for human movement and stretching recovery. Through the human body test, the sensor could also distinguish the direction of human movement. It will have application potential in the field of wearable textile.

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