Harmonic-Resonator-Based Triboelectric Nanogenerator as a Sustainable Power Source and a Self-Powered Active Vibration Sensor

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Energy harvesting of ambient wasted energy addresses limitations of traditional power supplies by providing a supplementary electric power source. Vibration, as a type of common mechanical motion, is ubiquitous in daily life, from operating household appliances, such as washing machines and refrigerators, to bouncing automobile tires on a gravel road. In recent years, it has become an attractive target for energy harvesting as a potentially alternative power source for battery-operated electronics. Until recently, the mechanisms of vibrational energy harvesting have been limited to transductions based on piezoelectric effect,[1–5] electromagnetic effect,[6] electrostatic effect,[7] and magnetostrictive effect.[8] Widespread usage of these techniques is likely to be shadowed by possible limitations, such as structure complexity,[9] fabrication of high-quality materials,[10] and reliance on external power source.[9] Furthermore, all of the mechanisms require energy-harvesting devices to operate at or within a very narrow range around resonance frequency. However, most ambient vibrations have a wide distribution of frequency spectrum, which may even drift over time, making the conventional mechanisms unsuitable in most circumstance. Generally, an effective vibrational energy harvester needs to meet at least two criteria.[11] First, it can be applicable to a broad range of vibration frequency instead of a single resonance frequency. Second, it can effectively respond to vibrations at low frequency (below a few hundred Hz), as most ambient vibrations lie in this range (the natural oscillation frequencies range from 1–10 Hz for human motion and 10–100 Hz for machine-induced vibrations).[12]

Recently, triboelectric nanogenerators (TENGs),[13–22] which are creative inventions for harvesting ambient mechanical energy on the basis of the triboelectric effect,[23–25] have proved to be a cost-effective, simple, and robust technique for self-powered devices and systems. Owing to coupling between the triboelectric effect and electrostatic induction, the periodic contact and separation between two materials with opposite triboelectric polarities alternatingly drives the induced electrons between electrodes.

Here, we introduce a new principle in harvesting vibration energy by fabricating a harmonic-resonator-based TENG. It is the first TENG that can harness random and tiny ambient vibration, which is the most common and usually the sole available mechanical source for self-powered electronics, especially in wireless sensor applications. The rationally designed TENG, operating at resonance frequency, produces a uniform quasi-sinusoidal signal output at an open-circuit voltage up to 287.4 V and a short-circuit current amplitude of 76.8 μA, corresponding to a peak power density of 726.1 mW m^{-2}. Compared to state-of-the-art nonlinear and topology-variation-based vibration energy harvesters,[26–28] it has a considerably wider working bandwidth of 13.4 Hz in low frequency range. It has proved to be effective in harvesting energy from common ambient vibrations including car engine and household furniture. With vibration amplitude less than 3 mm, it can still deliver stable electric output after operating for more than 1 million cycles (Figure S2, Supporting Information). In addition, the TENG can also act as a self-powered active sensor for detecting ambient vibration, such as roadside vibration triggered by normal human walking. The concept and design presented in this work can be further applied in various other circumstances for either energy-harvesting or sensing purposes: for example, highways, bridges, and tunnels. Therefore, it is a milestone in the development towards TENG-based self-powered electronics.

The harmonic-resonator-based TENG has a multilayer structure with acrylic as supporting substrates, as schematically shown in **Figure 1**a. Acrylic was selected as the structural material owing to its decent strength, light weight, good machinability, and low cost. A photograph of an as-fabricated TENG is shown in Figure 1b. On the upper substrate, aluminum thin film with nanoporous surface has dual roles as an electrode and a contact surface. A scanning electron microscopy (SEM) image of nanopores on the aluminum is presented in Figure 1c. The average diameter of aluminum nanopores are 57 ± 5 nm and a pore depth of 0.8 ± 0.2 μm with a distribution density of 212 μm^{-2}. A layer of polytetrafluoroethylene (PTFE) film was adhered to the lower substrate with deposited copper as another electrode. PTFE nanowires arrays were created on the exposed PTFE surface by a top-down method through reactive ion etching. SEM image of the PTFE nanowires is displayed in the Figure 1d. The average diameter of PTFE nanowires is 54 ± 3 nm with an average length of 1.5 ± 0.5 μm. The

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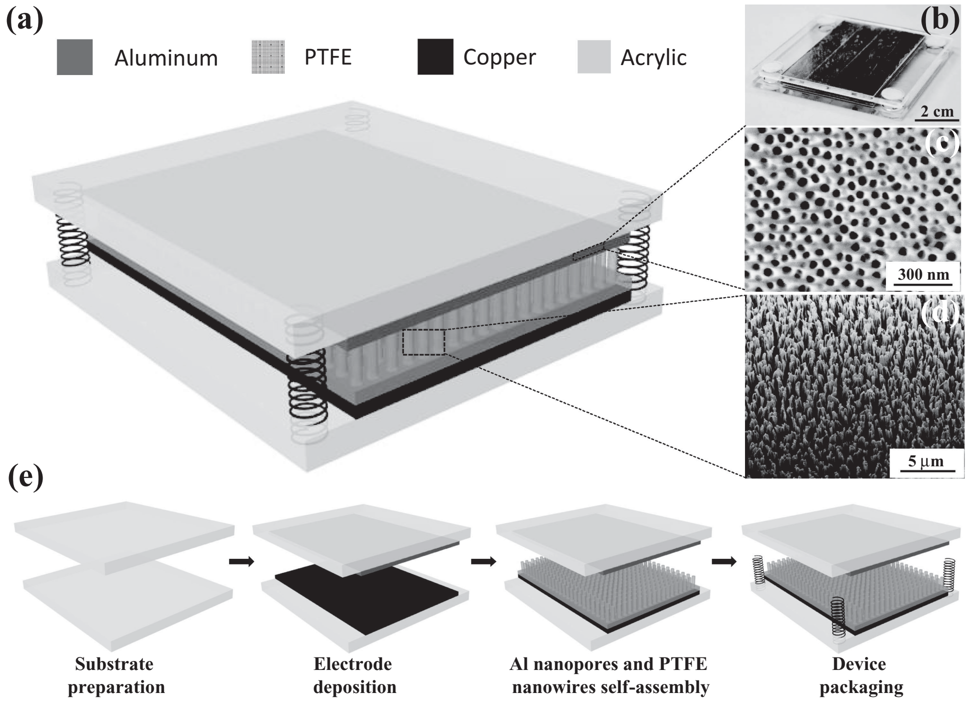

Figure 1. Harmonic-resonator-based triboelectric nanogenerator. a) A sketch and b) a photograph of a typical harmonic-resonator-based TENG. c) An SEM image of nanopores on aluminum electrode. d) An SEM image of PTFE nanowires. e) Process flow for fabricating the harmonic-resonator-based TENG.

fabrication process for the TENG is sketched in Figure 1e and discussed in details in the Experimental Section.

To operate, the bottom substrate of the TENG is attached to an external vibrational source. A cycle of electricity generation process is illustrated in **Figure 2**. At original position, the PTFE layer is in contact with the aluminum thin film. Because PTFE is much more triboelectrically negative than aluminum, electrons are injected from aluminum into PTFE, generating positive triboelectric charges on the aluminum side and negative charges on the PTFE side (Figure 2a).[13–15,29,30] Once an external vibration acts on the TENG, it accelerates and moves upwards. After the vibration source reaches the crest point, the lower substrate attached to the vibration source ceases to rise and starts dropping downwards. However, the upper substrate keeps moving up owing to its inertia. Thus, the two substrates move apart, leading to a separation between the PTFE and the aluminum. As a result, the positive triboelectric charges and the negative ones no longer coincide on the same plane and generate an inner dipole moment between the two contact surfaces. Such a dipole moment drives free electrons from the copper electrode to the aluminum electrode to balance out the electric field, producing positively induced charge on the copper electrode (Figure 2b). The flow of electrons lasts until the upper substrate reaches the highest point, where the corresponding separation is maximized (Figure 2c). Subsequently, the upper substrate is pulled downwards by the restoring force from the four stretched springs at corners. In reponse to the reduced seperation and thus to the weakened dipole moment, free electrons flow back to the copper electrode until the two contact surfaces come into collision, making a complete cycle of electricity generation process (Figure 2d). The upper electrode is then bounced upwards again after obtaining a momentum from the collision, starting another cycle. Therefore, the TENG acts as an electron pump that drives electrons back and forth between electrodes, producing alternating current in the external circuit.

To investigate the performance of the TENG in harvesting vibration energy, an electrodynamic shaker (from Labworks Inc.) that provides a sinusoidal wave was used as a vibration source with tunable frequency and amplitude. The lower substrate of the TENG was anchored on the shaker, leaving the the upper part free-standing. At a fixed vibration amplitude, the reliance of electric output on the input vibration frequency is presented in **Figure 3**a and Figure 3b. The electric output can be measured with broad input frequencies varying from 2 to 200 Hz. Compared to state-of-the-art vibration energy harvesters that are based on nonlinear and topology variation,[26–28] it has a considerably wider working bandwidth of 13.4 Hz (see Figure S3, Supporting Information).

Experimentally, both the open-circuit voltage (V_{oc}) and the short-circuit current (I_{sc}) are maximized at the vibration frequency of 14.5 Hz with maximum values of 287.4 V and 76.8 μA, respectively, indicating that 14.5 Hz is the resonance frequency of the TENG. Theoretically, for a single degree-of-freedom vibration system, the natural frequency is given by (see Supporting Information for detailed derivation):[31]

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{4k}{m_0}} \tag{1}$$

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