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High sensitivity knitted fabric strain sensors

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Abstract

Wearable sensors are increasingly used in smart garments for detecting and transferring vital signals and body posture, movement and respiration. Existing fabric strain sensors made from metallized yarns have low sensitivity, poor comfort and low durability to washing. Here we report a knitted fabric strain sensor made from a cotton/stainless steel (SS) fibre blended yarn which shows much higher sensitivity than sensors knitted from metallized yarns. The fabric feels softer than pure cotton textiles owing to the ultrafine stainless steel fibres and does not lose its electrical property after washing. The reason for the high sensitivity of the cotton/SS knitted fabric sensor was explored by comparing its sensing mechanism with the knitted fabric sensor made from metallized yarns. The results show that the cotton/SS yarn-to-yarn contact resistance is highly sensitive to strain applied to hooked yarn loops.

Keywords: knitted fabric, strain sensor, contact resistance, high sensitivity

(Some figures may appear in colour only in the online journal)

1. Introduction

Electronic textiles, also known as smart textiles, are innovative and high-knowledge-content fabrics integrating sensing, actuation, processing and power functions into a single garment [1, 2]. Wearable sensors integrated in the fabrics detect and transfer physiological signals of human body, such as temperature and moisture change in body microenvironment, posture and body movements, heartbeat, breath and respiration. Many flexible electro-active strain sensors have been investigated in recent years to detect human body movements and to perform posture classification. Early fabric strain sensors, which typically include coating a conductive material on a fabric to form a sensing patch [3, 4], are obtrusive sensing devices that do not look and feel like everyday textile fabrics. The sensing mechanism of these coated or printed strain sensors is based on piezo-resistive effect, where the conductive paths are changed due to interaction within the yarn as well as fabric deformation during the loading and unloading processes [5]. With the emergence of metallized fibres produced from conventional fibres coated with metal particles, true fabric strain sensors are produced using spinning [6], weaving [7] and knitting techniques [8–10]. These fabric sensors are far better in comfort and flexibility than the early fabric sensors. In comparison with conventional textile fabrics, however, the knitted fabric strain sensors made from metallized yarns still show a rough handle (poor skin contact comfort) due to the abrasive nature of the metal particles on the fibre surface and their electrical conductivity decays after repeated washing and wearing cycles because of falling off of metal particles [11]. In order to rid of these poor qualities, a new approach to manufacture knitted sensor is needed.

Knitted fabrics can be stretched by 30% or more of its length easily. The tensile deformation of knitted fabric is mainly made by the change of the knit loop shape. The extensibility of the yarn itself usually contributes very little to the fabric stretch. So when a knitted fabric strain sensor is stretched, the knit loop segments (head loop, leg and sinker loop) change their relative lengths, causing the resistivity of the fabric to change [9]. The sensitivity of strain sensors is commonly assessed by gauge factor (GF)

$$GF = \frac{\Delta R/R}{\varepsilon} \quad (1)$$

Where ε is the strain applied to the fabric and $\Delta R/R$ is the corresponding fractional change of fabric resistance. According to a review by Zhang [12], the GF range of most knitted strain sensors is between 0.42 and 5. For example, Lycra knitted fabric sensors coated with carbon-loaded rubber [13] has gauge factors of 0.42 within 50% strain in the length direction of the fabric and about 3.0 within strain of 20% in the fabric width direction.

In this paper, we will report a highly sensitive knitted fabric strain sensor consisting of a mixture of commodity cotton fibre and fine stainless steel (SS) short fibres. The fabric sensor looks and feels just like a conventional cotton fabric and is potentially robust for washing and wearing without losing electrical conductance because, unlike metal particles coated on metallized fibres, the SS fibres do not lose electrical conductivity and mechanical integrity when subjected to washing and wearing. The reason for the high sensitivity of the cotton/SS knitted fabric sensor was explored by comparing its sensing mechanism with knitted sensor made from metallized yarns. A novel technique for measuring the yarn-to-yarn contact resistance is also described.

2. Experimental

2.1. Materials

Cotton/SS blend yarns were produced from short stainless steel (SS) fibres and cotton fibres. The SS fibres have near circular cross-sections with an average diameter 8 μm (linear density 0.41 mg m^{-1}, or 0.41 tex), average length 50 mm and resistivity 7.84 × 10−7 Ω·m. The cotton fibres have kidney-shaped cross-sections with average linear density 0.17 tex and average length 32.7 mm. The electrical resistance of the cotton fibres is beyond the upper limit of our testing equipment (50 MΩ) and is thus treated as insulating material for the purpose of this study.

The production procedure of the knitted fabric strain sensor is shown schematically in figure 1(a). To produce a conductive yarn from a mixture (known as a blend in the textile industry) of cotton and SS fibres, the as-received cotton slivers and stainless steel slivers in a 50/50 weight ratio were fed into a drawing machine which is commonly used in the cotton textile industry. The initial blended sliver was folded and drawn repeatedly on the drawing machine to achieve thorough fibre mixing. The blended sliver was then spun into a 50 tex cotton/SS blended yarn on a ring spinning machine (tex is linear density of the yarn in g/km). The longitudinal and cross-sectional images of the yarn are shown as inset in figure 1(a). Although the weight ratio is 50/50, the number of SS fibres in the yarn cross-section is much smaller than the number of cotton fibres because of the huge difference in volume densities between cotton and SS fibres (8 g cm^{-3} for SS fibre, 1.5 g cm^{-3} for cotton fibre). Average electrical resistance per unit length of this blended yarn is 5 Ω/cm. The nature of electrical percolation in cotton/SS blended yarns has been studied and reported previously [14]. The cotton/SS blend yarn and a 50 tex pure cotton yarn were knitted into the conductive area and the non-conductive area of the fabric using a SHIMA SEIKA SES-SWG knitting machine. The course density and wale density of fabric sample are 67 wales/100 mm and 79 courses/100 mm, respectively, with a conductive area of 20 mm × 20 mm measured under tension on the machine.

The control conductive yarn is a commercial 110dtex/40 f metallized polyamide (nylon) multifilament yarn with electrical resistance 5 Ω/cm, shown in figure 1(b). The metallized nylon filaments are surface-coated with silver particles. In application, the knitted conductive patch can be placed strategically in a garment (figure 1(c)) to measure body movement and posture (figure 1(d)).

2.2. Methods

2.2.1. Resistance-strain test of knitted sensor. Figures 2(a) and (b) are enlarged optical images of the cotton/SS yarn knitted fabric sensor and the control metallized nylon yarn knitted fabric sensor. Two edges of knitted fabric samples in course direction were held by the clamps of Instron 5500R tensile testing machine. Fabrics was extended at a speed of 10 mm min^{-1}. The fabric sample was then tested in the wale-wise direction. The electrical resistance of the sample was measured during the tensile testing using a digital multi-meter DIGITECH QM1571. The clamp faces were insulated to prevent conduction between the fabric sample and the tensile testing machine.

2.2.2. Yarn-to-yarn contact resistance measurement. To measure the contact resistance between two interhooked conductive yarns AOB and COD, two clamps on Instron tensile testing machine are arranged perpendicular to each other, as shown schematically in figure 2(c) and photographically in figures 2(d) and (e). The two yarn specimens were connected to multimeters at positions A, B, C and D. Resistance readings are taken at each jaw position. Figure 2(f) shows the equivalent circuit of the setup, in which R_C is the contact resistance between the two interhooked yarns, R_{AO} is the resistance of the yarn segment AO, and R_{BO} is the resistance of the yarn segment BO, and so on. The resistance between A and B (R_{AOB}, resistance of top yarn AOB), the resistance between A and D (R_{AOD}), the resistance between B and C (R_{BOC}) and the resistance between C and D (R_{COD}) are measured simultaneous as load is applied to the pair of yarns by a tensile testing machine. From figure 2(f),

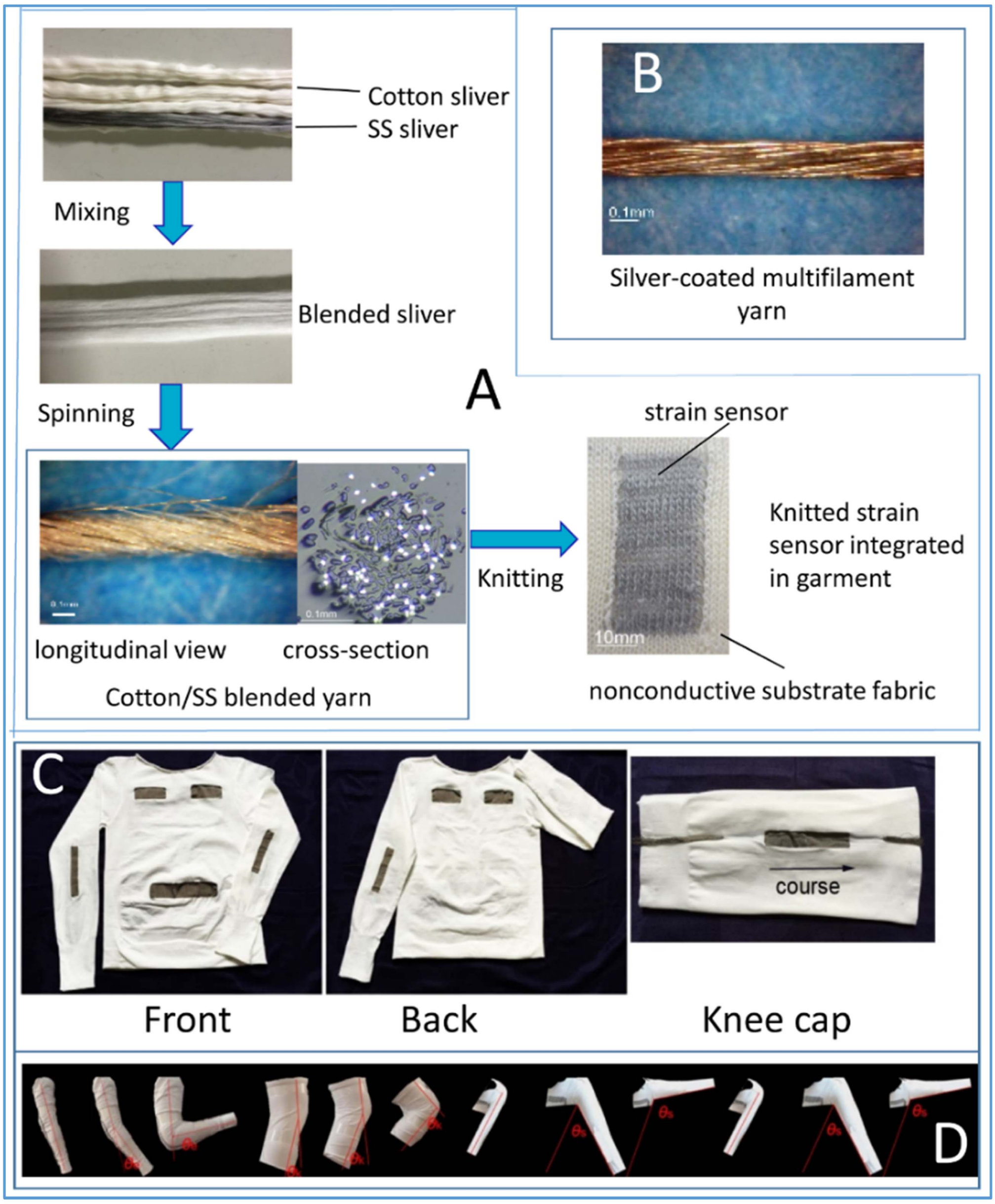

Figure 1. Knitted fabric strain sensor. (a) Manufacturing knitted fabric strain sensor from short stainless steel fibers and cotton. (b) Commercial metalized nylon multifilament yarn. (c) Strain sensors integrated in fully fashioned garments. (d) Knitted fabric strain sensors used to monitor body movement and posture.

we have

$$\begin{cases} R_{\mathrm{AOD}} = R_{\mathrm{AO}} + R_{\mathrm{C}} + R_{\mathrm{OD}} \\ R_{\mathrm{AOB}} = R_{\mathrm{AO}} + R_{\mathrm{OB}} \\ R_{\mathrm{BOC}} = R_{\mathrm{BO}} + R_{\mathrm{C}} + R_{\mathrm{OC}} \\ R_{\mathrm{COD}} = R_{\mathrm{CO}} + R_{\mathrm{OD}} \end{cases}$$

We can therefore calculate the yarn-to-yarn contact resistance using equation (2):

$$R_{\mathrm{C}} = (R_{\mathrm{AOD}} + R_{\mathrm{BOC}} - R_{\mathrm{AOB}} - R_{\mathrm{COD}})/2 \qquad (2)$$

Generally speaking, contact resistance between conductive materials is inversely proportional to their contact force and contact area [15]. By changing the distance between A and B on the upper clamp and simultaneously changing distance between C and D on the lower clamp, we can adjust the wrap angle ($180° - \theta$) between the two interhooked yarns, as shown in figure 2(g), where two angles θ (90° and 53°) were investigated.

3. Results and discussion

3.1. Resistance-strain test of knitted sensor

The resistance-strain curves of the knitted fabric sensors along with *GF*s are shown in figures 4(a)–(d). The *GF*s given in the figure were calculated using equation (1). In weft knitted fabrics, each course is formed by one yarn while different

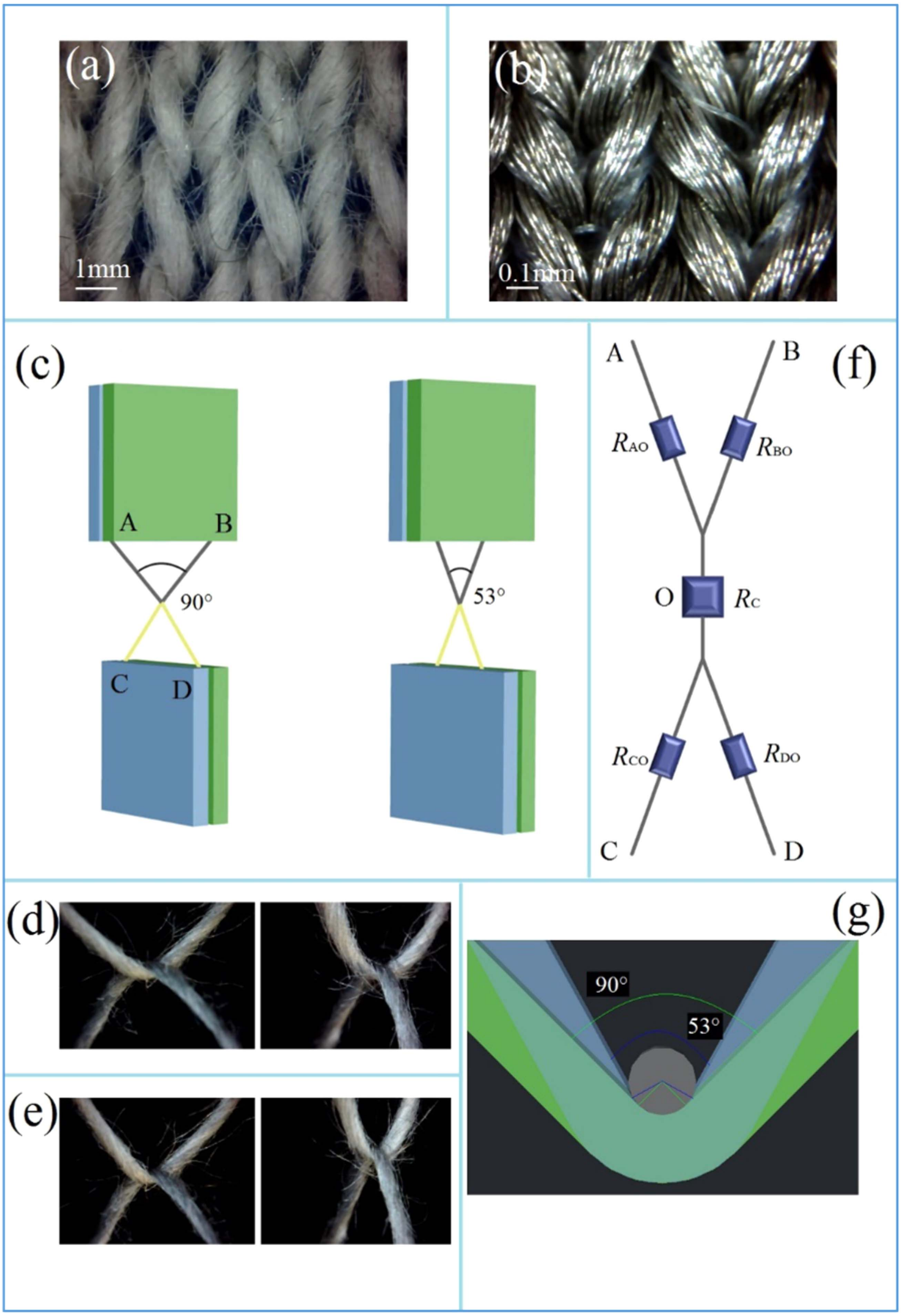

Figure 2. Measurement of yarn-to-yarn contact resistance. (a) Optical image of cotton/SS fabric; (b) Optical image of the control metallized nylon fabric; (c) Schematics of two interhooked yarns held by perpendicular clamps; Optical image of two interhooked yarns before applying tension (d) and under tension (e); (f) Circuit diagram of the yarn-to-yarn contact resistance measurement scheme; (g) Angle of wrap between the two yarns (180-θ).

yarns are interlocked along the wale direction, as illustrated in figure 3.

The metallized nylon fabric sensor behaves like most resistance-type strain sensors (positive piezo-resistive effect), i.e., its resistance increases as the fabric is extended in both directions (figures 4(b) and (d)), which gives a positive *GF*. The cotton/SS fabric sensor, by contrast, shows a negative piezo-resistive effect, i.e., its resistance decreases with fabric stretching in either course direction or wale direction (figures 4(a) and (c)), which leads to a negative *GF*. The metallized nylon fabric sensor shows approximately linear strain-resistance relationships in both course and wale

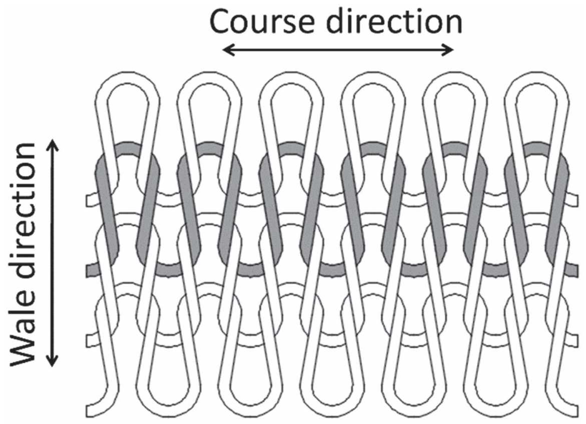

Figure 3. Yarn path in weft knitted fabric.

directions, whilst the cotton/SS sensor shows a very high wale-wise resistance and a somewhat lower course-wise resistance. The cotton/SS sensor provides very large absolute *GF*s (3.7 course-wise, 20 wale-wise) in the 0%–5% strain range, which are 10–400 times higher than the control metallized nylon fabric sensor in the corresponding directions. Even in high strain range of 10%–40%, the cotton/SS sensor shows 30 times greater *GF* than the metallized nylon sensor in the wale direction and three times greater *GF* in the course direction.

3.2. Yarn-to-yarn contact resistance measurement

As mentioned earlier, one-way stretch of knitted fabrics is dominated by geometrical change of the knit loops rather than the elongation of the constituent yarns. If yarn-to-yarn contact resistance is very small, the change of fabric resistance in response to strain is then dominated by yarn transferring among loops, i.e., change of the yarn segment lengths in the knit loop (head loop, leg and sinker loop) [9]. At the other extreme, if the yarn-to-yarn contact resistance is large, the knitted fabric resistance in the wale direction will be very large (i.e., almost non-conductive along each wale in figure 3) and the course-wise fabric resistance will be simply the combined resistance of parallel yarns (1/n of single yarn resistance, where n is the number of courses in the conductive patch).

The measured contact resistances for the two types of yarns at different jaw positions are presented in figures 5(a) and (b). The cotton/SS yarn showed more than two orders of magnitude higher contact resistance than the silver-coated nylon yarn. The reason for the very low yarn-to-yarn contact resistance of metallized nylon yarn is that the two yarns establish their electrical connection through direct metal-to-metal contact between numerous silver particles on the surface coatings. On the other hand, the electrical conduction between two cotton/SS fibre blend yarns is due to the contact between SS fibres randomly presenting on the opposing

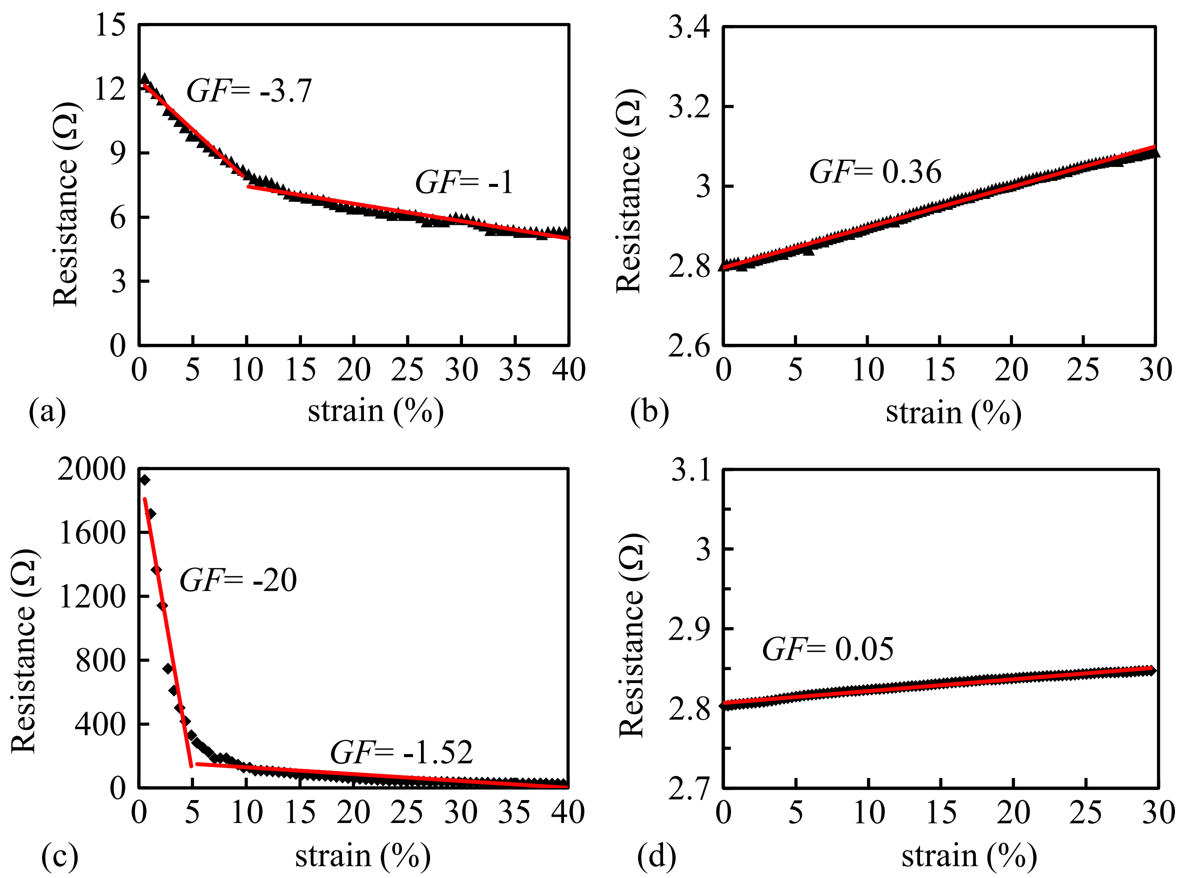

Figure 4. Resistance-course-wise extension curves of cotton/SS fabric (a) and of control metallized nylon fabric (b); Resistance—wale-wise extension curves of cotton/SS fabric (c) and of control metallized nylon fabric (d).

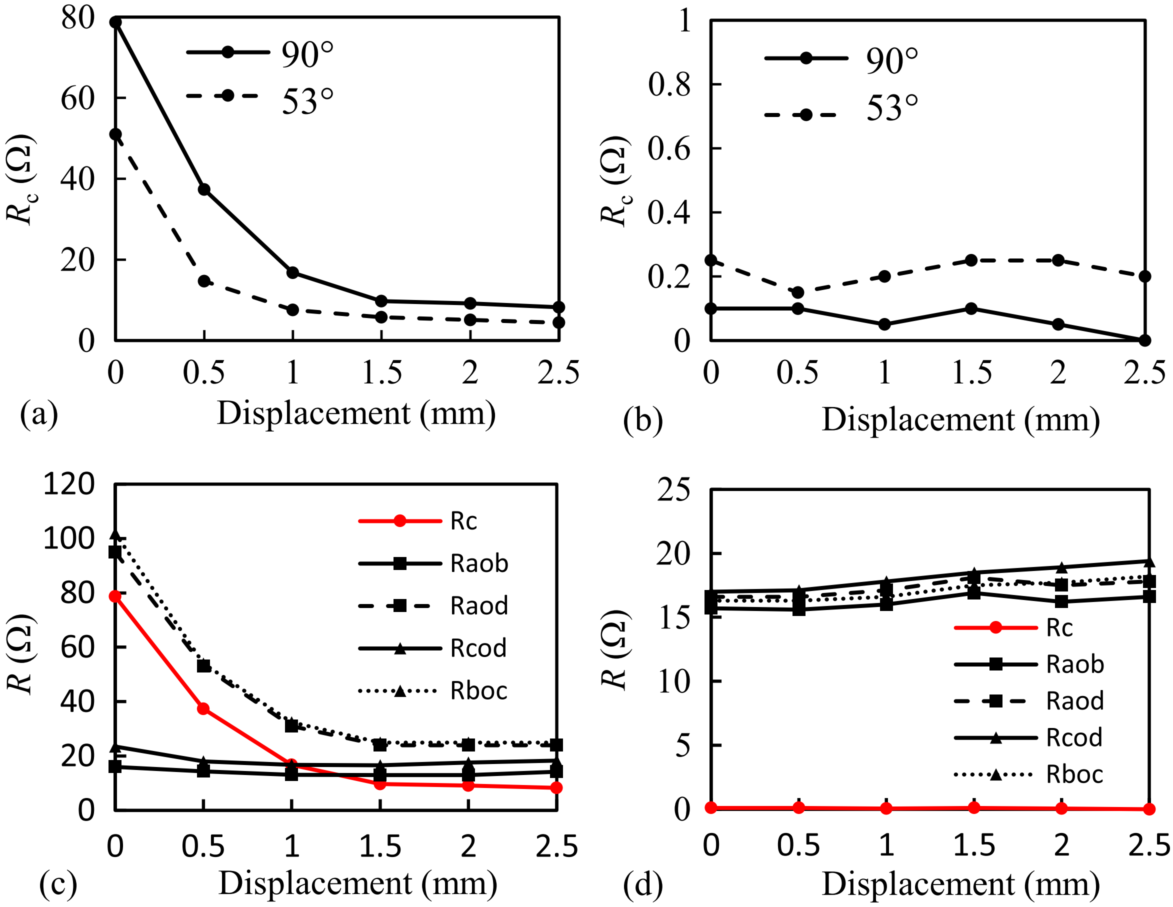

Figure 5. Results of yarn-to-yarn contact resistance measurement. (a)&(b) Yarn-to-yarn contact resistance results of cotton/SS blended yarn (a) and metallized nylon yarn (b) at two angles; (c)&(d) Measured yarn resistances (90° angle) for cotton/SS blended yarn (c) and metallized nylon yarn (d).

surfaces of the two yarns, where a combined percolation network is formed.

Before starting the test, the two contacting yarns were given a very small pre-tension (practically zero tension) so that the surface fibres in the two yarns could just touch each other. With the increase of tension, both contact force and contact area between the two yarns increase. This brings more and more SS fibres on the opposing surfaces of the two yarns into electrical connect, which leads to the significant downward trend of contact resistance in figure 5(a). As the contact force increases further, the void content in the yarns at the contact point reaches its minimum and the yarn compaction reaches its upper limit so that the contact resistance approaches a stable low value. Figure 5(a) also shows the influence of the yarn wrap angle on the yarn-to-yarn contact resistance. At a greater wrap angle $180-\theta$ ($\theta = 53°$), the contact area between the two yarns is larger, so the yarn-to-yarn contact resistance is lower. In comparison, metal-to-metal conduction between the silver-coated nylon yarns is very high and the contact resistance is not significantly affected by the pressure between the yarns, as shown in figure 5(b). The Digital multimeter used in this experiment has an error range $\pm 3.2\,\Omega$ according to the instrument manufacturer. This instrument error is small as a percentage of the yarn segment resistances for the cotton/SS yarn (figure 5(c)) and therefore the yarn-to-yarn resistance calculated using equation (2) is accurate. However, the instrument error is quite large as a percentage of the yarn segment resistances for the silver-coated yarn (figure 5(d)). The subsequently calculated yarn-to-yarn contact resistance from equation (2) (less than 0.3 Ω) was much smaller than the instrument error (3.2 Ω). So the values for R_c in figure 5(b) would mainly reflect instrument errors, rather than a trend according to displacement.

We can now explain why knitted sensor made from the cotton/SS blend yarn has a much higher sensitivity (*GF*) than that made from the silver-coated nylon yarn. Stretch of knitted fabric is realized mainly through the change of knit loop configuration rather than yarn elongation. So for easy explanation, we can ignore the influence of yarn resistance changes due to its elongation. In the metallized nylon fabric, the yarn-to-yarn contact resistance is very small so the fabric resistance change during stretching is mainly caused by the change of knit loop configuration [9], which gives a low *GF* (0.05–0.36). In the case of cotton/SS blend fabric, the fabric resistance in the wale direction is dominated by the change of yarn-to-yarn contact resistance while the change of knit loop configuration plays a relatively small part, although in the same way as in the case of metallized nylon fabric. The large yarn-to-yarn contact resistance and its high dependence on contact force result in a high wale-wise fabric resistance and very high sensitivity

($GF = -20$). On the other hand, the course-wise resistance in the cotton/SS fabrics is mainly affected by the yarn resistance due to the change of loop configuration (refer to figure 3) and to a smaller extent affected by the yarn-to-yarn contact resistance, resulting in a considerably lower GF value (-3.7) than that in the wale direction.

4. Conclusion

We have reported a knitted fabric strain sensor with far higher sensitivity than other knitted fabric strain sensors. The knitted fabric is made from a cotton/stainless steel fibre blended yarn, which looks and feels just like a conventional cotton fabric and is robust for washing and wearing without losing electrical conductance. In addition, we devised a novel method to measure the yarn-to-yarn contact resistance while the yarn strain is varied on a tensile testing machine. It is found that the high sensitivity of the cotton/SS knitted fabric sensor is mainly caused by the yarn-to-yarn contact resistance which changes dramatically with the tension applied to the yarns when the fabric is stretched.

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