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Harvesting vibration energy by a triple-cantilever based triboelectric nanogenerator

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ABSTRACT

Triboelectric nanogenerators (TENG), a unique technology for harvesting ambient mechanical energy based on triboelectric effect, have been proven to be a cost-effective, simple and robust approach for self-powered systems. Here, we demonstrate a rationally designed triple-cantilever based TENG for harvesting vibration energy. With the assistance of nanowire arrays fabricated onto the surfaces of beryllium–copper alloy foils, the newly designed TENG produces an open-circuit voltage up to 101 V and a short-circuit current of 55.7 μA with a peak power density of 252.3 mW/m^2. The TENG was systematically investigated and demonstrated as a direct power source for instantaneously lighting up 40 commercial light-emitting diodes. For the first time, a TENG device has been designed for harvesting vibration energy, especially at low frequencies, opening its application as a new energy technology.

1 Introduction

There are tremendous amounts of ambient vibration energy in our living environment at all times, such as ocean waves, motor vibration, and highway, bridge and tunnel vibration. Harvesting vibration energy mainly relies on piezoelectric [1–4], electromagnetic [5], electrostatic [6], and magnetostrictive [7] effects, with the aim of building self-powdered systems to drive small portable electronics [8, 9]. Recently, another creative invention is the cost-effective and robust triboelectric nanogenerator (TENG) [10–18], which is based on the universally known contact electrification effect [19–27] through a periodic contact and separation of two materials with opposite triboelectric polarizations. The contact and separation between polymer–polymer [10–12] or metal–polymer [12, 13] offer a charge-pump to drive electrons through an

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external load, in which current flows back and forth between the electrodes as alternating current (AC). TENG provides an effective means for harvesting ambient mechanical and vibration energy, and its performance is superior to other approaches of its kind. Previously reported TENGs have mainly involved harvesting energy from certain mechanical motions, such as pressing/triggering [10–16] and sliding [17, 18].

Here, we demonstrate a triple-cantilever based TENG for harvesting ambient vibration energy. Two cycles of striking and departure exist in one vibration cycle, which can double the output power of the TENG and significantly enhance the energy conversion efficiency. The open-circuit voltage (V_{OC}) and rectified short-circuit current (I_{SC}) reached up to about 101 V and 55.7 μA, respectively, with a peak power density of 252.3 mW/m^2. The output power of a single device with a size of 3.2 cm by 2.8 cm is high enough to simultaneously light up more than 40 commercial light-emitting diodes (LEDs), unambiguously demonstrating its feasibility of powering portable electronics, and sensors for environmental and infrastructure monitoring and security.

2 System design and characterization

The basic structure of the triple-cantilever based TENG is shown in Fig. 1(a), in which, three metal plates of beryllium–copper alloy foils are the three cantilevers. The bottom surface of the top cantilever and the top surface of the bottom cantilever are coated with polydimethylsiloxane (PDMS) films [11]. The surfaces of the middle cantilever are covered by ZnO nanowire arrays grown by chemical approach [28], on the top of which a layer of Cu was deposited. A mass is also attached at its end for effectiveness of vibration. Photos of a real device are shown in Figs. 1(b) and 1(d).

This device has three unique characteristics. Firstly, the middle cantilever has two chances to contact the top and bottom cantilevers in each cycle of the vibration, doubling the vibration energy conversion efficiency. Secondly, the PDMS film can be easily deformed to increase the effective contact area of the TENG [13]. Lastly, the nanowire arrays based surface modification plays an important role in the enhancement of output power (Fig. 1(c)). The nanowire arrays can deeply insert into the PDMS to increase the effective contact

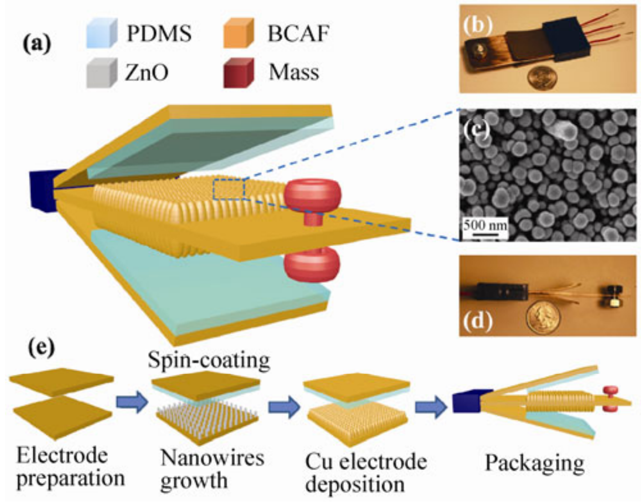

Figure 1 (a) Sketch and (b), (d) photographs of a typical triple-cantilever based TENG, with a size equivalent to a quarter dollar coin. (c) Scanning electron microscopy (SEM) image of Cu film coated ZnO nanowire arrays. (e) Fabrication process of the TENG.

area and thus leading to a substantially higher electric output. As sketched in Fig. 1(e), the fabrication process is simple and straightforward, without involving any complicated equipment or procedures. Detailed fabrication specifications are shown in the Experimental Section.

A cycle of electricity generation process for illustrating the mechanism of the TENG is indicated in Fig. 2, and can be explained by the coupling between a triboelectric effect and an electrostatic effect [10–18]. Once a periodic external force acts on the TENG, from the original position (Fig. 2(a)), the middle cantilever accelerates and moves into contact with the PDMS film on the bottom cantilever (Fig. 2(b)). According to the triboelectric series [29], a list of materials based on their tendency to gain or lose charges, electrons are injected from the Cu electrode into PDMS once they are in contact [10–12, 20, 30], resulting in net positive charges Q_0 at the surface of the PDMS film and net negative charges $-Q_0$ at the Cu electrode.

Subsequently, the middle cantilever quickly decelerates to the bottom position due to the resistance force from the bottom cantilever. After that, the bottom and middle cantilevers bounce back and then separate owing to the stored elastic potential energy of the TENG. When the distance of separation is appreciably large (Fig. 2(c)), the bottom cantilever possesses a lower electric potential than the middle cantilever, thus, the

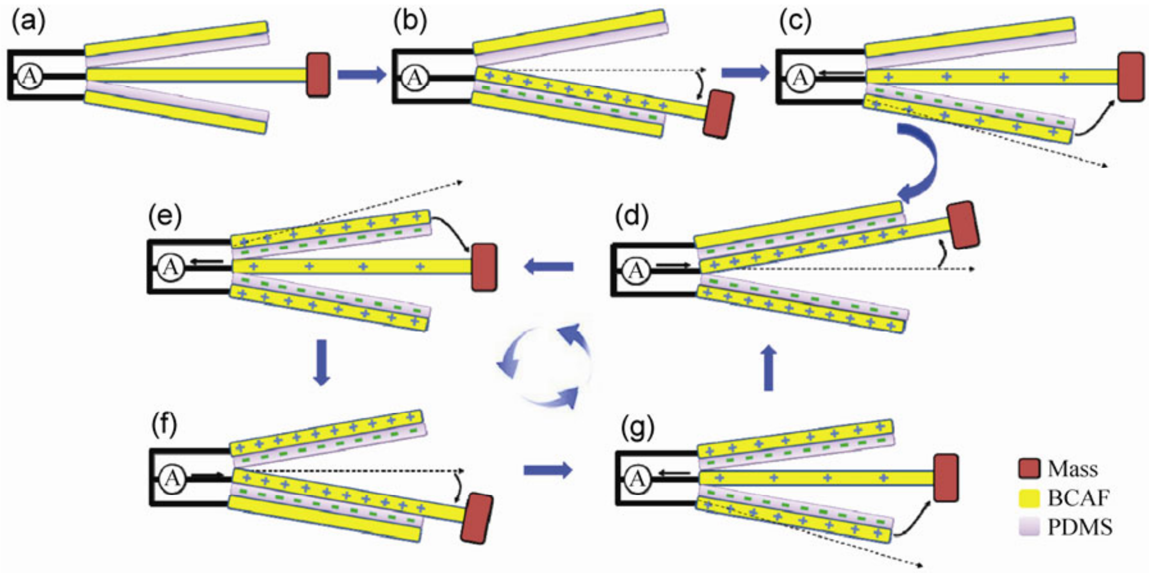

Figure 2 A cycle of electricity generation process for illustrating the mechanism of the triple-cantilever based TENG (see text). (a) Original position without vibration; (b) and (c) initial steps for generating the triboelectric charges via contact induced electrification. (d)–(g) Repeated processes for power generation during a cycled vibration of the cantilever.

positive charges in the middle cantilever flow into the bottom cantilever through the external load with a total charge of ΔQ. Meanwhile, the charge in the middle cantilever decreases to $Q_m = Q_0 - \Delta Q$. Once the middle cantilever touches the PDMS film on the top cantilever, triboelectrification makes both surfaces charged again (Fig. 2(d)). Then the middle cantilever is bounced back and separated from the top cantilever, the charge in the middle cantilever flows through the external load into the metal plate of the top cantilever to balance the potential difference (Fig. 2(e)). Once the middle cantilever strikes the bottom cantilever again, the charge in the metal plate of the bottom cantilever flows back into the middle cantilever to balance the electric field from the triboelectric charges on the PDMS film coated onto the bottom cantilever (Fig. 2(f)). Lastly, when the middle cantilever leaves the bottom cantilever, the created separation results in a higher electric potential on the middle cantilever than that on the beryllium-copper alloy of the bottom cantilever, screening the charges that are from the middle cantilever to the bottom cantilever. Consequently, there is a flow of charge from the middle cantilever to the bottom cantilever until the middle cantilever arrives at the middle position of the TENG, as shown in Fig. 2(g). The process shown in Figs. 2(d)–2(g) is a full cycle of charge generation and it is repeated for each cycle of the cantilever vibration [13]. It is worth noting that the working principle of this nanogenerator relies on the coupling between triboelectric effects and electrostatic effects, which is a new design and totally different from piezoelectric nanogenerators. ZnO nanowires, with a non-centrosymmetric wurtzite crystal structure, are widely utilized to fabricate piezoelectric nanogenerators [1, 2, 31, 32]. However, in this study, the ZnO nanowire arrays only act as a surface modifier to increase the effective contact area, and thus the amount of triboelectric charge generated in contact electrification, and hence the electric output of the TENG. As indicated in Fig. S1 (in the Electronic Supplementary Material (ESM)), even if there is strain in the ZnO nanowires array, no current or voltage output would be contributed from this, because the conductive beryllium–copper alloy foil is physically well connected with the deposited copper thin film, and the ZnO nanowires are sandwiched between them.

3 Experimental section

3.1 Fabrication of a triple-cantilever based TENG

A beryllium–copper alloy foil (BCAF) (65 mm × 28 mm × 0.2 mm) (Goodfellow Company) with a tip mass of

12.29 g acted as not only contact electrode, but also the spring lamination for vibration energy harvesting. The other two BCAFs (45 mm × 28 mm × 0.2 mm) with spin-coated PDMS (32 mm × 28 mm × 0.6 mm) act as the two back electrodes. All electrodes were connected in parallel by external electric wires.

3.2 Nanowire array based surface modification

An aqueous solution of hexamethylenetetramine (Sigma Aldrich) and zinc nitrate hexahydrate (Sigma Aldrich) in equal concentrations (10 mM) was used in the growth of ZnO nanowire arrays on the corresponding position of both sides of the longer BCAF via a hydrothermal method. Growth of ZnO nanowire arrays was carried out in a mechanical convection oven at 85 °C for 4 h. Subsequently, Cu film with a thickness of 100 nm was deposited on ZnO nanowire arrays by physical vapour deposition (PVD75, Kurt J. Lesker Company).

3.3 Preparation of the polymer film

The PDMS elastomer and cross-linker (Sylgard 184, Dow Corning) were mixed in a ratio of 10:1 (*w*/*w*), then cast on BCAF substrates. After a degassing process, the elastomer mixture was spin-coated at 500 rpm for 50 s (SCS 6800 spin coater, Specialty Coating System). Finally, the uniform PDMS film was obtained by heating in a mechanical convection oven at 85 °C for 2 h.

4 Results and discussion

Electric output measurements were performed on a triple-cantilever based TENG device with effective contact area of 3.2 cm × 2.8 cm, at triggering frequencies of 3.5 Hz, 3.7 Hz, and 4.0 Hz (Fig. 3). The open-circuit voltages (V_{OC}) at 3.5 Hz (Fig. 3(a)), 3.7 Hz (Fig. 3(b)), and 4.0 Hz (Fig. 3(c)) are about 89 V, 101 V, and 81 V, respectively, indicating that the 3.7 Hz is the resonance frequency of the TENG. As shown in the inset of Fig. 3(c), a positive voltage is generated due to the immediate charge separation on the departure of the middle cantilever from the PDMS film on the bottom cantilever. Since the electrons cannot flow back to screen the induced electric potential difference between the two electrodes under the open-circuit condition, the voltage remains at a plateau until the next contact [10–14]. Moreover, the peak values of the rectified short-circuit current (I_{SC}) at 3.5 Hz (Fig. 3(d)), 3.7 Hz (Fig. 3(e)) and 4.0 Hz (Fig. 3(f)) also reach up to 45.9 μA,

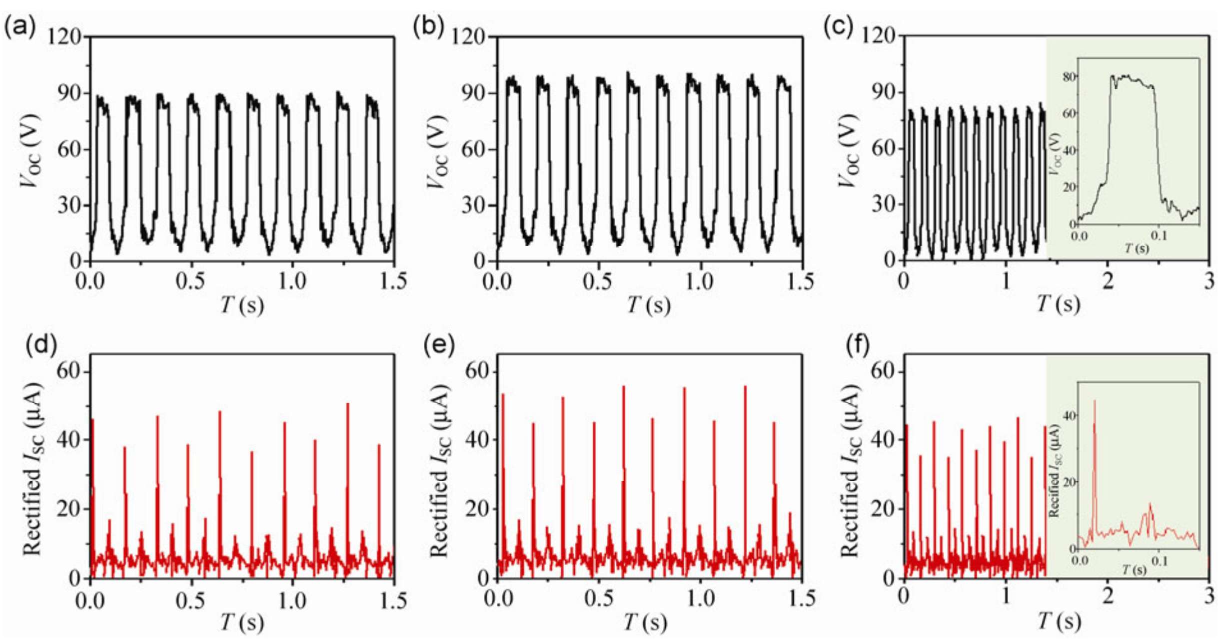

Figure 3 Open-circuit voltage (V_{OC}) at vibration frequencies of 3.5 Hz (a), 3.7 Hz (b), and 4.0 Hz (c) and rectified short-circuit current (I_{SC}) at vibration frequencies of 3.5 Hz (d), 3.7 Hz (e), and 4.0 Hz (f). The insets of (c) and (f) are enlarged views of half cycles of the V_{OC} and I_{SC} at 4.0 Hz, respectively.

55.7 μA, and 44.5 μA, respectively. As indicated in the inset of Fig. 3(f), the peak value of the rectified short-circuit current in response to the two cantilevers approaching is much larger than that when they are separating, due to difference in contact time [10–18]. The rocking in output current is mainly due to residual mechanical vibration (Fig. S2 in the ESM).

In addition, the triggering vibration frequency is another critical factor that could significantly affect the TENG's output. Theoretically, at the resonance frequency, the TENG achieves its maximum mechanical to electrical energy conversion efficiency and the natural resonance frequency can be tuned by the weight of the tip mass and size of the cantilevers according to the Bernoulli–Euler theory [33]. Meanwhile, experimentally, it was found that the natural resonance frequency of the triple-cantilever based TENG decreased with the increasing length of middle cantilever, as well as with increasing weight of the tip mass, as shown in Fig. S3 (in the ESM). This property of tunable natural frequency should ensure the extensive applicability of the TENG, by allowing the widely-distributed frequency spectrum of common ambient vibrations to be covered. The triple-cantilever based TENG was tested by measuring its open-circuit voltage (V_{OC}) and rectified short-circuit current (I_{SC}) for a range of frequencies from 2.5 to 5.0 Hz with the same amplitude. From Figs. 4(a) and 4(b), it is safe to conclude that the triple-cantilever based TENG is suitable for harvesting low-frequency vibration energy such as ocean waves, motor vibration, and highway, bridge and tunnel vibration when vehicles pass by.

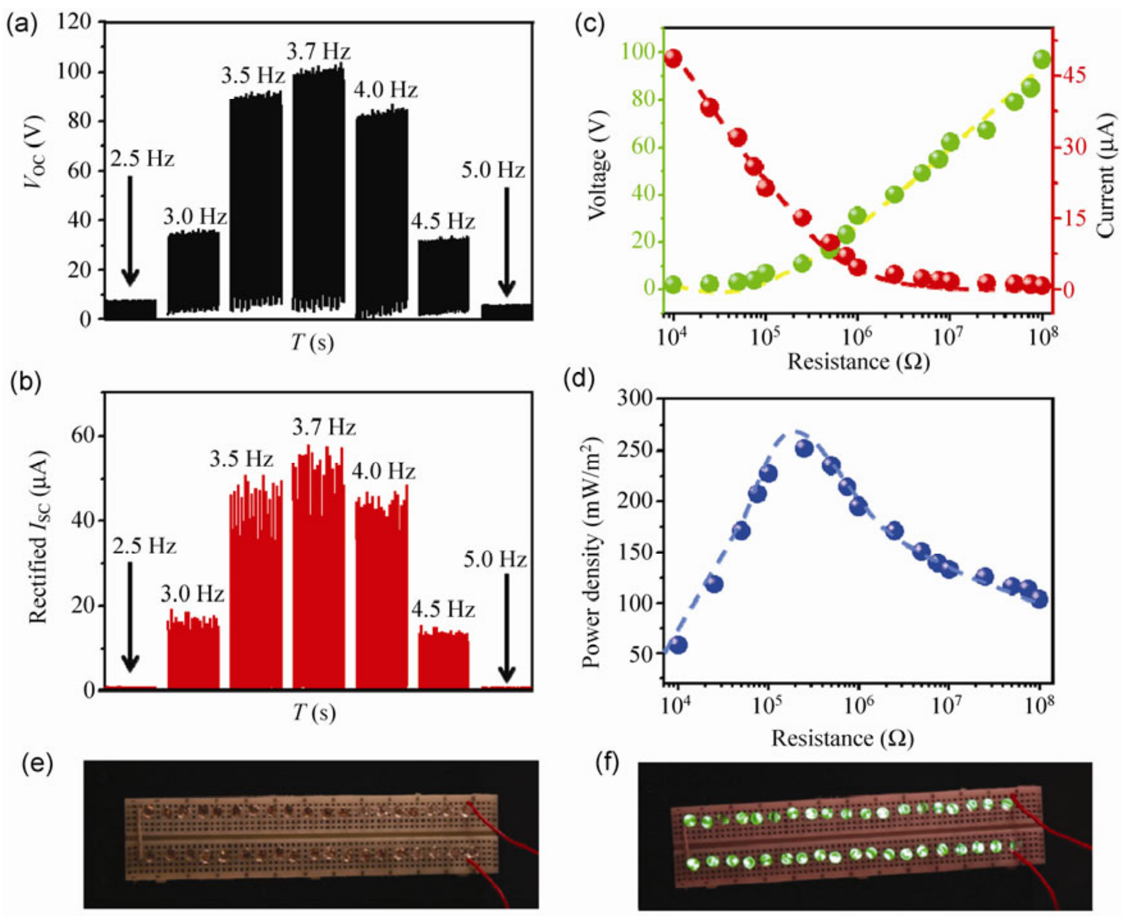

Figure 4 The triple-cantilever based TENG as a direct power source to power electronic devices. (a) Open-circuit voltage (V_{OC}) and (b) rectified short-circuit current (I_{SC}) for vibration frequencies from 2.5 Hz to 5.0 Hz, showing that 3.7 Hz is the resonant frequency of the TENG. When the TENG works under an external load, the dependence of (c) the output voltage and current, and (d) instantaneous power density on the resistance of the load. The TENG simultaneously lights up 40 LEDs in real time: (e) Photographs of LEDs when there is no vibration and (f) lit up LEDs by a vibration at a frequency of 3.7 Hz.

In addition, we also investigated the dependence of the electric output power on the external load under a vibration frequency of 3.7 Hz. As indicated in Fig. 4(c), with increasing resistance of the external load, the maximum current and voltage decreased and increased, respectively. Correspondingly, the instantaneous output power density ($P_d = UI/S_{eff}$) as a function of the external resistance is shown in Fig. 4(d). A peak power density of 252.3 mW/m^2 can be achieved at a load resistance of 0.25 MΩ. In addition, the robustness of the TENG was studied at a resonance frequency of 3.7 Hz. As demonstrated in Fig. S4 (in the ESM), only a slight decline of about 10% is observed for the initial short-circuit current after more than 0.1 million cycles of vibration. However, non-ideal experimental factors, such as humidity and particle contamination in the air, may potentially have a negative impact on the electric performance and thus the longevity of the triple-cantilever based TENG. As a result, the device packaging is critical when the TENG is applied outdoors or in harsh environments, and could greatly extend the life time of the device up to even several years. The performance of the triple-cantilever based TENG is affected by three factors. First, by growing ZnO nanowire arrays on the surface of the middle cantilever, the output is dramatically enhanced. The peak value of the TENG without nanowires is only about 42.6% of the TENG with the nanowires (Fig. S5 in the ESM). Secondly, the use of beryllium–copper alloy foils with high elasticity as the vibration energy conversion medium is also very critical to harvest vibration energy in ambient environments. Lastly, the resonance state of the device maximizes the amplitude of vibration and thus enhances the output power.

The triple-cantilever based TENG is intended to power electronic devices by harvesting small-scale vibration energy. A total of 40 commercial LED bulbs were assembled in series on a piece of electric board (Fig. 4(e)), connected to the triple-cantilever based TENG. As triggered by the shaker under a vibration frequency of 3.7 Hz, the TENG directly and simultaneously lights up all these 40 LED bulbs (Fig. 4(f) and the video in the ESM).

5 Conclusions

We have demonstrated a novel triple-cantilever based TENG for harvesting vibration energy in ambient environments. This innovative structure provides the middle cantilever with two chances to contact the top and bottom cantilevers in each cycle of the vibration, doubling the vibration energy conversion efficiency. Also, the surface modification by Cu film coated nanowire arrays plays an important role in improving the output. At the resonance frequency of 3.7 Hz, the newly invented TENG produces an open-circuit voltage up to 101 V, and a short-circuit current of 55.7 μA with a peak power density 252.3 mW/m^2. Relying on the harvested vibration energy, the TENG is able to simultaneously light up 40 LED bulbs. Our newly designed TENG provides a new approach for harvesting low-frequency vibration energy, opening its applications in self-powered electronics and systems.

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Electronic Supplementary Material: Supplementary material (a sketch of the central component with ZnO nanowire surface modification, enlarged peaks of one cycle of short-circuit current (I_{SC}) under the vibration frequency 3.7 Hz, robustness investigation of the triple-cantilever based TENG at 3.7 Hz and the rectified short-circuit current comparison between the two kinds of devices with or without surface modification at 3.7 Hz) is available in the online version of this article at http://dx.doi.org/10.1007/s12274-013-0364-0

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