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RAPID COMMUNICATION

High performance sound driven triboelectric nanogenerator for harvesting noise energy

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Abstract
Sound energy is one kind of the most widely distributed energies in the environment. Harvesting the sound energy, reducing noise and converting it into electricity have great potential to power nano/microsensors for internet of things, structure monitoring, environment monitoring, etc. Based on electrospun polyvinylidene fluoride (PVDF) nanofibers, we have fabricated a sound driven triboelectric nanogenerator (TENG) that can work stably in broad bandwidth ranging from 50 Hz to 425 Hz. Its maximum output current reaches up to 0.45 mA and its charging rate is 61 μC/s. Furthermore, the TENG continuously worked for 7 days and vibrated 100 million cycles, no decay in output signal was observed. The high performance and good robustness provide with great prospect to scavenge the noise energy in environment.

Introduction

Sound wave is a kind of clean, ubiquitous and sustainable energy source existing in every corner of the world. And it is always taken as an unwanted or even irritated noise, which is polluting our daily life [1,2]. Finding a convenient and feasible way to harvest such kind of energy is an important

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issue not only from an environmental point of view, for example adsorbing ambient noise, but also for the energy harvesting for powering personal electronics and sensors [3-6]. However, only a few researches and applications about acoustic energy harvesting have been conducted due to the following reasons. First, like most ambient vibrations, sound wave vibration has a special vibrational frequency with a certain bandwidth, which may even drift and fluctuate with time and location. Second, compared to the pressure on the contact-mode vibrational energy harvesters [7-10], the sound pressure applied on the surface of sound harvesting device is extremely small. Pressure of the sound at 100 dB is only 2 Pa. Therefore, some characters must be required for the sound harvesting device to effectively harvest the acoustic energy, including that it should be applicable to a broad and proper vibration frequency range instead of a single resonance frequency and should be much more sensitive than other vibrational energy harvesters. In previous explorations of the sound energy harvesting, the most reported works were focused on the nanogenerators based on piezoelectric effect [11-16]. However, their output performance is relatively low because of the following two reasons. One is the mismatch between inherent frequency of the device and the common sound-wave frequency, which results in a great energy loss in the process of sound harvesting. To date, the best output current of the piezoelectric sound harvester is only 300 nA/cm^2 [15]. The other problem is the small bandwidth of the device. A nanogenerator made up of rigid piezoelectric material often has a certain resonant frequency. Once the driven frequency was away from the resonant frequency, the generator would hardly work properly. To solve this problem, a more reasonable harvesting principle and structure roots to the characters of sound wave are needed.

Recently, an innovative triboelectric nanogenerator (TENG) based on triboelectric effect has been developed for harvesting mechanical vibration energy [17-21]. By coupling with the triboelectric effect and the electrostatic induction, TENG can convert almost any type of mechanical energy into electric energy [5,22-24]. With a cycled process of contact and separation between two different materials in the triboelectric series, electrons will be driven to flow in the external circuit between the electrodes. In previous works, researchers reported that acoustic energy can be harvested by a flat organic film TENG [25,26]. Typically, the maximal current density and power output of the device have reached 1.6 mA m^{-2} and 60.2 mW m^{-2}, respectively [25]. However, the continuous flat substrate used in the TENG cannot absorb the sound wave effectively.

Here, we have developed a new mesh-membrane based TENG which rooted to the characteristics of sound wave. The thin and lightweight vibrating membrane facilitates to absorb the low frequency sound wave energy and displays a sensitive response to small sound-wave pressure. Also, the porous mesh substrate facilitates sound-wave spread greatly and reduces the sound energy loss in substrate. Our experimental results show that the TENG device can be driven by sound-wave in broad bandwidth ranging from 50 Hz to

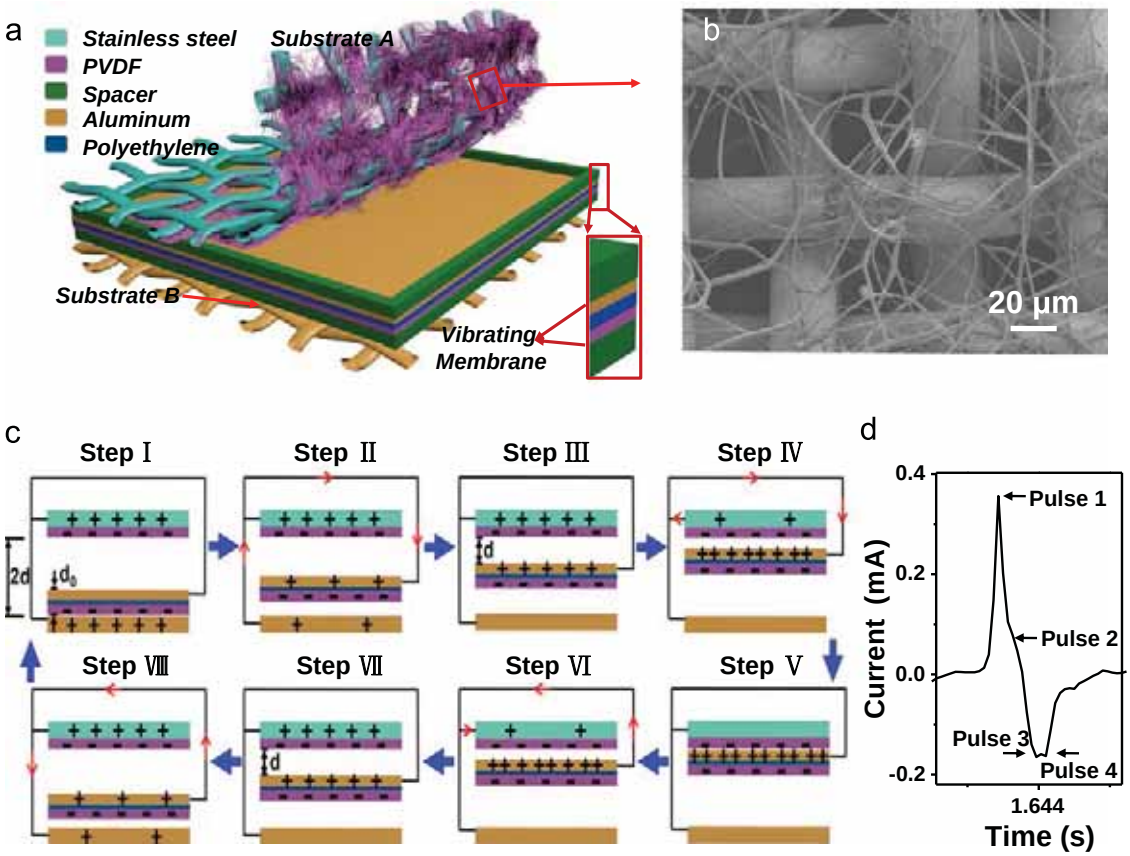

Figure 1 (a) Schematic of a fabricated sound driven TENG. (b) SEM image of the PVDF nanofibers on the stainless steel mesh. (c) Working mechanism of the sound driven TENG. (d) The output current signal in one cycle.

425 Hz. And it reaches a short-circuit current density as high as 45 mA m^{-2} and peak power density of 202 mW m^{-2}, which are 28 times and 3.4 times higher than that of the previous report [25]. Moreover, this type of TENG shows stable electric output and good robustness. It is believed that this design can be expanded in a variety of other circumstances for energy harvesting purposes.

Materials and methods

Preparation of PVDF nanofibers

3.75 g PVDF, 8.50 g N,N-dimethylacetamide (DMAC) and 12.75 g acetone are mixed in a 50 mL triangular flask. After vigorous stirring at 60 °C for 30 min, a homogeneous sol-gel solution is formed. Then the solution is transferred into a syringe for electrospinning. The electrospinning process is performed at 15 kV, with 16 cm spacing between the needle tip and collector, and a feed rate of 3 mL/h. The electrospun nanofibers are dried at 60 °C for 30 min in a ventilated oven.

Fabrication of the TENG

As shown in Figure 1a, the device is a sandwich structure composed of two substrates (substrates A and B) and one vibrating membrane. The mesh structure allows the air circulation and benefits to the penetration of sound wave. The substrate B acts as the contact surface and the bottom electrode. And the substrate A works as the top electrode. Figure 1b shows the distribution of nanofibers on the substrate A's surface. First, to fabricate the TENG, two pieces of flat stainless steel mesh with side length of 10 cm and mesh aperture of 40 μm are used as substrates. A layer of Al thin film is deposited on one of the steel meshes using magnetron sputtering. This Al covered mesh acts as bottom substrate (substrate B) as shown in Figure 1a. And then a layer of PVDF nanofibers is deposited on another steel mesh by electrospinning [27], as the top substrate (substrate A) as shown in Figure 1a. After that, a piece of polyethylene film with side length of 10 cm is used as the vibrating membrane of the device, whose one surface is coated with Al thin film and the other surface is coated with PVDF nanofibers layer (Figure 1a). Finally the vibrating membrane consists of three layers from bottom to top: PVDF nanofibers layer, polyethylene thin film and Al film. The thickness of the whole vibrating membrane is about 5 μm. To form a small space for the vibration, two spacers are installed. One is between the substrate A and the vibrating membrane, and the other is between the substrate B and the vibrating membrane. Double sticky tapes are used as spacers to bond the two substrates and the vibrating membrane together to form a sandwich structure. The thickness and width of the spacers are 50 μm and 5 mm respectively. Finally, conducting wires are connected to the three metal layers as leads for subsequent electrical measurement.

Results and discussion

The electric energy generation process can be attributed to the coupling between triboelectric effect and electrostatic effect, as sketched in Figure 1c. As the initial state, the polyethylene film is close to the bottom stainless steel mesh due to the gravity, and the distance between the two substrates is 2d. The thickness of the vibrating membrane is d_0, which is much less than 2d. When the acoustic source is turned on, driven by the fluctuant air pressure, the polyethylene membrane will vibrate. In this process the Al and PVDF nanofibers are brought into contact. According to the triboelectric series ranking materials' tendency to gain or lose electrostatic charges, electrons in the electrodes will be driven to flow from Al into PVDF and will be retained on the PVDF (Step I in Figure 1c). When the polyethylene membrane begins to move upwards, Al film on its surface, which can be called middle electrode here, possesses a lower electric potential than bottom substrate. And then the current will flow from bottom substrate to the middle electrode (Step II in Figure 1c). As the polyethylene membrane moving to the middle of the two substrates, all the positive charges accumulated at the bottom electrode are transferred to the middle electrode (Step III in Figure 1c). When the polyethylene membrane moves upwards unceasingly, the middle electrode possesses a lower electric potential than the top substrate and the current will flow from the top substrate to the middle electrode (Step IV in Figure 1c). Until the membrane rises to the top, all of the positive charges will be transferred to the middle electrode (Step V in Figure 1c). When the membrane reverts back to the middle position, the current will flow from the middle electrode to the top substrate to maintain the lowest electric potential energy in the system (Steps VI-VII in Figure 1c). And the distribution of the charge returns to Step I when the membrane reverts back to the original position, which makes the current flow from the middle electrode to the bottom electrode, as illustrated in Steps VIII-I in Figure 1c. Thus a whole cycle should compose of four current pulses, two forward pulses and two backward pulses. The details of the current output signal in one cycle can be observed in Figure 1d. It can be found that this current signal consists of four pulses, two pulses are in the forward direction, and the other two are in the backward direction. The insulating PVDF permits long-time retention of the triboelectric charges on its surface. Along with the vibration of the PVDF, the position of the bound charges changes constantly, and the free electrons in the external circuit will also flow from one electrode to another. With the membrane vibrating continually, the sound energy will be converted into AC electricity.

To trigger the TENG, a mini speaker is used to supply the sonic wave. The sound intensity level (SIL) and the driving frequency are controlled by a program that is written with the LabVIEW program. And the SIL is measured with a decibelmeter. Open-circuit voltage and short-circuit current of the TENG at different frequencies with the SIL of 100 dB are presented in Figure 2a and b respectively. Figure 2c and d show the enlarged views of the voltage and current output when the driving frequency is fixed at 175 Hz. They indicate that the TENG can work in a wide range of sound frequency from 50 Hz to 425 Hz. It can also be found that the output voltage and current increase with frequency rising at the range from 50 Hz to 175 Hz, and then decrease from 175 Hz to 425 Hz, which can be attributed to that the resonant frequency of the membrane is just around 175 Hz. Under

the resonance frequency, the enhanced amplitude would generate a larger contact area of the surfaces, which would cause a larger current. Conversely, when the driving frequency deviates from the resonance point, the reduced amplitude would cause the current decreasing. Typically, at the frequency of about 175 Hz, both the output voltage and current reach a maximum value of 90 V and 0.18 mA. For a TENG with the area of 0.01 m^2, the current density is 18 mA m^{-2}. When the driving frequency reaches 425 Hz, the output current reduces to 18 μA, which is one tenth of the peak value of the maximum current.

Apart from the frequency, the TENG's electric output is also related to the SIL. With the raising of SIL, the sound pressure increases continually. As a result, the contact area of the surfaces will increase, and the output current increases accordingly. Figure 2e and f shows the output

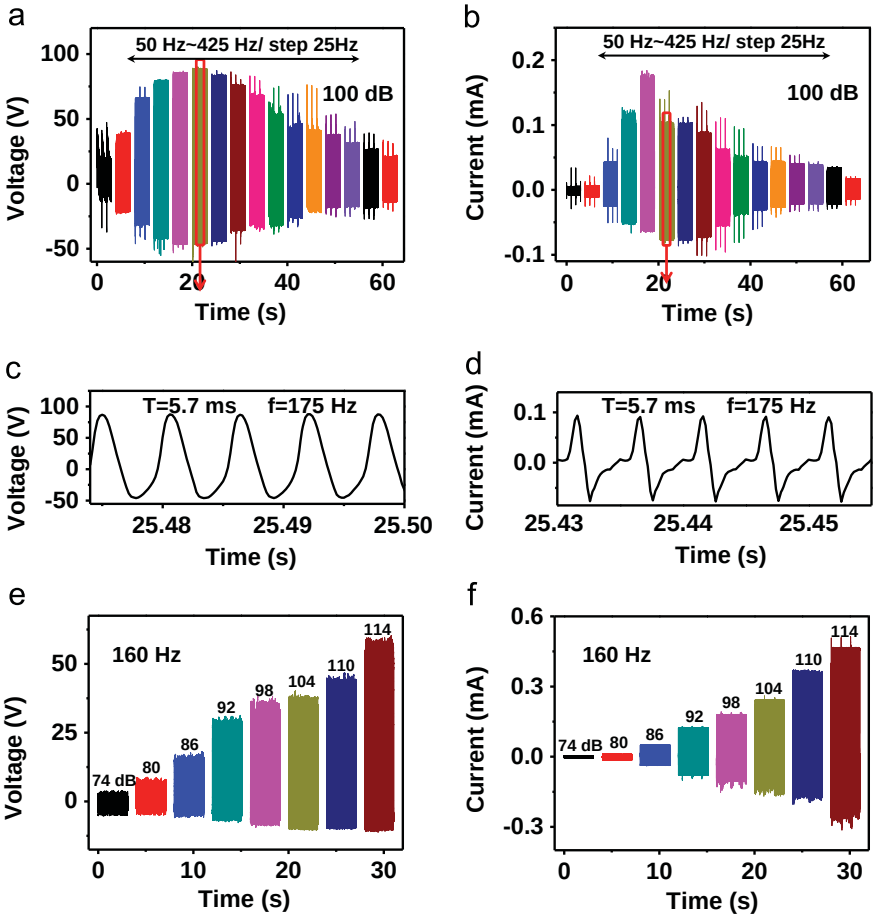

Figure 2 (a) Open-circuit voltage and (b) short-circuit current at different driving frequency from 50 to 425 Hz (step is 25 Hz). The loudness keeps at 100 dB. (c) The enlarged view of the voltage output signal at driving frequency of 175 Hz. The frequency of the voltage signal is also 175 Hz accurately. (d) Enlarged view of the current output signal at driving frequency of 175 Hz. (e) Open-circuit voltage and (f) short-circuit current at different loudness from 74 dB to 114 dB with the frequency keeping at 160 Hz.

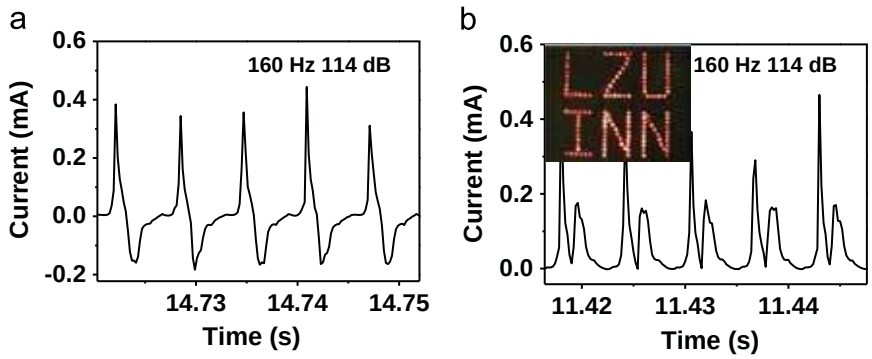

Figure 3 (a) The enlarged view of the short-circuit current when the frequency and the loudness of the sound are adjusted to 160 Hz and 114 dB respectively. The peak value of the current reaches 0.45 mA. (b) Rectified short-circuit current by a full-wave bridge at driving frequency of 175 Hz. The inset is the photograph of 138 lighted LEDs driven by TENG.

current and voltage signals driven by 160 Hz sonic wave at different loudness. With the increasing of the SIL from 74 dB to 114 dB, the output signals increase monotonically. As we adjust the SIL to 114 dB, the peak value of the current reaches 0.45 mA and the corresponding electric current density is 45 mA m^{-2}. As a result, the peak power (I^2R) density at the load resistance of 100 Ω is 202 mW m^{-2}. The current density and power density are 28 times and 3.4 times higher than those of previous reports [25]. The enlarged view of the output current signal is shown in Figure 3a. Furthermore, the AC output could be transferred to direct current pulse output simply by using a full-wave rectifying bridge (Figure 3b). And in this case, our device can instantaneously power the LEDs without energy storage process. Working in 114 dB/160 Hz noise environment, our nanogenerator could instantaneously light up as many as 138 LEDs (inset of Figure 3b and Supporting information Video 1). Besides this we also took a simple test on the side of road. To harvest the noise energy of the passing automobile, we fixed the TENG on one side of a resonating chamber and put the whole chamber on the sidewalk. Using a universal meter, the output voltage signals of 0.1–0.8 V can be detected. And the test process is shown in Supporting information Video 2. Considering above relations of output electrical signal with frequency and SIL, and the large output electricity, this new developed sound-driven TENG shows potential to be applied as a self-powered sound sensor.

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.nanoen.2015.04.008.

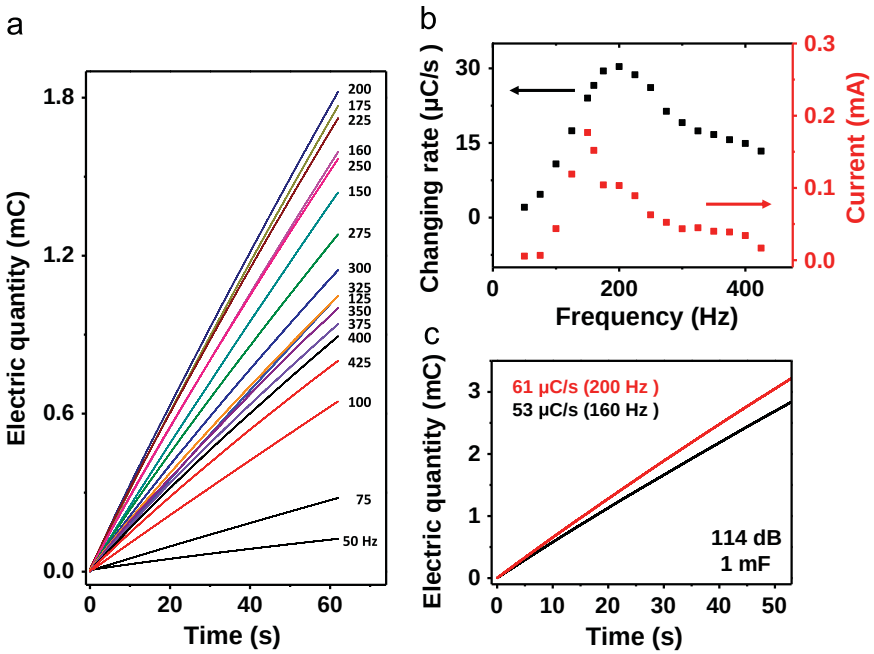

Figure 4 (a) Charging curves of the TENG at different driving frequency from 50 to 425 Hz (step is 25 Hz). Via a full-wave bridge, the electrons are pumped into a capacitor of 1 mF. The SIL keeps in 100 dB. (b) Charging rates of the TENG at the different driving frequency (black squares). The peak values of the current at the different driving frequency (red squares). (c) Charging curves of the TENG at 160 (black line) and 200 Hz (red line). The maximum charging rate at 200 Hz reaches 61 μC/s when the SIL is adjusted to 114 dB.

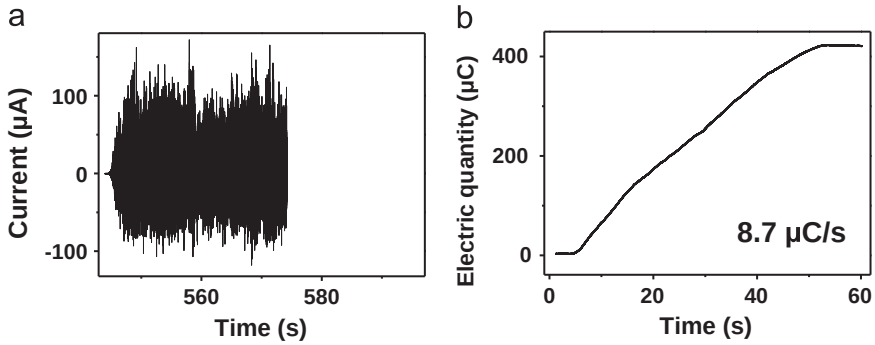

Figure 5 (a) Current output signal of the TENG in the simulated busy street environment. The SIL is controlled at 90 dB. (b) Charge curve of the TENG in the simulated busy street environment. The charging rate is 8.7 μC/s.

The output current of the TENG is consisted of many current pulses. In another word, there is a time-gap between each two pulses. So the peak value of the current pulse cannot completely represent the output properties of the sound energy harvester. What we value more is the actual electrical charge generated by the TENG. Obviously the peak value and the frequency together determine the final output charge. Keep the SIL at 100 dB, adjust the sound frequency from 50 Hz to 425 Hz and then charge a 1 mF capacitor respectively. As demonstrated in Figure 4a, the sound with different frequencies give different charging rates. When the driving frequency is adjusted to 200 Hz, the device achieves its maximum charging rate of 30.4 μC/s and the voltage of the capacitor reaches 1.8 V within only 1 min. In Figure 4b we can find that with the increase of driving frequency, the charging rate (black triangles) initially increases and then decreases. Similarly, the peak value of the current also has the same characteristic (red squares in Figure 4b). But the maximum peak value of the current is obtained at 160 Hz while the maximum charging rate point is at 200 Hz. This is because different factors work on the current and the charging rate. The peak current is determined by the amplitude of vibrating membrane, but the charging rate is determined by peak current and frequency. Furthermore when the SIL increases to 114 dB the charging rate of our device at 200 Hz can reach 61 μC/s. In this case, charging a 1 mF capacitor to 3 V only needs 49 s. So if this TENG can be used to collect energy from the noisy environment such as workshop, busy street and expressway, the saved energy would be rather appreciable.

The energy harvesting ability of our TENG is excellent for the single-frequency noise. But usually our environment includes every kinds of noise, we must test the property of TENG in conditions with broadband frequency noises. We gather a busy streets audio recording which includes horns, rumpus, and the shouts of street vendors etc. We use this audio recording as noise source to drive the TENG and keep the SIL of the sound at 90 dB. The current output of the TENG is shown in Figure 5a. The whole harvesting process lasts for 52 s and the peak value of the current reaches 180 μA. In this process we collect a total charge of 422 μC in the 1 mF capacitor (Figure 5b).

In addition to the output characteristic, the robustness of the sound driven TENG is also very important to practical application. Here we demonstrate an endurance test of the TENG. Keeping the TENG continually working at 100 dB/160 Hz sound for seven days (the vibrating membrane vibrates 100 million times totally) without any pause, the output current signal at regular intervals is measured. The result is shown in Figure 6a–d. From the initial moment to 1 h, the output current increases slowly. One day later the output current is stable at 0.22 mA. After sustained working for seven days, the output current still has no attenuation. And the contact surface of the working TENG is further checked by SEM. The SEM images show that the nanofibers coated on the membrane do not have any breakage compared with the initial configuration (Figure 6e and f), which further indicates our sound driven TENG has a very strong robustness. The strong robustness paves the way for the actual application of the sound driven TENG.

Conclusions

In summary, we developed a new type of sound driven TENG that can be used to harvest the noise energy in the environment. This TENG shows good performances of noise harvesting in a wide frequency bandwidth. The maximum short-circuit

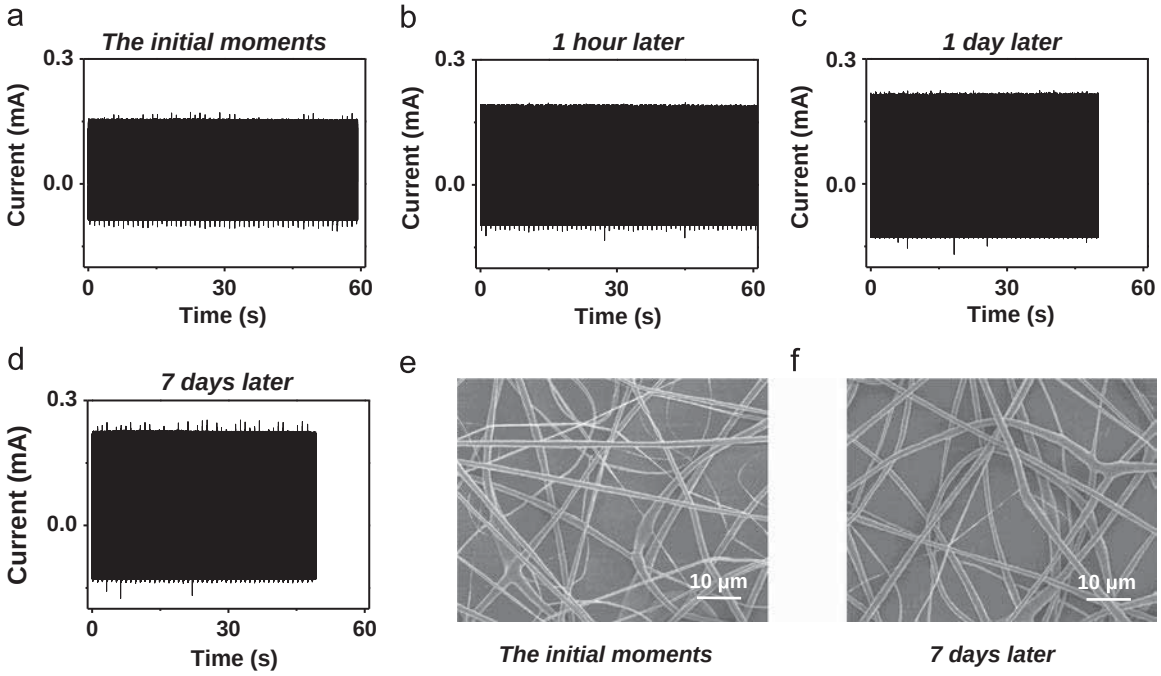

Figure 6 Robustness of the sound driven TENG working at 100 dB/160 Hz. (a) The current output of the TENG at the initial moment. The peak value of the current is 0.15 mA. (b) One hour later the current rose to 0.19 mA. (c) After a day the current has stabilized at 0.22 mA. (d) Seven days later, the output current still stabilized at 0.22 mA. In the whole process the vibrating membrane has vibrated 100 million times totally. (e, f) The SEM images of the PVDF nanofiber microstructure in the sound driven TENG before and after continuous working for seven days.

current density and open-circuit voltage reach 45 mA m^{-2} and 90 V. Furthermore, the sound energy harvester has a high charging rate of 61 μC/s and a maximum power density of 202 mW m^{-2}. Compared to the previous reported results, this TENG presents much better output performance. After sustained working of 7 days, the output signal has no attenuation, which displays a perfect durability of the TENG. And because of these excellent output performances and the outstanding durability characteristics, the sound driven TENG demonstrated in this work can be further applied in a variety of circumstances for either noise energy harvesting or sensing purposes. It benefits to the field of noise energy harvesting, and gives a way to power internet of things and other widely spread sensors.

Acknowledgments

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.nanoen.2015.04.008.

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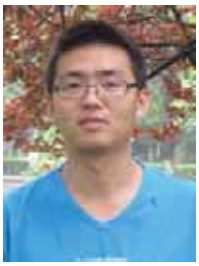

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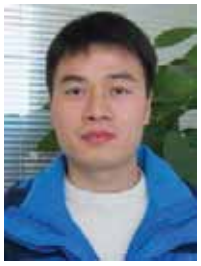

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