A SINGLE-ELECTRODE WEARABLE TRIBOELECTRIC NANOGENERATOR BASED ON CONDUCTIVE & STRETCHABLE FABRIC

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ABSTRACT

This paper reports a wearable triboelectric nanogenerator (TENG) based on the conductive and stretchable composite fabric, which is cost-effective and can be easily mass produced. Multi-wall carbon nanotubes (MWCNT) are directly composited with the cotton knitting fabric through dipping and drying method. The sheet resistance reduces to 505 Ω/sq after 10 cycles. Using this single knitting fabric electrode, the peak output power density of the TENG achieves ~12 μW/cm2.

INTRODUCTION

Fabric has been used as clothes material for thousands of years because of its outstanding softness, flexibility, breathability and thermal insulation [1]. Fabric-based wearable electronics with various functions, such as transistors [2], conductive films [3], sensors [4] as well as power generators [5-7], show potential promises in the field of wearable electronics. Furthermore, fiber and fabric provide an apt substrate to build some large-scaled electronic network and system [8].

With the principle, structure and fabrication process development, the performance of TENG has been improved remarkably [1, 9-15]. The previous work on the principle of TENG which analyzes the correlative factors detailedly makes it possible to design the structure of TENG with better performance [9]. The utilization of micro structure [11], nanowire arrays [12] and plasma treatment [13] enhance the accumulation of charges on the friction surface, which is critical to improve the output of TENG. In addition, the structure improvement [15] also contribute to the rise of energy harvesting efficiency and the extension of the application range.

The principle and fabrication progress of general TENG also have a considerable impact on various fiber and fabric based wearable TENG. Several fiber-based TENGs have been developed through different processes and many applications have been achieved. For example, conductive fiber is woven into a commercial fabric as a TENG [5], and the average output power density is 0.1 $\mu W/cm^2$. This TENG is used as "power shirt" to trigger the wireless body temperature sensor system. Cotton fabric was coated with carbon nanotubes which make it conductive but not stretchable [3], it is applied as electrodes of the capacitor. In our work, the stretchable cotton knitting fabric are coated with MWCNT and then utilized to make a TENG. The combination of the advantages of knitting fabric and WMCNTs not only makes this TENG stretchable, but also enhance the performance significantly.

CONCEPT AND PRINCIPLE

The structure of wearable TENG with 3 functional layers in total is shown in Fig. 1. The stretchable conductive fabric layer is fixed on the surface of the substrate Dielectric 1 corresponding to the blue coat shown in Fig. 1b specifically. The conductive fabric connecting with the external equipment, such as mobile phones and portable health monitors, is not only as the electrode but as the friction surface. The Dielectric 2 is placed as another friction surface to form a friction pair with conductive fabric. When this wearable TENG works, the Dielectric 2 contacts with the conductive fabric. Due to the different position in the triboelectric series, the electron will be transferred from the conductive fabric to the Dielectric 2, which has a better ability to attract electrons. Therefore, the Dielectric 2 and conductive fabric are charged with opposite charges and an electrical field are built between them. With the separation of Dielectric 2 and the conductive fabric, the electrical filed will decay and the positive charges on the conductive fabric decrease. The excessive positive charges will flow into the ground through the load equipment which will form the current and drive the equipment. Then with the approaching of Dielectric 2 to the conductive electrode, the reverse process occurred. The electrical field is rebuilt and the positive charge are attracted back to the conductive fabric and the reverse current are formed in the load equipment. Specifically, as is shown in Fig. 1b, with the movement of people, the contact and separation of the MWCNT based conductive fabric and the white T-shirt will cause opposite charges on the friction surface, as well as the current in the load equipment. Through this way, the kinetic energy of human movement is transferred into electrical energy which can conveniently provide power supply to the portable electronics.

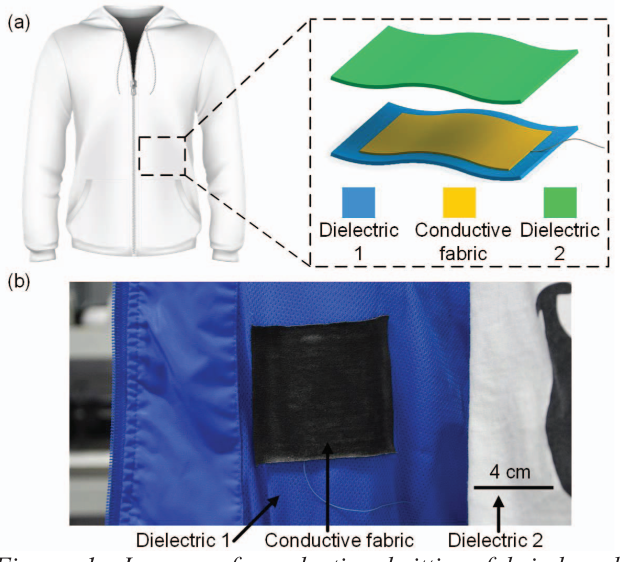

Figure 1: Images of conductive knitting fabric-based single electrode TENG. (a) Detail Structure of this TENG. (b) Photograph of TENG on a coat.

FABRICATION

To form a wearable single electrode TENG, a cotton knitting fabric based electrode is fabricated due to its remarkable flexibility, stretchability, breathability and thermal insulation. [1] In addition, MWCNT is elected to compound with the stretchable cotton fabric because of the excellent conductivity and the nature of strong chemical attachment with the cotton fiber. [3]

1 mg/ml MWCNT are dispersed in the deionized water containing 10 mg/ml surfactants sodium dodecylbenzene sulfonate (NaDDBS). The commercial stretchable cotton knitting fabric are cleaned with ethanol and deionized water. After drying, the fabric is dipped into the MWCNT solution and sonicated for 5 min. Then, dry the fabric on the hot plate at 100 °C for 15 min. Repeat the process 10 times, as is shown in Fig. 2. Then the conductive fabric is ready. With this conductive fabric, the triboelectric generator can be fabricated as Fig. 1b. The conductive fabric is stitched on the clothes as electrode. When the generator works, the friction occurred between the conductive fabric and the dielectric 2 to form a single electrode TENG.

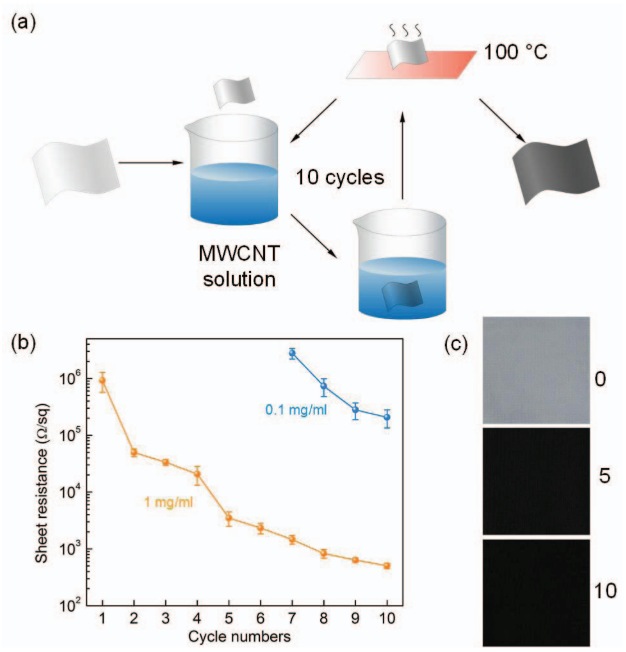

Figure 2: Fabrication of conductive knitting fabric. (a) Schematic diagram of the fabricating process. (b) Change of sheet resistance with dipping cycle increasing in the 1 mg/ml MWCNT solutions and 0.1 mg/ml solutions. (c) With the increasing cycle number, the color of knitting fabric is deepened.

RESULT AND DISCUSSION

Fig. 2b and c present the reduction of sheet resistance and the deepened color when the fabric is dipped more times. The sheet resistance decreases with the increasing times of repetition, typically, 3.50 kΩ/sq after 5 cycles and 505 Ω/sq after 10 cycles. As a comparison, the MWCNT solution of 0.1mg/ml is used to dip the fabric. The conductivity also falls when dipped more, however the conductivity is always much higher than the fabric dipped in the 1mg/ml solution with the same cycles, which implies that the concentration of MWCNT in the solution affects the deposit amount on cotton fiber intensely.

SEM images shown in Fig. 3a and b prove that MWCNTs are densely coated on the surface of fibers and form the conductive network. Especially, in Fig. 3b, MWCNTs is adhering on the surface of cotton fiber obviously to provide the sinuous and continuous conductive path. This conductive fabric shows predominant stretchability to ~20% presented in Fig. 3c and d. After stretching and releasing, the sheet resistance can be kept at ~1 kΩ/sq. Furthermore, this conductive fabric shows good durability that the sheet resistance of the fabric keeps ~2 kΩ/sq after rinsing in deionized water and sonicated for 10 min.

The power generation performance of a 9 cm^2 TENG are presented at Fig. 4. The test is applied with a vibration system which can provide vibration of 10 Hz. With the increase of the load resistance, the maximum voltage rises to over 200 V and the current falls as is shown in Fig. 3a, which is well consistent with the previous theoretical analysis [4]. The output voltage and current changes swiftly when the load resistance is relatively low and changes slowly with a high load resistance over 100 MΩ.

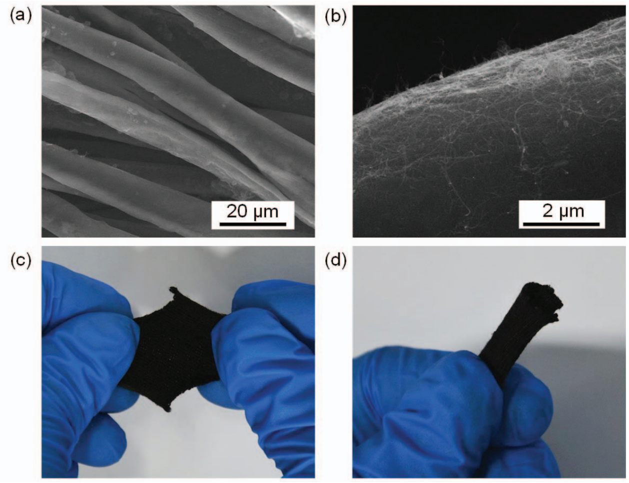

Figure 3: Images of conductive knitting fabric. (a)(b) SEM of WMCNT coated cotton fibber. (c) stretch and (d) roll of conductive knitting fabric.

With the best matched load resistance of 400 MΩ, the peak output power density reaches to ~12 μW/cm^2 (average output power density is 1.23 μW/cm^2) and the transferred charge density is 1.79 nC/cm^2, which are much better than the references [2,5] in Table 1. The remarkable output shows an opportunity to drive the portable electronics directly without any battery or energy storage device. In addition, the high best matched load suggested that the electricity consumer should have high input resistance to increase the efficiency.

Due to the high output, commercial blue LED can be lighted directly by this wearable TENG and it is demonstrated in Fig 3c to e. The LED which is powered by the 9 cm^2 single electrode wearable TENG shows high luminance and the light is visible both in the bright and dark environment.

Table 1. Comparison of various fabric based TENG.

Reference	*Average power density ($\mu W/cm^2$)*	*Peak power density ($\mu W/cm^2$)*	*Short-circuit current ($\mu A/cm^2$)*	*Transferred charge density (nC/cm^2)*
[5]	*~0.1*	*~0.91*	-	-
[6]	-	-	*~0.1*	*0.96*
This work	*1.23*	*12*	*0.143*	*1.79*

-: Not mentioned.

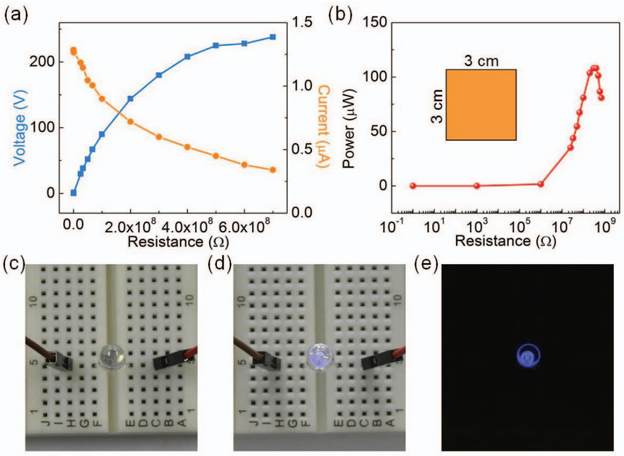

Figure 4: Power generation performance of a 9 cm² wearable triboelectric nanogenerator. Teflon film is selected as the dielectric 2 and friction frequency is 10 Hz. (a) The peak voltage and current output with different load resistance. (b) The power output changes with the increasing load resistance. (c) The commercial LED can be directly lighted and visible in both (d) bright and (e) dark environment.

Fig. 5 shows the various external conditions affect this generator. Different friction pair will lead to different output power. In comparison, Teflon presents best performance when it rubs with conductive fabric because of its outstanding ability to catch electrons. Considering the application of the wearable TENG, nylon fabric and linen are tested because that they are broad used as clothes. In further tests, Nylon fabric performs better than linen as is show in Fig. 5a.

When vibration frequency rises from 3 Hz to 11 Hz, the output current becomes larger. The movement of people is usually in the low frequency range [10], therefore the test of this wearable TENG is applied only in low frequency. The output current increases quicker in the range of 3 Hz to 7 Hz and the current also rise from 7 Hz to 11 Hz but slower.

Finally, this single electrode wearable generator is used to charge a 1 μF capacitor to test the ability of power output. The vibration of 10 Hz is applied on the wearable TENG to get the alternating current output. Then, the output is connected with the full wave rectifying circuit (insert of Fig.5c) to convert the alternating current into direct current, which are more convenient for most of the portable electronics. After 7 min vibration and charging process by this wearable TENG, the voltage of the capacitor reaches ~40V.

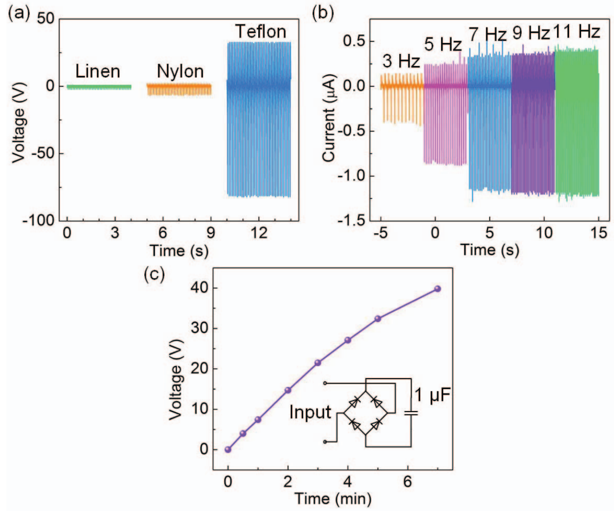

Figure 5: Performance of generator in various conditions. (a) Different voltage output when linen, nylon and Teflon are used as dielectric 2. Load resistance is 100 MΩ. (b) Frequency affected the current output of generator. (c) Voltage curve when a 1 μF capacitor are charged by the generator through a bridge rectifier circuit.

CONCLUSIONS

The development of wearable electronics presents precious opportunity for us to make our daily life more convenient. This wearable single electrode TENG provides a method to collect human movement energy effectively to power the wearable electronics. It can extend the service time and even make the wearable electronics battery-free, which will obviously expand its working area. Because of the good performance and the natural advantages of cotton knitting fabric, it is of great potential to use this wearable TENG in various area such as mobile phones, intelligent monitoring and diagnosis, wireless sensor network and electronic skin, etc.

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