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Magnetic Force-driven Noncontact Triboelectric Nanogenerator Based on Fe_3O_4 NPs Embedded PVDF Nanofibers

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Abstract

A novel magnetic force-driven noncontact triboelectric nanogenerator (TENG) for scavenging biomechanical energy to sustainably power-portable electronics is presented. PVDF fiber membrane with Fe_3O_4 nanoparticles embedded, based on the electrospun, is employed as a triboelectric layer. A magnet is utilized as the trigger to drive contact-separation mode TENG in a noncontact way due to the magnetic responsiveness of triboelectric materials. TENG with a small dimension has a peak output power of 0.23 mW under a load resistance of 25 MΩ. It exhibits a good stability for the output and charging performance, so it can be utilized to charge energy storage devices and sustainably power some portable electronics.

Keywords: nanogenerator, magnetic drive, energy harvesting

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1. Introduction

Due to the huge environmental issue from energy consumption of fossil fuels, harvesting green energy such as solar, wind, geothermal, and ambient mechanical energy has attracted much attention not only in academic pool, but also from industries. Traditional power supply methods with wires and batteries cannot fully meet the extensive requirement of portability of microelectronics [1]. By contrast, harvesting environmental energy, such as vibration, would be a potential way to address the issue. Currently, three main types of triboelectric nanogenerator (TENGs), including vertical contact-separation type, in-plane sliding type, single-electrode type, have been developed. Note that all these TENG devices have to contact directly with external mechanical motions, such as punch, friction, and so on [2, 3]. Unfortunately, those external mechanical motions may lead to some unavoidable and uncontrollable problems. For instance, the external mechanical motion in real world is very complex, including impact motion, rotation, and so on [4–6]. In this work, we propose and fabricate a novel type of magnetic driven noncontact TENG, in which the device contact is separated from external mechanical motion. By creative employing a magnetic triboelectric membrane layer made of PVDF fiber with Fe_3O_4 nanoparticles (NPs) embedded, which shows strong magnetic response, the TENG can be triggered in a noncontact way by external magnetic field. Direct contact between external mechanical motion and devices will contaminate and damage the electrode and polymer surface of TENG, which may seriously deteriorate the performance of the device in practical applications. The magnetically driven noncontact TENG may provide a solution to this problem.

2. Methods

2.1. Preparation of the Fe_3O_4@PVDF fiber membrane

The Fe_3O_4 nanoparticles were prepared via a solvothermal method as reported previously. For the preparation of Fe_3O_4@PVDF fibers, 10 wt% PVDF powder was initially dissolved in a mixture of acetone and N,N-Dimethylformamide (DMF). The ratio of acetone and DMF was 1:4. The synthesized Fe_3O_4 were then inserted into the PVDF solution. The electrospinning process was conducted under an electric field of 20 kV with a spray rate of 1 mL/h, in a closed box maintained at a relative humidity of less than 30%. The distance between the syringe tip and collector was about 15 cm. The composite fibers were directly collected on an Al foil. The resultant fiber membranes were dried at 80°C for 1 h.

2.2. Fabrication and measurement of the nanogenerator

An aluminum foil was fixed on the epoxy resin substrate, which served as both positively charged triboelectric layer and electrode of TENG. Then, the Al foil with a size of 6×3 mm^2, collecting composite fibers, was pasted on a PET strip with arch structure as the other electrode. The arch PET strip guaranteed the contact and separation process of the TENG with the action of applied magnetic field. Finally, an acrylic groove was employed to encapsulate the whole device. The open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}) of the devices were measured by a Keithley 2410 source measurement unit, and the data were collected and analyzed through a software platform Based on LabVIEW.

3. Results

To make triboelectric material having magnetic response, as-synthesized Fe_3O_4 NPs were embedded into PVDF fibers by electrospinning as shown in Figure 1(a). Figure 1(b) shows a SEM image of Fe_3O_4 NPs embedded into PVDF fibers; the diameter of fiber was in the range of 200–300 nm, and a small amount of Fe_3O_4 NPs were attached to the PVDF fibers. In order to illustrate the distribution of Fe_3O_4 NPs in PVDF fibers, a transmission electron microscopy (TEM) image of the composite fibers is shown in the inset of Figure 1(b). It can be seen that the Fe_3O_4 NPs were dispersed uniformly in PVDF fibers without agglomeration. The device structure is schematically illustrated in Figure 1(c). The electrospun Fe_3O_4@PVDF fiber membrane served as negatively triboelectric material and Al foil electrode was attached on the arch PET strip. A photograph of the as-fabricated TENG is demonstrated in Figure 1(d).

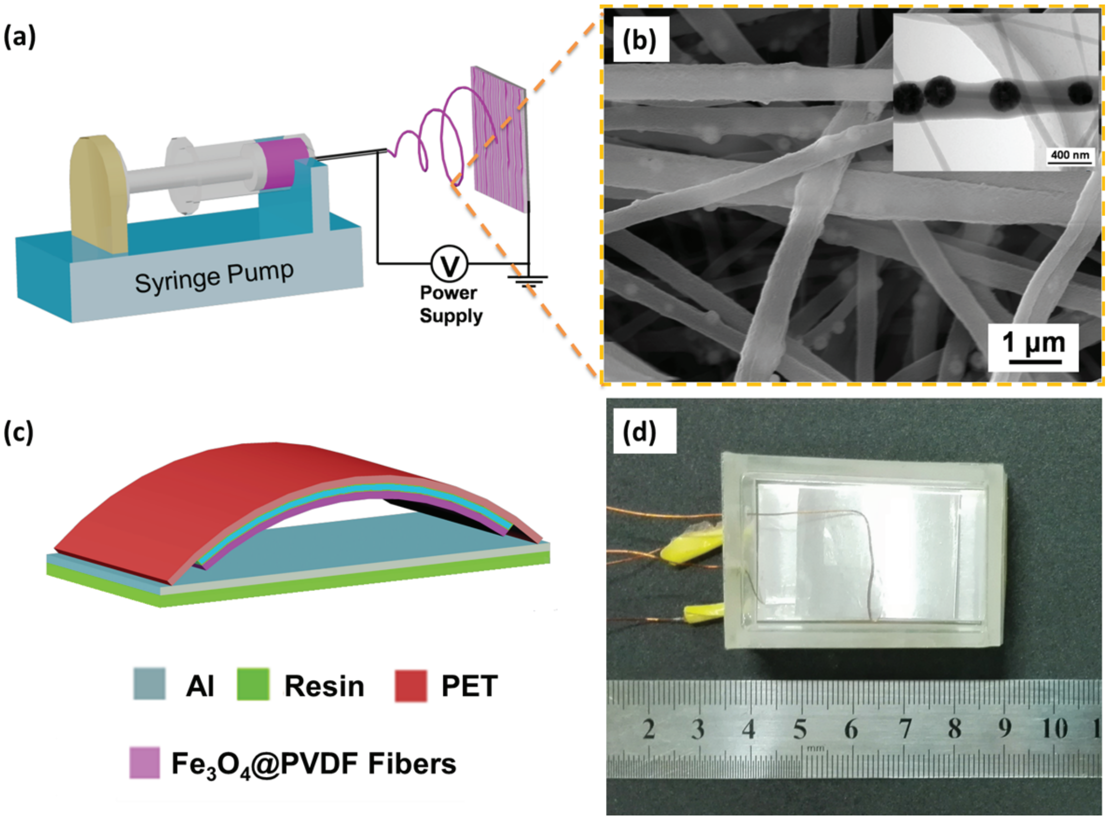

Figure 1: (a) Schematic illustration of preparing Fe_3O_4 NPs embedded PVDF fibers. (b) SEM and TEM image of Fe_3O_4 NPs embedded PVDF fibers. (c) Schematic illustration and (d) photograph of the magnetically driven triboelectric nanogenerator.

The electricity generated from the nanogenerator can be schematically illustrated in Figure 2. At the first state, the PVDF fiber membrane fully contacts the surface of Al foil, when the magnet stays near the device due to the magnetic absorption by the Fe_3O_4 NPs embedded in PVDF fibers (Figure 2(a)). In this process, as Al is much more

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triboelectrically positive than PVDF, electrons are injected from Al into the surface of PVDF fibers, which results in negative charging of PVDF fibers and positive charging of Al. Then, since the magnet derived by external mechanical force moves away from the device along the vertical, the surface of PVDF fiber membrane will be released with Al foil due to the arch-shaped PET strip. The separation of PVDF fiber membrane and Al foil can produce the electric potential difference between two electrodes of TENG. Because of that, the surface of PVDF fibers remains negative for a prolonged period of time owing to the insulation property of PVDF, consequently resulting in electron current in external circuit from the top electrode to the bottom one to keep electrostatic equilibrium (Figure 2(b)). The electrons' flow from the TENG can last until the distance between the magnet and the device reaches the maximum as presented in the third state (Figure 2(c)). Conversely, when the magnet re-approaches the generator along the vertical again, the electric potential difference starts to decline, producing the induced electrons' flow in a reverse direction, from the bottom electrode to the top one. Until the magnet stays near the device again, a full cycle of the electricity generation process finishes and a new cycle starts.

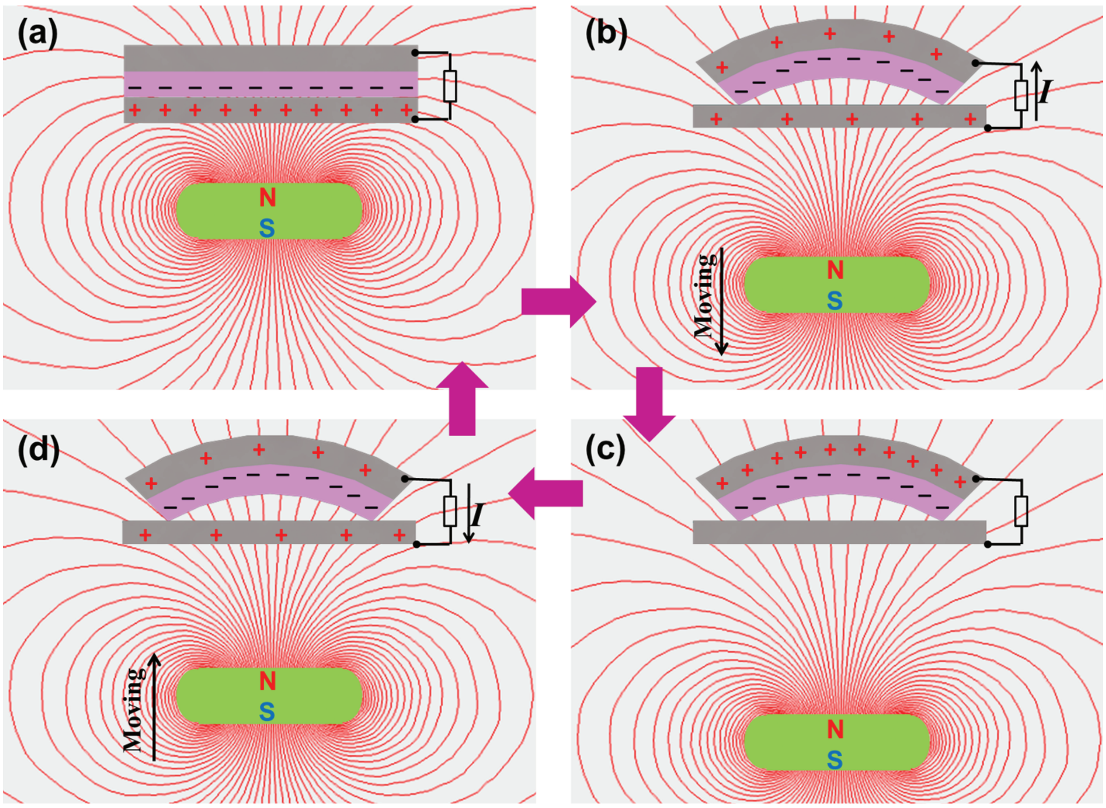

Figure 2: Schematic diagrams of the working principle of the magnetically driven triboelectric nanogenerator.

To evaluate the electricity generated from the TENG triggered by magnet under different distance between the device and the magnet, a liner motor is employed to simulate the separation-closing motion of the magnet to the generator as shown in Figure 3(a), the distance between the generator and magnet (d) ranges from 0 to 20 mm. The typical power generation capacities including V_{OC} and I_{SC} for TENG are shown in Figure 4(b). The results indicate that increasing the distance *d* leads to an obvious decrease in V_{OC} and I_{SC} for TENG. As displayed in Figure 4(a), for TENG, the measured peak value of V_{OC} reduces from ~88 V to ~14 V, and that of I_{SC} reduces from ~6 μA to ~0.85 μA as the distance d increasing from 0 to 20 mm. For further evaluation of the overall output capability for the TENG, the output current and output power of TENG under different external loading resistances were measured and calculated. As presented in Figure 4(c), the output current of TENG decreases dramatically as the external loading resistance varies from 1 to 100 MΩ. Consequently, the TENG has a maximum output power of about 0.23 mW under an external loading resistance of 25 MΩ. To demonstrate the reliability and durability of the TENG, the short-circuit current of the TENG was measured for more than 5000 cycles. Figure 4(d) shows that no decline is observed for TENG after long-term continuous operation. The charging voltage curves of the commercial capacitor by TENG are depicted in Figure 4(e), which suggests that the charging voltage of TENG can reach 5.5 V in about 300 seconds. Several applications were demonstrated by utilizing this self-powered system to sustainably drive various commercial electronic devices. Four LEDs, a thermohygrometer, and a digital watch were demonstrated as shown in Figure 4(e).

4. Conclusion

In summary, a noncontact magnetic force driven triboelectric nanogenerator has been demonstrated, utilizing for scavenging biomechanical energy to sustainably power electronics during human doing daily natural movement. The nanogenerator has a peak output power of 0.23 mW, which can be driven in a noncontact way by a locomotive magnet. The nanogenerator has a small dimension and a good stability for the output performance. Based on design of magnetic force drive, the nanogenerator can be separated with external mechanical motion, which protects the device from degradation and contamination caused by direct contact between external mechanical motion and the device. Moreover, the nanogenerator can be utilized to charge energy storage devices and sustainably power some portable electronics such as digital watch

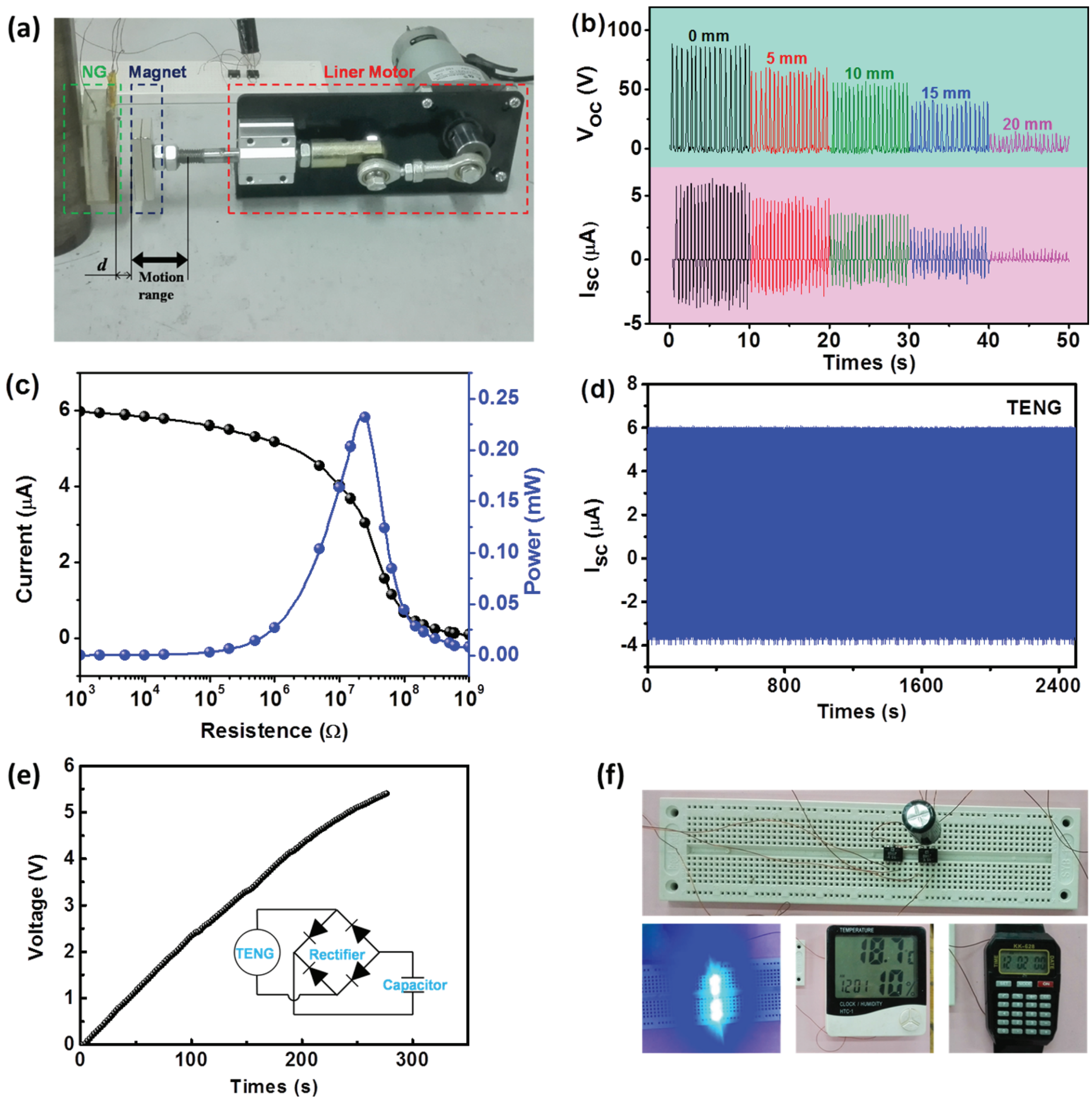

Figure 3: (a) Photograph of the setup for measuring the output performance. (b) The V_{OC} and I_{SC} versus time of TENG with different distances between the generator and the magnet. (c) The output power on the external loading resistance of the TENG. (d) The durability of the TENG. (e) The charging voltage curve of the commercial capacitor by TENG. (f) Demonstration of the self-powered electronic devices.

and thermo-hygrometer. This work demonstrates a novel prototype of hybrid nanogenerators toward harvesting human biomechanical energy and its potential applications in building up self-powered systems.

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