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Wearable nanofiber-based triboelectric nanogenerator for body motion energy harvesting

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Abstract—Self-powered wearable devices are gaining increasing attention to fulfil the sensing and energy harvesting needs for the next-generation wearable systems and body sensor networks. Here, we developed a wearable, flexible and lightweight nanofiber-based triboelectric nanogenerator (NF-TENG) for body motion energy harvesting. Polyvinylidene difluoride (PVDF) and nylon were electrospun into nanofiber films to form the two triboelectric materials. Under a load force of 10 N, the NF-TENG could generate an output voltage of 140 V, current of 0.5 μ A and transferred charges of 50 nC. Preliminary body energy harvesting applications of the proposed NF-TENG were demonstrated, wherein the NF-TENG was able to generate an output voltage of 8 V and 10 V during typing and elbow bending, respectively.

Keywords—triboelectric nanogenerator; PVDF nanofibers; nylon nanofibers; body motion; energy harvesting

I. INTRODUCTION

Wearable devices are smart devices or sensor systems which can be worn directly or integrated into apparel, for sensing various vital body movement parameters as well as for harvesting energy from body motion. Wearable devices are now widely used in the field of computing [1], infotainment [2] and especially in monitoring vital human body parameters, such as heartbeat [3], heart rate [4], dehydration [5] and sleeping conditions [6]. Such numerous wearable devices and wearable energy harvesters that sense information from various body parts are quintessential in order to realize a body sensor network (BSN) [7], which can provide a comprehensive analysis of the human movement. In addition to the specific sensing performances, aspects such as the wearable comfort, apparel integrability, and reliability of such devices are also gaining more and more attention [8]. As a result, there is a necessity for the wearables to preferably be low powered or even self-powered in addition to being flexible and lightweight. However, the methods currently used to power the wearable sensors are mainly based on the bulky and rigid batteries, which greatly hinder the wearable nature of such sensors. Consequently, a novel power supply solution for the next-generation wearable devices and BSNs is highly desirable.

Triboelectric nanogenerators (TENGs) [9] as an emerging technology for energy harvesting was invented based on the coupling effect of contact electrification and electrostatic induction. Compared to other commonly employed wearable sensors that use electromagnetic,

piezoresistive, capacitive, piezoelectric, and thermoelectric principles, triboelectric offers huge advantages in energy harvesting in terms of the ability to harvest mechanical stimuli involving low-frequencies and random movements [10], which is exactly a characteristic feature of human body movements. Moreover, the wide choice of triboelectric materials, simple structure and variable working modes enable TENGs to be designed into wearable, flexible and lightweight energy harvesters and self-powered sensors [11]. Such merits rank TENGs as one of the top candidates to harvest body motion energy, which can not only act as supplementary energy for low power consumption wearable devices, but could also make self-powered wearable devices a possibility.

Here, we propose a wearable, flexible and lightweight nanofiber-based TENG (NF-TENG) for body motion energy harvesting. The device mainly consists of two triboelectric materials: polyvinylidene difluoride (PVDF) and nylon, which are electrospun into nanofibers to increase the surface area. Experimental results demonstrated that the NF-TENG was able to generate an output voltage of 140 V, current of 0.5 μ A, and transferred charges of 50 nC under a 10 N load force. The NF-TENG demonstrated a good performance in harvesting low-frequency mechanical energy, coinciding with the moving frequency of human body. In response to human body movements such as finger typing and elbow bending, the NF-TENG was able to generate an output voltage of 8 V and 10 V, respectively.

II. ELECTROSPUN NANOFIBER TENG

A. Fabrication of nanofiber triboelectric films

In order to form electrospun PVDF films, 15% weight/volume of PVDF solution in N,N-dimethyl formamide and acetone (6:4 ratio) was prepared. The solution was fed at a constant flow rate of 1 ml/hr employing a syringe pump by a 10 ml syringe and 18G needle. Electrospinning was conducted at a voltage of 18 kV and the nanofibers were collected on a mandrel rotating at a speed of 1500 rpm. To attain nylon nanofiber films, 25% weight/volume of nylon solution in formic acid was prepared. The solution was fed at a flow rate of 0.4 ml/hr employing a standard syringe pump by a 10 ml syringe and 18G needle. The nanofibers were collected on a mandrel rotating at 1500 rpm in the presence of a voltage of 24 kV.

Morphological characterizations were conducted on the nanofiber mats employing a scanning electron microscope (Philips XL 30 E-SEM). The micrographs in Fig. 1a and c show the attained PVDF and nylon nanofibers, respectively. The SEM images were processed using ImageJ software to

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Fig. 1. SEM micrograph (a) and diameter distribution (b) of PVDF nanofibers. SEM micrograph (c) and diameter distribution (d) of nylon nanofibers.

examine the diameter distribution of the nanofibers. The histogram in Fig. 1b and d show the diameter distributions for the PVDF and nylon nanofibers respectively. Mean diameters of 171 nm and 98 nm were observed for the PVDF and nylon nanofibers, respectively.

B. Structure of NF-TENG

The NF-TENG consisted of PVDF and nylon nanofiber triboelectric layers, Al electrodes (20 μm thick) and polyethylene (PE) substrates. PVDF and nylon were chosen as triboelectric materials due to the large difference in triboelectric polarity. A 50 μm thick PE membrane was attached on the Al electrodes as substrate and protection layer. All the applied materials are flexible and lightweight, offering wearability to the NF-TENG. The device structure of the NF-TENG is schematically illustrated in Fig. 2.

C. Working principle of NF-TENG

The working mechanism of the NF-TENG is illustrated in Fig. 3. Based on the contact electrification and electrostatic induction effects, the NF-TENG can convert ambient mechanical stimuli into electricity. Due to the contact electrification effect and the ability to lose electrons, in the presence of external stimulation negative charges are generated on the PVDF nanofibers while equal amount positive charges are induced on the nylon nanofibers. There is no charge flow between the two electrodes when the two nanofiber films are fully in contact, as shown in state I. When the two triboelectric layers begin to separate, electrons flow from the bottom electrode to the top electrode driven by the electric potential between the two electrodes as a result of the electrostatic induction effect (state II). The charge flow gets to a halt when PVDF and nylon films are fully separated

Fig. 2. Schematic illustration of the structure of the NF-TENG.

Fig. 3. Working mechanism of the NF-TENG.

where a new electrostatic balance is achieved (state III). A reverse flow of the electrons occurs when the two layers are again approaching towards contact (state IV), and this flow lasts until they are fully in contact (state I).

III. RESULTS AND DISSICUSION

To investigate the electrical performance of the NF-TENG, a square-shaped device of dimensions $40 \times 40 \text{ mm}^2$ was fabricated. The two triboelectric layers were fixed onto the two controllable piston heads (MTS 810 Materials Testing System) by double-side foam tape, which can ensure an intimate contact between the two layers. A controlled contact-separation movement was conducted over a contact-separation distance of 5 mm. Firstly, the output of the NF-TENG under various load forces was investigated at a frequency of 0.5 Hz. As shown in Fig. 4a-c, the open-circuit voltage (V_{OC}), short-circuit current (I_{SC}) and short-circuit transferred charges (Q_{SC}) of the NF-TENG increased as a result of incremental applied load force, which appeared to saturate at higher forces. Specifically, the V_{OC} , I_{SC} and Q_{SC} were as high as 140 V, 0.5 μA and 50 nC, respectively, under the load force of 10 N that is the typical load intensity during body movements [12]. As the load force applied on the NF-TENG increased, the contact between the two triboelectric layers were more intimate, thus the effective contact area accordingly increased until it reached a maximum.

In order to understand the energy harvesting ability of the NF-TENG during body movement, the relationship between the output of the NF-TENG and working frequency was studied. The testing frequencies were set to discrete values at 0.5, 1, 1.5, 2 Hz, while the load force was maintained at 10 N. The corresponding results are shown in Fig. 4d-f. It can be seen that the V_{OC} and Q_{SC} of the NF-TENG remained the same despite the increase in the frequency. However, the I_{SC} showed a nearly linear increase with increasing frequency within the range of 0.5 Hz to 2 Hz. This could be attributed to the fact that the maximum output voltage as well as the transferred charge is depended on the surface charge density and total contact area, while the output current is related to the total transferred charges and contact-separation speed. When the working frequency increases, the contact-separation speed also increases but the total contact area still remains the same.

The output stability of the NF-TENG was also investigated as it is crucial for real-world applications. As it can be observed from Fig. 5, the NF-TENG demonstrated an

Fig. 4. Outputs of the NF-TENG under different forces and frequencies. a) V_{OC} , b) I_{SC} , and c) Q_{SC} of the NF-TENG under different forces. d) V_{OC} , e) I_{SC} , and f) Q_{SC} of the NF-TENG under different frequencies (at 10 N load).

excellent stability in its output without any observable degradation over 1000 working cycles. With the high-performance and stable output, the energy harvested by the NF-TENG can be stored in capacitors or batteries. Fig. 6 demonstrates the charging ability of the NF-TENG when it was connected to a 1 μ F capacitor using a rectifier bridge. As it can be seen, the NF-TENG (2 Hz and 10 N) just took 110 s to charge the capacitor to 10 V, which could be used to power loads like LEDs.

As all the materials applied in the NF-TENG are flexible, microscale thick and lightweight, the NF-TENGs are quite wearable with good comfort. To demonstrate the potential of

Fig. 5. Stability test of the NF-TENG.

Fig. 6. Charging ability of the NF-TENG.

Fig. 7. Demonstration of harvesting typing energy using the NF-TENG.

Fig. 8. Demonstration of harvesting elbow bending energy using the NF-TENG.

the NF-TENG in harvesting body motion energy, a NF-TENG (10×10 mm²) was fixed on the fingertip by double-side Kapton tape to harvest energy from typing on a keyboard. As shown in Fig. 7, the NF-TENG could generate an output voltage of 8 V as the device contacted various keys on the keyboard during typing. The rather small output could be attributed to the small force exerted on the NF-TENG and thus less contact-separation distance during typing.

A 40×40 mm² NF-TENG was further developed to be worn in the elbow, as demonstrated in Fig. 8. PDMS spacers (1 mm) were applied here to enable necessary gap between the two triboelectric layers. Due to the flexible materials and small spacer distance, the actual contact area and contact-separation are quite small. When the elbow is in a release state (unbent), the two nanofiber layers stay partially separated due to the embedded spacer. As the elbow gradually bends, the two triboelectric layers get into contact with each other and thereafter separate when the elbow joint relaxes again to unbent position. As a result, the NF-TENG converts the mechanical energy of the elbow bending into electrical energy. As it can be seen, the output voltage of the NF-TENG is ~10 V during the act of elbow bending. The above proof-of-concept demonstrations show the promising potential of the proposed NF-TENG as wearable energy harvester for powering wearable devices and the BSN.

IV. CONCLUSION

In conclusion, a wearable, flexible and lightweight nanofiber-based TENG for body motion harvesting was demonstrated. Electrospun polyvinylidene difluoride and nylon nanofibers were employed to form the two triboelectric layers featuring large surface area. When stimulated by a 10 N force, the NF-TENG was able to generate an output voltage of 140 V, current of 0.5 μ A, and transferred charges of 50 nC, respectively. Finally, the NF-TENG was attached on the fingertip and elbow joint to harvest typing and elbow bending energy, during which an output voltage of 8 V and 10 V was generated respectively. The developed NF-TENG demonstrates a promising potential as wearable energy harvester and creates possibilities for powering wearable devices and BSNs.

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