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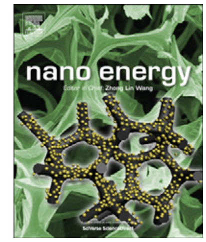

RAPID COMMUNICATION

Triboelectric nanogenerator built inside shoe insole for harvesting walking energy

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Abstract
We report a simple fabrication, great performance and cost-effective triboelectric nanogenerator (TENG), which is based on the cycled contact-separation between a polydimethylsiloxane (PDMS) film and a polyethylene terephthalate (PET) film, for effectively harvesting footfall energy. The elastic sponge is first used as the spacer in the TENG, where the size and the thickness of the spacers have a significant effect on the output performance of the TENG. By using the optimized device, a TENG-based shoe insole is used to harvest human walking energy, where the maximum output voltage and current density reached up to 220 V and 40 μA, respectively. We also demonstrate that the fabricated shoe insole using a single layer of TENG can be directly used to light up 30 white light-emitting diodes (LEDs) in serial connection. By taking the merits of this simple fabrication, outstanding performance, robust characteristic and low-cost technology, we believe that TENG can open up great opportunities not only for powering small electronics, but also can contribute to large-scale energy harvesting through engineering design.

Introduction

Harvesting energy, such as light [1], heat [2,3] and vibration [4], from our ambient environment, has been an active subject since the beginning of this century [5] due to the drastically increasing needs in world energy. In recent years, with the increase of the wireless electronic devices, like implantable sensors, environmental/industrial monitoring device or long

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range asset tracking system, developing long-life, sustainable and yet maintenance-free energy sources is essentially necessary [6,7]. With the abundant amount of mechanical energy found in our living surroundings such as human walking energy up to 67 W [8], numerous emerging technologies have been developed to convert green mechanical energy/vibration to electricity for driving practical and functional devices [9–18]. In 2012, our research group has developed a triboelectric nanogenerator (TENG) technology to harvest the irregular mechanical energy [19–23]. The mechanism of the TENG is based on the electron flow as driven by the triboelectric effect induced electrostatic charges on the surfaces of two different triboelectric materials [21]. Currently, some attempts about the applications of the TENG have been demonstrated such as the electrodeposition (PED) [21], driving the commercial cell phone and wireless sensor [22,23], and degradation of methyl orange [24]. However, there is no any report on the TENG-based shoe insole, which has potential commercial applications for harvesting human walking energy, so that the cell phone battery can be charged while walking.

Usually, the fabricated TENG includes two layers of triboelectric materials and spacer between them. The output of the TENG is based on the contact and separation between the two triboelectric materials to induce the charge generation and separation processes. The spacer plays an important role in separation process of the two materials. Till now, although some kinds of spacers were used to fabricate the TENG [21,24], there is no any report about the effect of the spacers on the output performance of the TENG. These investigations are very crucial for choosing the optimized structure of TENG. Here, in this paper, we focus on the optimization of the TENG in terms of the spacer, including fabric, number, area coverage and thickness. Moreover, through ubiquitous human walking energy, which is prevalent anywhere at any time, we designed an optimized TENG-based shoe insole, which can be used to instantaneously light up 30 commercial white LEDs connected in series. We believe this technology can not only efficiently harvest ubiquitous walking energy, but also open up new possibilities in waste mechanical energy recycling toward a large-scale power system in the near future.

Experimental section

A. Fabrication of the TENG

The fabrication process starts off with a layer of patterned polydimethylsiloxane (PDMS) film. The elastomer and the cross-linker (Sylgard 184, Dow Corning) were mixed in a 10:1 ratio (w/w). After degassing under vacuum for 2 h, the mixture was spun-coated on the plastic mold with patterned concave dome at 500 rpm for 100 s. Then the PDMS and mold were put in a conventional oven (Yamato Scientific America, Inc. DKN402) to cure at 85 °C for 3 h. After peeling off the patterned PDMS with convex dome-shaped bump on the surface from the plastic mold, a nearly 400 μm thick PDMS layer was sat on top of the copper sheet as the bottom electrode. Another polymer layer, polyethylene terephthalate (PET) film with a thickness of 127 μm, was deposited with a 300 nm-thick indium tin oxide (ITO) as the top electrode. A layer of spacers were inserted in between the PDMS and PET film layers to sustain the device. The spacer layer was chosen from the different fabrics, area size and thickness detailed in the following discussion in order to obtain the maximum electrical output. Finally, silver paste was applied to connect the top/bottom electrode to the copper conducting wires.

B. Fabrication and electrical measurement of the shoe insole

The fabricated shoe insole was based on the most optimized conditions of spacers. We scaled up the original TENG to a shoe size with 27 cm in length and 9 cm in width. Besides, we affixed the enlarged TENG with two cloths at the bottom and atop.

The TENG was connected to the measurement system to detect the output signals. SR560 and SR570 low noise current amplifiers (Stanford Research Systems) were used to acquire voltage/current signals, respectively. A mechanical linear motor (Labworks Inc.) was employed to apply a loading force to the TENG.

Results and discussion

The design of the TENG device is based on optimizing the best spacer condition between two triboelectric films. Fig. 1a is a schematic diagram of the fabricated TENG. The PET (top layer) and PDMS (bottom layer) materials were used to induce the triboelectric charges. The PET film was coated with an ITO film with a thickness of 300 nm as the top electrode, and patterned PDMS was put on top of a Cu sheet. In order to sustain these two polymers and make the charge generation and separation processes effectively, numerous pieces of spacers were inserted between these two triboelectric films. To simplify the fabrication process, we only put 5 pieces of spacers as a model unit in the TENG, as shown in Figure 1b. The area of TENG is 4.5 cm × 4.5 cm and each spacer is 1 cm × 1 cm in size.

In order to obtain the highest output performance of the TENG, three types of materials as the spacers were used to fabricate the devices. Figure 2a, b and c are sports socks (80% cotton mixed with 10% acrylic and 10% nylon), T-shirt (100% cotton), and sponge (polyurethane), respectively. Those three items are all easily obtained in daily life. The corresponding output performance (short-circuit current density and open-circuit voltage) are displayed in Figure 2. We can find that the sponge spacer-based TENG has the best performance among the three materials as the spacer. The corresponding current density can reach 0.06 $\mu A/cm^2$ and the voltage is nearly 28 V as compared with the TENG with sports socks spacers, which has less than 0.02 $\mu A/cm^2$ and 7 V for the output current density and voltage, respectively. In this study, all the measurements of the fabricated TENGs were tested by switching the polarities to verify that the measured signals were generated by the TENGs rather than the measurement system (supporting information, see Figure S1). Taking sponge case as an example, when the TENG was reversely connected to the measurement system, the output current density also shows

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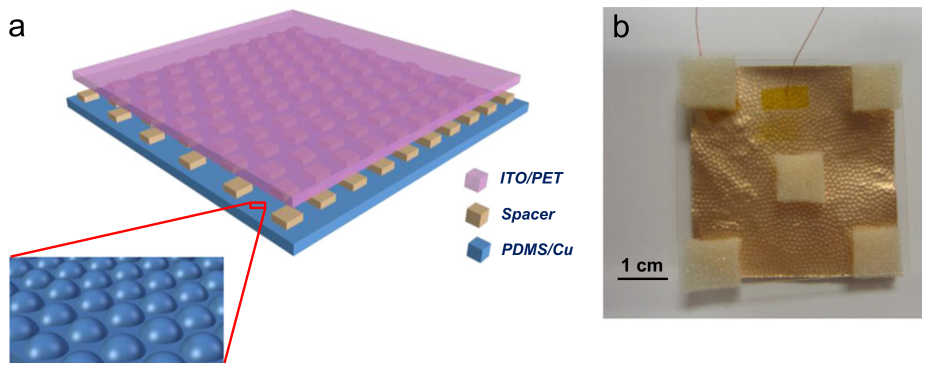

Figure 1 Structure of the fabricated TENG. (a) Illustration diagram of the TENG with dome-shaped bumps on micrometer scale shown in the inset. (b) Image of a working TENG device with the spacers, elastic sponge in this case, in between the two polymer layers.

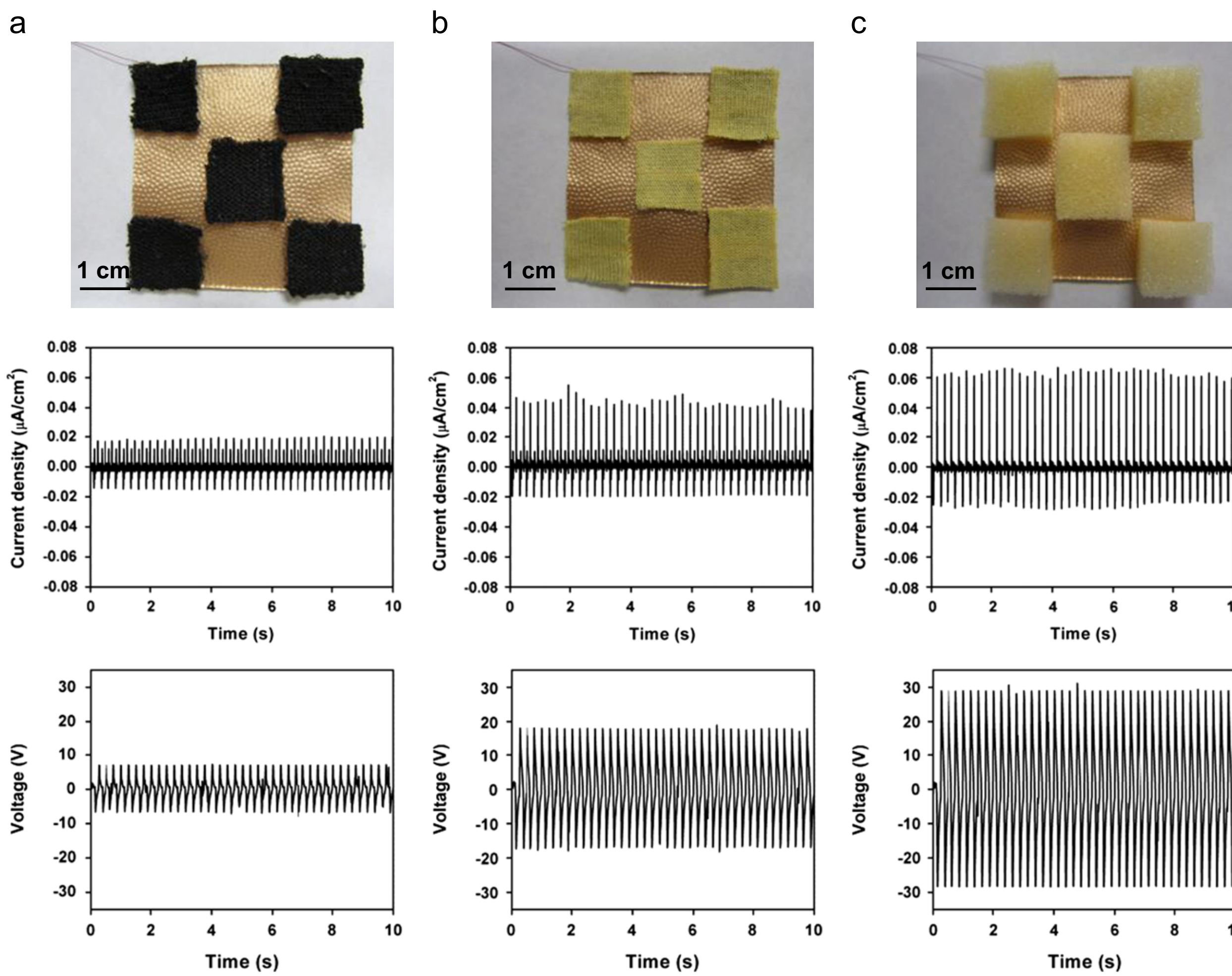

Figure 2 Comparison of the electrical output performance (short-circuit current density and open-circuit voltage) of TENG inserted in different kinds of fabric as spacer when subjecting to a cyclic force. (a) Sports socks, which consist of 80% cotton, 10% acrylic and 10% nylon, used as spacer. (b) T-shirt, which is 100% cotton, used as spacer. (c) Elastic sponge, or polyurethane, used as spacer. All the data shown in this figure were obtained from the same TENG except replacing the spacers.

a reversed value of 0.06 $\mu A/cm^2$ (Figure S1b), indicating that the signals are from the TENG itself.

We also investigated the effect of the number of spacers on the output performance of the TENG. Figure 3 shows the effect of the number of spacers from 5 to 40 on the electricity generation, where the device used here has the same spacer-coverage area. The result (Figure 3f) reveals that both current density and voltage decrease with increasing the number of spacers, which is associated with the smaller effective contact charging area when the number of spacers increases. To further explore how the fabricated spacers affect the output performance of TENG, we investigate the effect of

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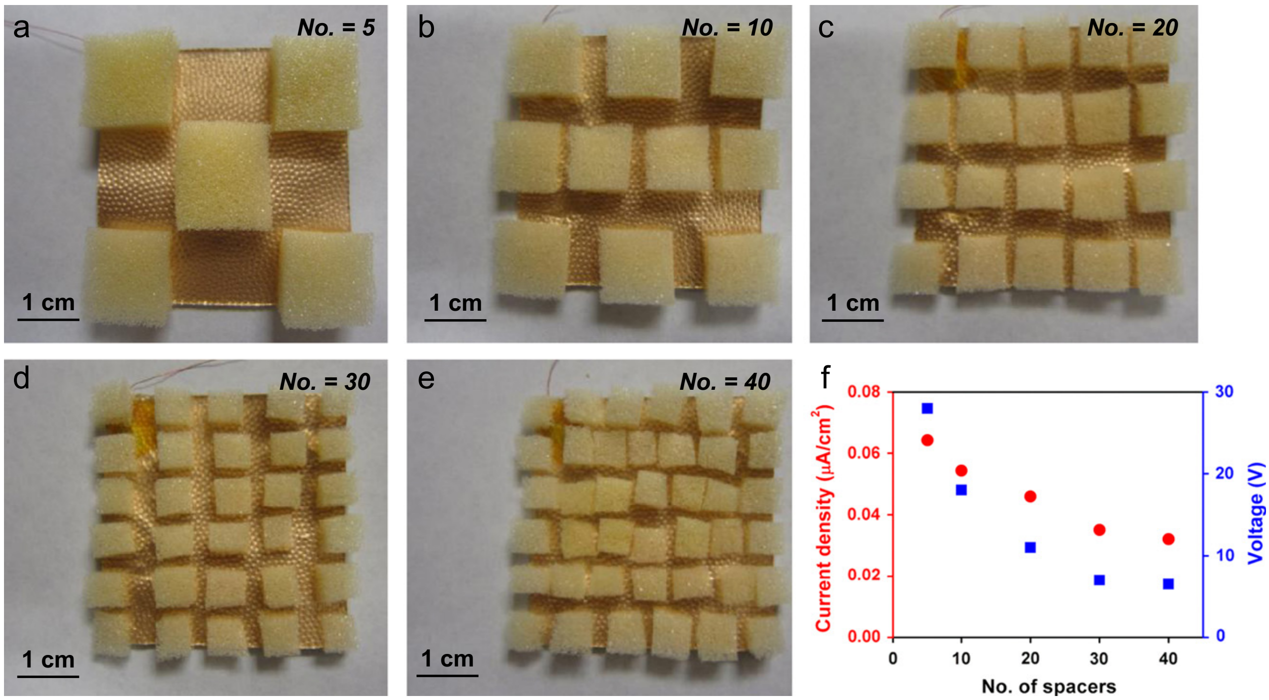

Figure 3 Number of spacer dependence while keeping all the open area the same. Number of spacer is (a) 5, (b) 10, (c) 20, (d) 30, (e) 40 and (e) Corresponding short-circuit current density and open-circuit voltage with different number of spacer. All the data shown in this figure were obtained from the same TENG except replacing the spacers.

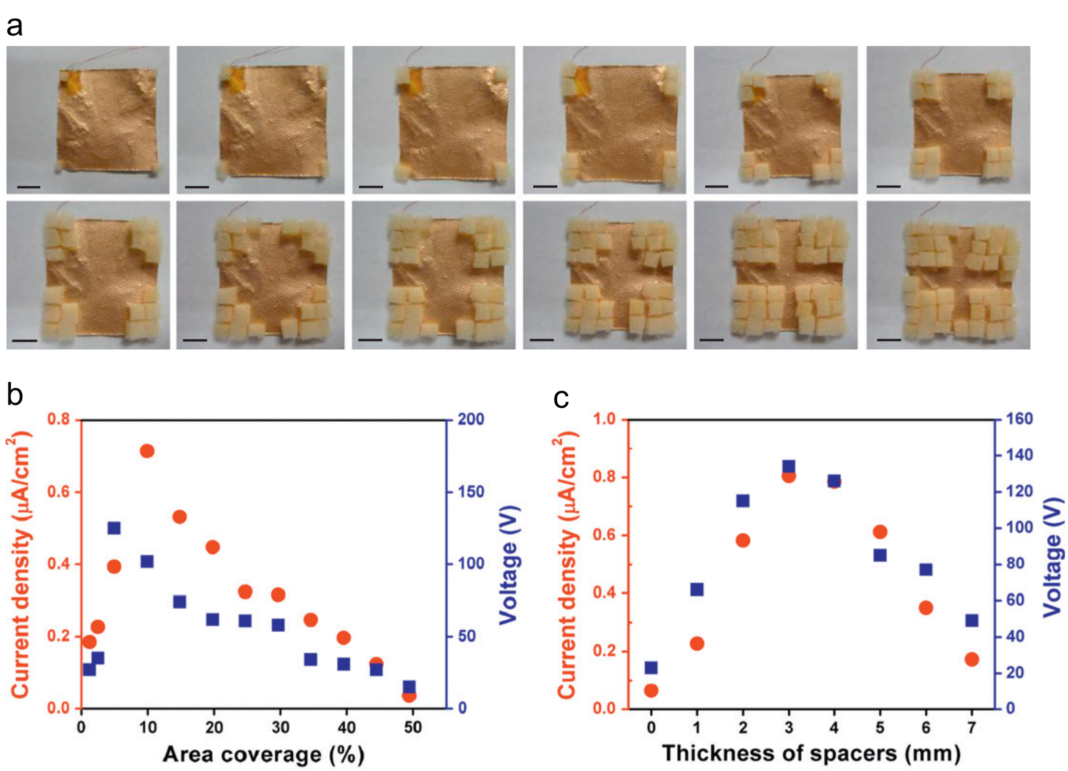

Figure 4 Influence of the area coverage and thickness of spacers on output characteristics of TENG. (a) The number of spacer at each corner is 0.25, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10. The scale bars represent 1 cm. (b) Output signal at different area coverage of spacers. (c) Output signal with spacers in thickness 0 (without any spacer)-7 mm. All the data shown in this figure were obtained from the same TENG except replacing the spacers.

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spacer coverage area on the output performance of the device. Figure 4a shows the optical images of the TENGs with the different spacer coverage area ratio from 1% to 50%. The corresponding output electricity is summarized in Figure 4b. The maximum current density is found under the coverage area ratio of about 10%, and the maximum voltage can reach up to 125 V at the coverage area ratio of 5%. Based on the maximum output current condition with the coverage area ratio of 10%, we then explored the optimized condition by varying the thickness of the spacers. The results suggest that both the maximum current density and voltage peak have the highest values of 0.8 $\mu A/cm^2$ and 135 V at the thickness of spacers of 3 mm, respectively. The open-circuit output voltage $\boldsymbol{V_{oc}}$ of TENG [21,24] can be approximately expressed as

$$V_{OC(TENG)} = \frac{\sigma d}{\varepsilon_0}. \quad (1)$$

where σ is the triboelectric charge density on the surface, $\boldsymbol{d}$ is the interlayer distance, which is the thickness of the spacer in this case, and $\boldsymbol{\varepsilon_0}$ is the vacuum permittivity. According to the Eq. (1), the output voltage $\boldsymbol{V_{oc}}$ will increase with increasing the interlayer distance $\boldsymbol{d}$ (the thickness of the spacer). However, we found that the output voltage $\boldsymbol{V_{oc}}$ decreases with increasing the thickness of the spacer higher than 3 mm.

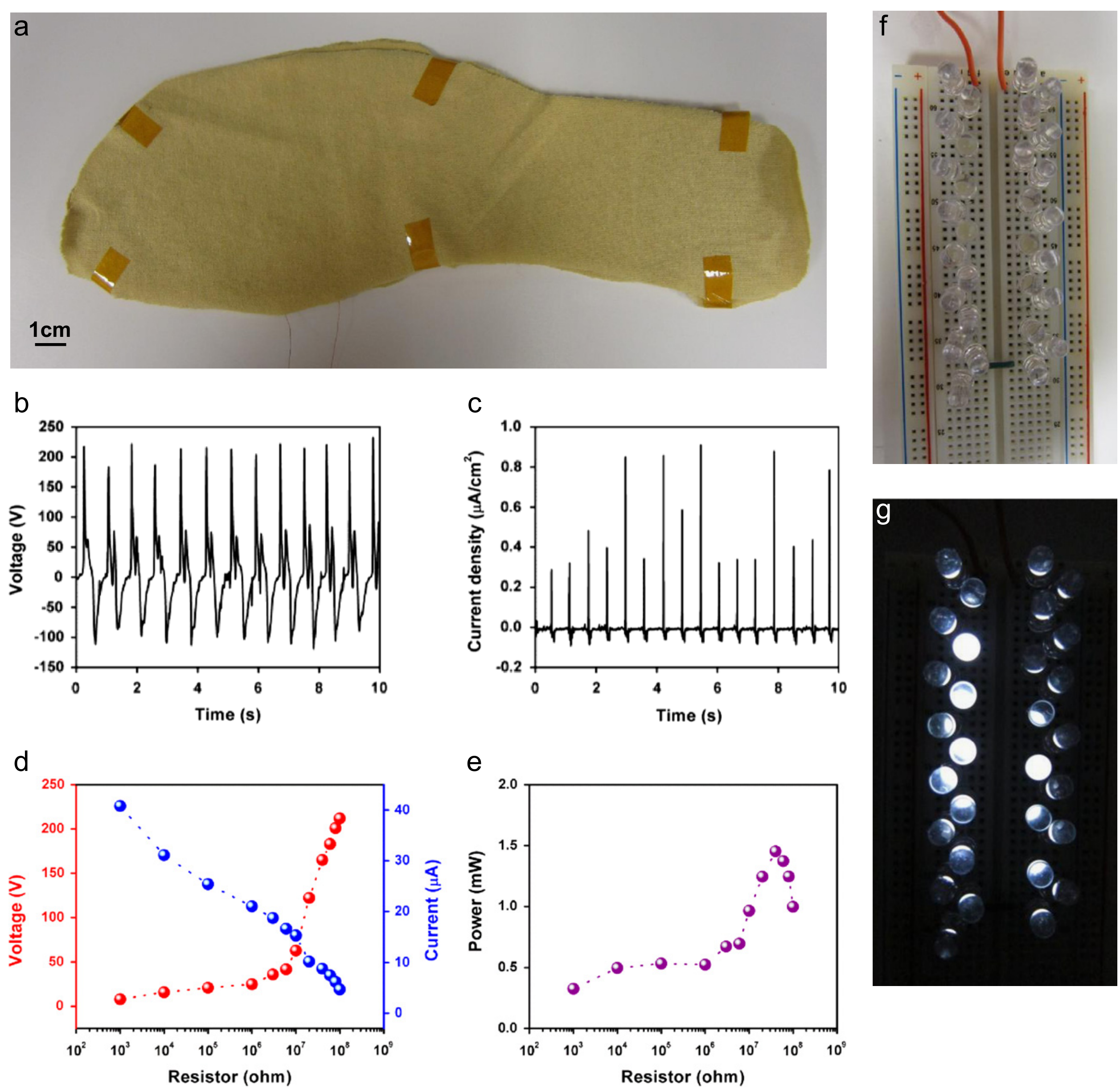

Figure 5 A TENG-based shoe insole as a direct power source for harvesting human walking energy to drive 30 white LEDs in serial connection. (a) Image of a shoe insole composed of TENG inside. (b) The corresponding output voltage and (c) current density generated by the shoe insole. (d) The voltage and current density as a function of the load resistance. (e) The load resistance dependence of instantaneous electrical power from the shoe insole. (f) Snapshots of 30 white LEDs connected in series before and (g) while stepping on top of the shoe insole.

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This is possibly because that when the thickness of the spacer is larger than 3 mm, the contact between the PDMS and PET films is not effective, and the effect becomes more obvious with increasing the thickness of the spacer.

Since the mechanical energy existing in the environment is always irregular and alters in frequency, we characterized the output current density of TENG at different working frequencies from 4 to 8 Hz shown in Figure S2. The curve clearly reveals an increasing trend with the increase of the frequencies, because the strain rate increases with the straining frequency, which results in a higher current, but the total amount of induced charges is constant under the same circumstance except for driving frequency [22].

The object of the development of NG is to power electronic devices by harvesting mechanical energy surrounded in our living environment. In this regard, we have fabricated a shoe insole based on the optimized spacer condition discussed above. Figure 5a displays an optical image of the fabricated shoe insole. The output performance of the shoe insole has been investigated while stepping on top of this fabricated device. Figure 5b and c shows the corresponding short-circuit voltage and open-circuit current density, respectively. It can be seen that the voltage and the current density can reach up to 220 V and 0.8 $\mu A/cm^2$, respectively. In practical use, the output power for the load depends on the resistance of the load itself. Therefore, we characterize the external load matching with the working TENG-based shoe insole by changing the resistor from 10^3-10^8 Ω. As shown in Figure 5d, the current decreases with an increase of load resistance owing to the ohmic loss; however, the voltage across the load goes up when the resistance becomes lager. The instantaneous maximum power value is nearly 1.4 mW shown in Figure 5e. This finding also indicates that the TENG-based shoe insole runs most efficiently if the load has a resistance of several MΩ.

The instantaneous electrical output of the TENG-based shoe insole can simultaneously light up 30 white LEDs (3.0-3.4 V, 24 mA max, 27,000 mcd) connected in series successfully (Figure S3 shows the experimental setup, where the TENG-based shoed insole is connected to a rectifier and a string of white LEDs). Figure 5f and g are the pictures of LEDs taken before and while stepping on the shoe insole directly. Video I (see the supporting information) records these 30 commercial white LEDs driven by human walking energy in a real-time manner. Moreover, with the benefits like this, TENG-based shoe insole is expected to use the high voltage for stimulating nerves (such as foot massage) and other medical purposes.

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.nanoen.2013.03.001.

Summary and conclusions

In summary, we have fabricated a TENG based on the contact-separation between a PDMS film and a PET film using the triboelectric effect. Through optimizing conditions of spacers such as number, area size and thickness, a TENG with 4.5×4.5 cm^2 in size can generate up to 0.8 $\mu A/cm^2$ and 135 V, respectively. Furthermore, the TENG-based shoe insole is first fabricated, which can be used to harvest the walking energy. We demonstrate that it can be used to light up 30 white LEDs connected in series simply with human stepping force. By means of this simple fabrication, high electrical performance, robust characteristic and low-cost technique, we believe that TENG can open up great opportunities not only for powering up small electronics, but also potentially large-scale energy harvesting.

Acknowledgments

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Appendix A. Supplementary Information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.nanoen.2013.03.001.

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