STRETCHABLE THIN-FILM GENERATOR WITH DUAL WORKING MODES FOR BODY MOTION ENERGY HARVESTING

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ABSTRACT

This work reports a novel stretchable thin-film generator based on electrification for effectively harvesting body motion energy. It has two working modes, the folding mode and the contact-separation (C-S) mode, under the same circuit connection. Electrospinning PU nanofibers are employed to integrate electrodes, making it not only flexible but also highly stretchable up to 100%. Micro-patterned PDMS is employed to increase the contact area of the friction layer, which contributes a higher surface charge density. Due to its paired electrode structure design, the instantaneous peak power density of the two electrode device can be improved to 336.4 μW/cm^2. The film structure makes the device very convenient be attached onto cloth or skin as a wearable energy harvester or self-powered e-skin.

INTRODUCTION

In recent years, wearable electronic devices have experienced an explosive growth in the market and open up a new life pattern for consumers, since they can be integrated with clothes [1], eye glasses [2], wrist watches [3] and even skin sensors [4], playing an increasingly important role in enriching human life, health monitoring and entertainment. However, all of these electronics face a common technical issue, must be powered by rechargeable batteries, which greatly confines their sustainable operation and distribution range. Therefore, flexible and sustainable energy source that scavenges body motion energy are of urgent demand for solving this problem, which is one of the most ideally suitable solution for wearable electronics.

Triboelectric nanogenerator (TENG) is a promising alternative technology for it can sustainably transform mechanical vibration into considerable electric output and various materials can be adopted to fabricate a TENG with simple and relative low-cost technique [5]. To date, several kinds of wearable TENGs have been demonstrated for various applications, such as a kind of textile-based generator integrated with cloth for power generation from the friction of clothes [6,7], a woven-structured TENG based on common fabric to harvest body motion energy [8,9], and a fiber-based generator to detect human motion or harvest energy from human walking [10,11]. However, all of these TENGs must be mounted on cloth to realize their function, which blocks the way as electronic skins and the lack of stretch ability also reduces the comfort when integrate them with common cloth.

Herein, we developed a stretchable thin-film generator with two working modes to scavenge energy from human motions. Since the substrate of the device is biocompatible and stretchable, the new design can be directly attached on the surface of human skin as a power-generation electronic skin. As one of the key components of TENG, soft and stretchable electrode is crucial to develop a wearable TENG. To achieve this, electrospinning PU nanofibers are employed as template for absorbing conductive nanomaterials, which enables the electrode highly conductive even after stretching to 100%. The rough and soft surface of the electrode also contribute to increasing the friction area. In order to make the device have a high power generation efficiency and enrich its operation range, parallel electrode is adopted and one of which is coated with micro-patterned PDMS to enlarge the contact area. At first, the mechanical and conductive properties of the as fabricated nanofiber membrane are investigated to verify its utility as a stretchable electrode. Then, the device is tested under two working modes to analyze its electrical output performance. At last, we demonstrate the thin film TENG as a real energy harvester by mounted it on different parts of human body for harvesting versatile motion energy (*i.e.*, flapping of hands and movement of joints).

STRUCTURAL DESIGN

The overall 3D structure schematic and the cross section view of the device are diagramed in Figure 1a and 1b. Two pieces of conductive AgNWs/CNT/PU nanofibers are parallel embedded into flexible PDMS thin film as electrodes, which make the total structure very thin and flexible. One of the electrode is coated with micro-patterned PDMS as a friction layer while the other one is directly used as another friction layer. As all the materials chosen to fabricate the device are stretchable, the thin-film generator can be stretched along arbitrary directions, which could provide better accommodation to stretchable surface (e.g. human skin). The photo of fabricated device is shown in Figure 1c, which has a size of 35 mm × 35 mm.

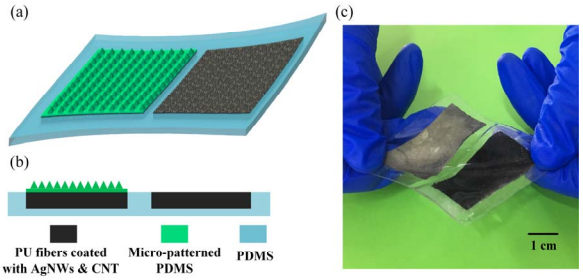

Figure 1: (a) Structure schematic of the stretchable thin-film TENG. (b) Cross section view of the device. (c) Optical image of the fabricated device.

FABRICATION PROCESS

The fabrication process of the stretchable thin-film generator is demonstrated in Figure 2, which begins with the preparation of stretchable electrode. As the conductive electrode is one of the key components in a TENG, it if crucial to develop a soft and stretchable conductor for wearable TENG. Firstly, the polyurethane non-woven porous membrane for doping with AgNWs/MWCNT was prepared by electrospinning from polyurethane dimethyl formamide/tetrahydrofuran (DMF/THF, 2:3) solution with the polymer concentration of 13%wt. Then the solution was fed up through a plastic syringe at a constant speed of 1ml/h. The nanofibers were formed under a high voltage of 8 kV and were collected at the distance of 7.5 cm. After that, the PU nanofiber membrane was immerged into the AgNW solution and then evaporated on a hot plate to remove the solvent and make the AgNWs firmly stick to the surface of the PU nanofibers. The AgNWs have a diameter of about 30 nm and length of 2~20 um. After repeating this procedure for several times the PU nanofibers was coated with AgNWs and become conductive. Because the metal Ag is easy to be oxidized in the air, then the MWCNTs with length of 10-30 um were further added to the PU fibers by the same method to enhance the conductivity and strength of the electrode.

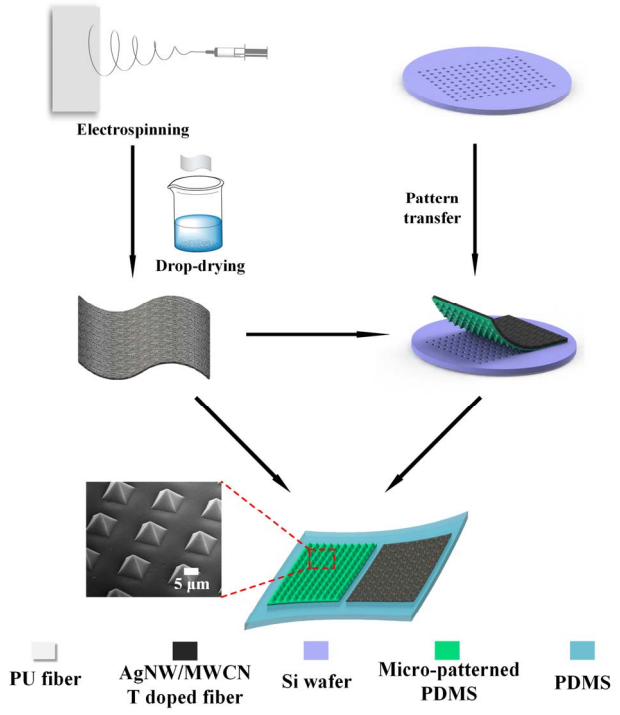

Figure 2: Fabrication process of stretchable TFG. The inset optical graph is the SEM image of the micro-patterned PDMS.

The micro-patterned PDMS was formed by duplicating the pattern on Si wafer. After the PDMS elastomer and cross-linker (Sylgard 184, Tow Corning) were thoroughly mixed in a 10:1 ratio (w/w) and degassed, it was spin-coated onto the Si wafer with inverted pyramid structure. When the PDMS was partially cured, one piece of electrode with a size of 1.5 cm× 3cm was coated on it and peeled off with PDMS together after it was cured at 80 □ for 30 minutes.

Finally, the micro-patterned PDMS coated PU fibers and another piece of PU fibers were assembled together through uncured PDMS and forming a thin film structure. The inset SEM image in Figure 2 was the micro-patterned structure of PDMS.

CHARACTERIZATION OF ELECTRODE

The nanofiber morphologies before and after coating AgNWs and MWCNTs were studied by scanning electron microscope (SEM) as shown in Figure 3. After electrospinning, the PU nanofibers form a porous non-woven structure thus the nano-materials solution can infiltrate into the membrane sufficiently. As shown in Fig 3b, the Ag nanowires coated along the surface of PU nanofibers, especially at the junctions, forming an interconnection conductive network. After dropping MWCNTs, PU nanofibers and AgNWs are fully packaged inside them, forming protection for the AgNWs. Besides, some holes are also filled by the CNT clusters and further enhancing the conductivity of the network.

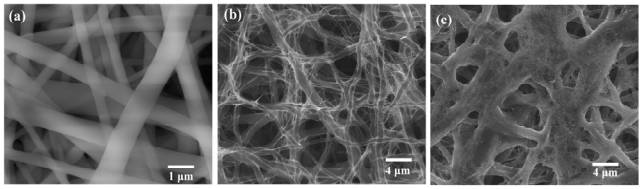

Figure 3: SEM images of the (a) PU nanofibers, (b) fibers coated with AgNWs, (c)fibers coated with AgNWs & CNT.

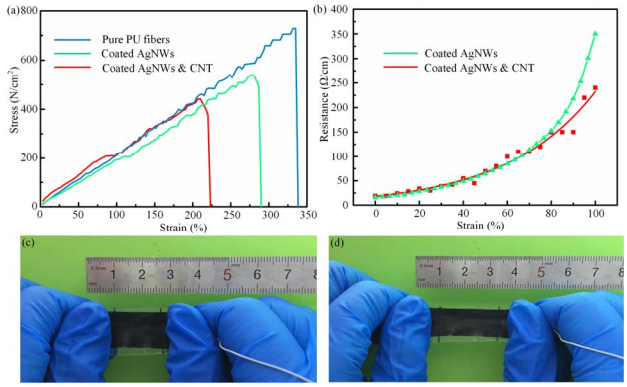

Figure 4: (a) The strain stress curves of the PU fibers at different fabrication processes. (b) The resistance changes of the PU fibers coated with and without CNTs. The inset is the photographs of the conductive fibers packaged with PDMS in the origin state and stretched to 33% state.

To investigate the tensile strain capacity of the electrode after each process, a stress strain gauge with precise length control was used to apply tensile stress. As can be seen in Figure 4a, after addition of nano materials or packaging, the stretch ability of the electrode weakens a lot. For the pure PU nanofiber membrane, it can be stretched to 330% of its original length, while the value decreases to 225% after coating with AgNWs/MWCNTs, which may be induced by the stronger mechanical strength of AgNWs and MWCNTs. Furthermore, we investigate the conductivity of the electrode under various tensile strains.

The resistance increases slowly within the deformation of 70% while show a sharp increase under further elongation. It should be noted that the addition of MWCNTs can effectively decrease the resistance more than 100 Ω/cm under large deformations. Figure 4c illustrates the images of the electrode under tensile strain of 0% and 33%.

WORKING PRINCIPLE

The soft and thin-film structure of the TENG enables the device to be bent, folded, stretched and attached to curved surface arbitrarily, and thus providing versatile operation modes. The structure of the thin-film generator under folding mode is diagramed in Figure 5a, where the film is folded along the central line and brought the two electrodes into contact. As one of the electrode is coated with micro-patterned PDMS, the difference of attracting electron abilities between PDMS and CNT will generate charges with opposite polarities on the surfaces of two friction layers. Once the device is unfolded, the triboelectrification charges remained on the friction surfaces will drive electrons flow between the two electrodes via external load.

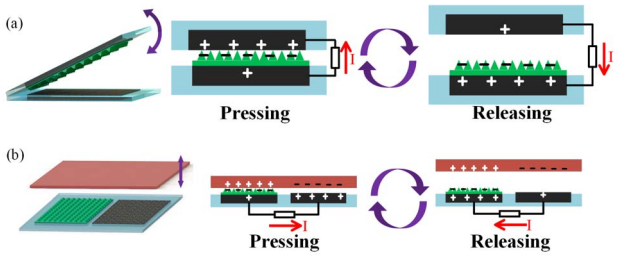

Figure 5: Working mechanism of the thin-film generator under (a) folding mode and (b) contact-separation (C-S) mode.

Additionally, the device can also generate electric output through contact with other materials since PDMS and CNT have a large gap in the triboelectric series and most common materials are listed between them. Similarly, the structure of the device under vertical contact-separation mode is shown in Figure 5b, where a third friction material (*e.g.*, skin, cloth and plastic) is employed to contact with the two electrodes simultaneously. As the electron affinity of the third friction material is between PDMS and CNT, charges with opposite polarity will also be generated on them. After the contact material is removed, the left friction charges will also drive electron flow between the two electrodes.

ELECTARICAL MEASUREMENT

To evaluate the electric generation ability of the device, output voltage was measured using a digital oscilloscope (Agilent DSO-X 2014A) via a 100 MΩ probe (HP9258), and the current was tested through a SR570 low noise current amplifier from Stanford Research systems under the folding mode. Under the trigger of vibrator at 5Hz with this mode, 670 V peak-to-peak voltage (Figure 6a) and 29.3 μA (Figure 6b) peak-to-peak current are obtained. To investigate the power generation dependence on the variation of external load, output current was measured as the resistance increase from 100 Ω to 200 MΩ. The calculated output instantaneous peak power achieves maximum of 3.875 mW at the load resistance of 180 MΩ as shown in Figure 6c. The electric output of the device can be stored in a capacitor after rectifying for providing energy to other electronic devices. For our TFG, a 1 μF capacitor can be quickly charged to 10 V in 100s (Figure 6d). Compared with previous reported wearable TENGs [6,8], the output performance of our device shows a great improvement, which is mainly benefit from the two electrode configuration and optimized material selection.

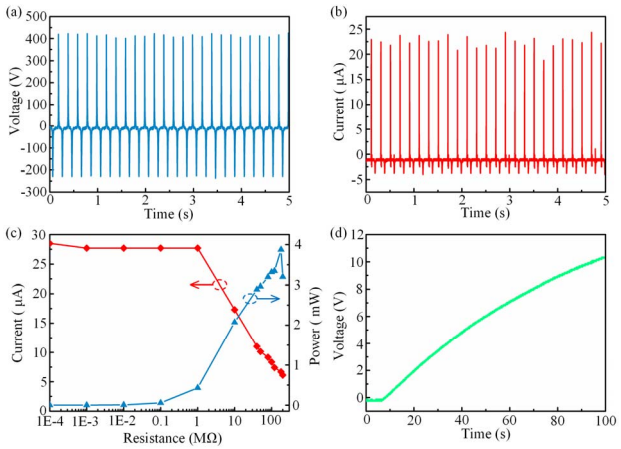

Figure 6: (a) output voltage and (b) current of the thin-film generator under folding mode. (d) the current and power outputs change with the increasing load resistance. (e) charging curve for a 1uF capacitance.

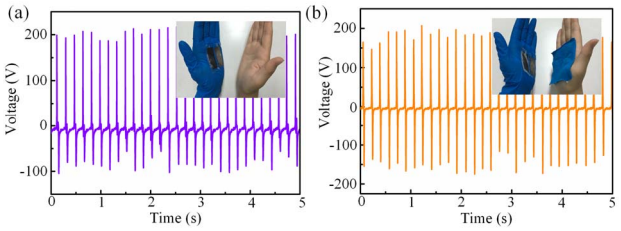

Figure 7: Measured output voltage of the generator under C-S mode when contact with skin (a) and cotton cloth (b) through flap.

The parallel electrode structure also enables the device to harvest energy when contact with other materials at the C-S mode. When the generator is mounted on hand and contact with common materials such as skin and cotton cloth through flap, which can generate output voltage of 342 V and 547 V, respectively (Figure 7).

APPLICATION

As for the application in real situations, the thin-film generator can not only be attached on the surface of cloth to harvest energy through the C-S mode but also can be conformally attached on the human skin to scavenge body motion energy through both modes. Additionally, thanks to the thin-film, parallel-electrode and stretchable structure design of the device, the generator can be conveniently mounted on any curved surfaces for harvesting mechanical energy or as an active sensor. In our demonstration, the device was attached on margin of cloth and joint of arm to harvest different body motion energies through the two

working modes. When people touch the cloth during walking or bend the elbow, the device can generate peak voltage of 26.1 V and 27.9 V at a relatively low frequency of about 2 Hz, respectively (Figure 8).

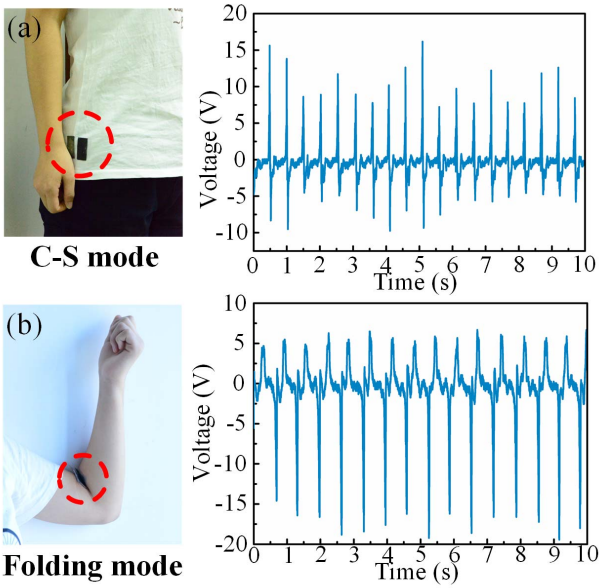

Figure 8: The optical images and corresponding output voltages when the thin-film generator was fixed at different positions of human body.

CONCLUSIONS

In summary, a novel stretchable thin-film TENG with two parallel electrodes for versatile energy harvesting is demonstrated in this work. The electrode combining the intrinsic PU nanofiber membrane and conductive nanomaterials ensures the stretchability and conductivity of the device, which makes the electrode have a resistance lower than 250 Ω/cm even after stretched to 100%. By utilizing paired electrode, an output voltage of 670 V and short-circuit current of 29.3 μA is achieved under trigger of vibrator, and a maximum instantaneous power density of 336.4 μW/cm^2 is observed with the folding working mode. When work at C-S mode, the contact with human skin and cotton cloth through hands flap can generate output voltage of 342 V and 547 V, respectively. Facilitated by its stretch ability and thin-film structure, the device can be conformally mounted on the cloth or human skin to effectively scavenge body motion energy, which paves the way for stretchable power-generation e-skins and wearable energy source.

ACKNOWLEDGEMENTS

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