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Textile Manufacturing Compatible Triboelectric Nanogenerator with Alternating Positive and Negative Freestanding Grating Structure †

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Abstract: This paper demonstrates a novel design of textile-based triboelectric nanogenerator (TENG), which is compatible with standard textile manufacturing. The device can convert kinetic energy occurring during frictional contact between two dissimilar materials into electricity based on contact electrification and the electrostatic induction effect. The TENG can generate an RMS open-circuit voltage of 136 V, an RMS short-circuit current of 2.68 μA and a maximum RMS power of 125 μW (38.8 mW/m$_2$). To demonstrate practical applications, the TENG was embedded into a lab coat. The energy is generated from the relative movement between the arm and torso. Its output was used to drive a digital watch, a wearable night-time warning indicator for pedestrians, a wireless transmitter and a pedometer.

Keywords: triboelectric nanogenerator; E-textile; energy harvesting

1. Introduction

Although the wearable and portable electronics have been substantially developed over the past decades, most of these types of devices still rely on batteries, which require persistent recharging and replacement. An effective way to solve this problem is to introduce a wearable self-charging power system using an energy harvester to scavenge energy from the surrounding environment. Triboelectric nanogenerators (TENGs) are one of the most promising candidates for powering these systems. They can efficiently convert kinetic energy occurring during frictional contact between two dissimilar materials into electricity based on contact electrification and the electrostatic induction effect [1]. Various examples of TENGs have demonstrated flexibility, lightness, biocompatibility and good performance that are essential for wearable devices [2]. According to these properties textile-based TENGs are determined to be highly suitable for powering wearable devices and electronic textiles (e-textiles) [3–5].

This paper proposes a novel structure of textile-based TENG with alternate grated strips of positive and negative triboelectric material operating in freestanding triboelectric-layer mode; defined as a pnG-TENG. Whilst most grating-structured TENGs operating in a freestanding triboelectric-layer mode comprise gratings of one type of triboelectric material separated by air gaps [1,6], this design reveals a replacement of the air gaps by a triboelectric material with the opposite polarity to the existing triboelectric material.

2. Device and Working Principle

A schematic illustration of the proposed pnG-TENG is shown in Figure 1. It is composed of an upper substrate with *N* alternate strips of nylon and polyvinyl chloride heat transfer vinyl (PVC HTV) (*N* = 10 for Figure 1a) and a lower substrate with two interdigitated silver (Ag) electrodes (IDEs) with matching periodicity, shown in Figure 1b. The upper substrate was fabricated by heat-pressing PVC HTV on nylon fabric. The lower substrate was fabricated by screen-printing Ag ink (Fabinks TC-C4001) on PVC coated fabric. Nylon fabric was selected as the positive triboelectric material as it is one of the most positive fabrics in the triboelectric series. PVC HTV is chosen as the negative triboelectric material because of its stretchability, washability and durability. It is also widely used in the textile industry as it can last the lifetime of the fabric with no fading or cracking. Moreover, the processes involved in the manufacture of the pnG-TENG, namely screen-printing and heat transfer, are cost-effective, straightforward and compatible with standard textile manufacturing. The acrylic layer and the fabric substrate are just for testing to make it a consistent and repeatable test and are not required in an actual e-textile device. The flexibility of the pnG-TENG is demonstrated in the photographs of the upper and lower substrates of the pnG-TENG (*N* = 10) in Figure 1c,d, respectively. The SEM images of the upper and lower substrates are illustrated in Figure 1e,f, respectively. They show that the PVC HTC and the Ag IDE are firmly bonded to the lower fabric substrates.

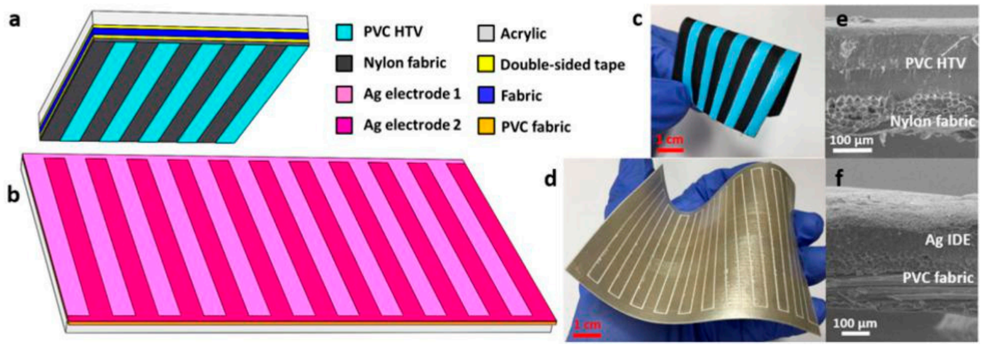

Figure 1. Schematic illustration of (**a**) the upper substrate of pnG-TENG for *N* = 10 with PVC HTV as negative material and nylon fabric as positive material and (**b**) the lower substrate of pnG-TENG with interdigitated Ag electrodes. Photograph of (**c**) the upper substrate and (**d**) the lower substrate of pnG-TENG without the acrylic sheet. SEM images of (**e**) the upper substrate and (**f**) the lower substrate.

The working principle of pnG-TENG is illustrated in Figure 2 (for *N* = 2). When the positive and negative triboelectric materials with respect to the metal electrodes are brought into contact with the metal electrodes, positive and negative charges build up at their surface respectively and at the same time, the same amount of charge with the opposite polarity is transferred to the electrodes because of the triboelectric effect. Through a sliding movement of the grated triboelectric materials across the tines of the IDEs, the electrons are induced and transferred between the tines resulting in multiple alternating currents. The number of current cycles per moving cycle is twice the grating number. As shown in Figure 2ii,iv,vi,viii, four current cycles are generated in one moving cycle.

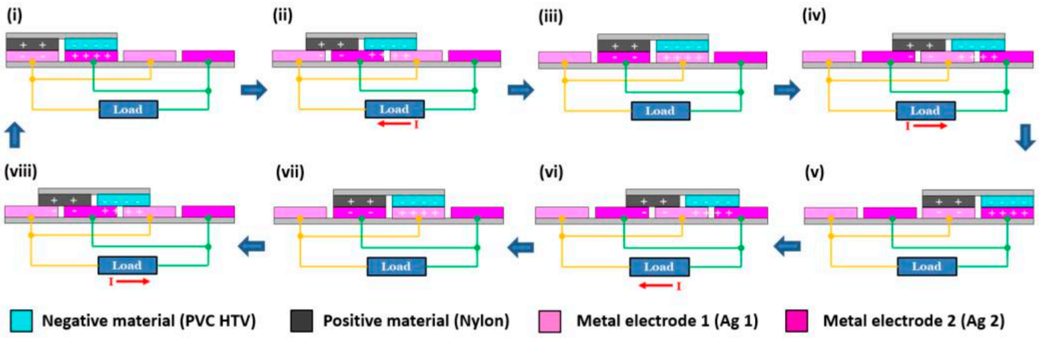

Figure 2. Schematic illustration of the operating mechanism of pnG-TENG for $N = 2$.

3. Experimental Results

All experiments were performed using a belt drive linear actuator at a mechanical oscillation frequency of 2 Hz and a contact force of 5 N, which cyclically slides the upper substrate over the bottom substrate. The open-circuit voltage (V_{OC}) measurements were carried out using an oscilloscope (Agilent DSO3062A) with a load resistance of 1 GΩ and the short-circuit current (I_{SC}) was measured using a DC power analyser (Agilent N6705B). In Figure 3a,b, the experimental results for RMS V_{OC} shows a decreased tendency, while the RMS I_{SC} rises significantly with increasing grating number. The outputs of the pnG-TENGs are greater than that of the TENGs with single positive material (pG-TENGs), the TENGs with single negative material (nG-TENGs) and TENGs with no gratings ($N = 1$) for all the grating numbers. The pnG-TENG ($N = 10$) generates an RMS V_{OC} of 139 V, an RMS I_{SC} of 2.66 μA. In Figure 3c, the load-dependent RMS power (P) of the different TENGs demonstrates that the pnG-TENG (Nylon/PVC HTV, $N = 10$) produces a maximum RMS power of 125 μW at a load resistance of 50 MΩ, corresponding to a maximum power density of 38.8 mW/m^2, which is 1.94 and 6.43 times greater than the power generated by the TENG with single triboelectric material (PVC HTV, $N = 10$) and the TENG with no grating at the same load (PVC HTV, $N = 1$).

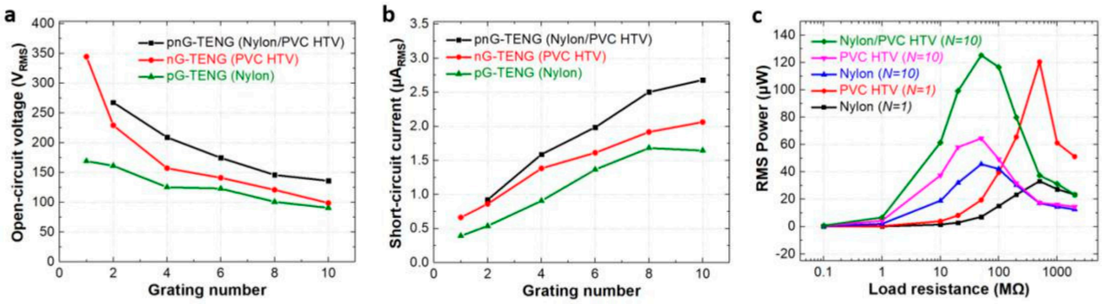

Figure 3. (**a**) V_{OC}, (**b**) I_{SC} and (**c**) P for different triboelectric nanogenerators (TENGs) and different grating numbers.

To demonstrate a possible use of the pnG-TENG in wearable electronics, the pnG-TENG ($N = 10$) was embedded into a lab coat. The energy is generated from the relative movement between the arm and torso during walking and running. The output of the pnG-TENG was used to charge the capacitors with different capacitances. The capacitors can be charged to a useful voltage for wearable electronics in a short period of time. For example, it takes 3 s and 11 s to charge the 1-μF capacitor to 3 V for running (Figure 4a) and walking (Figure 4b), respectively.

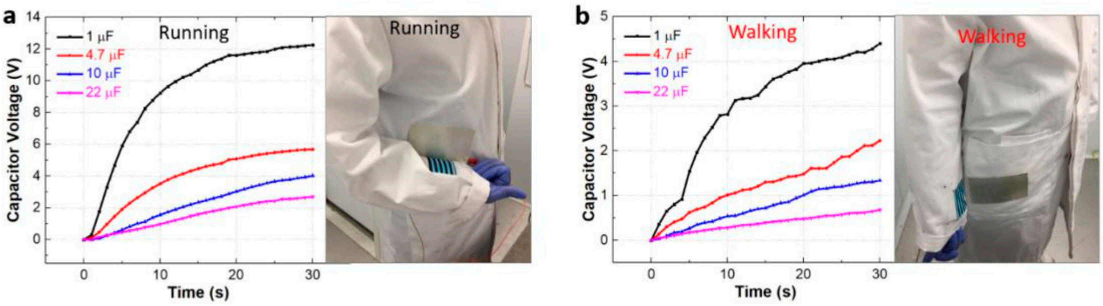

Figure 4. Capacitor voltage of the pnG-TENG as a function of time for different capacitors charged by (**a**) running and (**b**) walking.

The output of the pnG-TENG was used to drive a digital watch (Figure 5a), a wearable night-time warning indicator for pedestrians (Figure 5b) and a wireless transmitter. As a demonstration of a sensing device, the voltage peaks of the pnG-TENG was detected and applied for step counting by means of arm motion (pedometer), shown in Figure 5c.

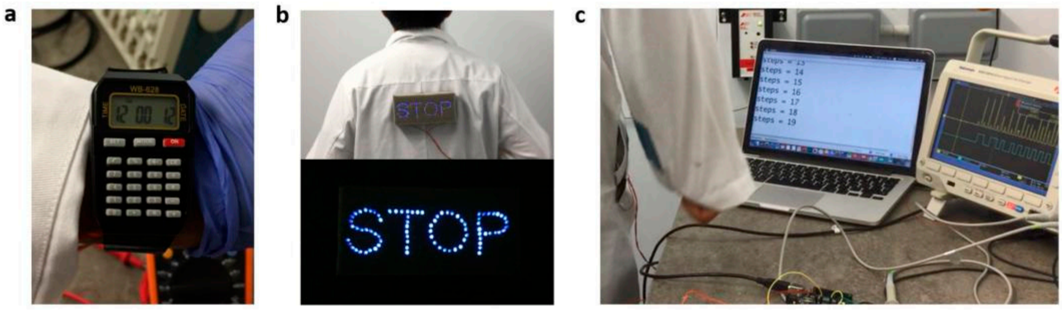

Figure 5. Photographs of (**a**) digital watch and (**b**) wearable night-time warning indicator for pedestrians driven by the output of pnG-TENG during running. (**c**) Photograph showing the utilisation of the pnG-TENG as a sensor for step counting via arm motion (pedometer).

4. Conclusions

A novel textile-based triboelectric generator was successfully fabricated using the processes that are compatible with standard textile manufacturing, including screen-printing and heat-press-transfer printing. The TENG comprises two alternate grated strips of positive triboelectric material (nylon fabric) and negative triboelectric material (PVC HTV), defined as a pnG-TENG. The pnG-TENGs show significant improvement in performance compared to single positive material (pG-TENGs), single negative material (nG-TENGs) and TENGs with no gratings. Applications for the png-TENG, including a digital watch, a wearable night-time warning indicator, a wireless transmitter and a pedometer, have been demonstrated.

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References

1. Xie, Y.; Wang, S.; Niu, S.; Lin, L.; Jing, Q.; Yang, J.; Wu, Z.; Wang, Z.L. Grating-structured freestanding triboelectric-layer nanogenerator for harvesting mechanical energy at 85% total conversion efficiency. *Adv. Mater.* **2014**, *26*, 6599–6607.

2. Paosangthong, W.; Torah, R.; Beeby, S. Recent progress on textile-based triboelectric nanogenerators. *Nano Energy* **2019**, *55*, 401–423.
3. Chen, J.; Guo, H.; Pu, X.; Wang, X.; Xi, Y.; Hu, C. Traditional weaving craft for one-piece self-charging power textile for wearable electronics. *Nano Energy* **2018**, *50*, 536–543.
4. Cui, N.; Liu, J.; Gu, L.; Bai, S.; Chen, X.; Qin, Y. Wearable Triboelectric Generator for Powering the Portable Electronic Devices. *ACS Appl. Mater. Interfaces* **2015**, *7*, 18225–18230.
5. Zhou, T.; Zhang, C.; Han, C.B.; Fan, F.R.; Tang, W.; Wang, Z.L. Woven structured triboelectric nanogenerator for wearable devices. *ACS Appl. Mater. Interfaces* **2014**, *6*, 14695–14701.
6. Zhu, G.; Chen, J.; Zhang, T.; Jing, Q.; Wang, Z.L. Radial-arrayed rotary electrification for high performance triboelectric generator. *Nat. Commun.* **2014**, *5*, 1–9.