Waterproof and stretchable triboelectric nanogenerator for biomechanical energy harvesting and self-powered sensing

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Waterproof and stretchable triboelectric nanogenerator for biomechanical energy harvesting and self-powered sensing

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We introduce a waterproof and stretchable triboelectric nanogenerator (TENG) that can be attached on the human body, such as fingers and the wrist, to harvest mechanical energy from body movement. The whole device is composed of stretchable material, making it able to endure diverse mechanical deformations and scavenge energy from them. Under gentle mechanical motions of pressing, stretching and bending, the device with an effective area of $1 \times 2\,\text{cm}^2$ can generate the peak-to-peak output current of 257.5 nA, 50.2 nA, and 33.5 nA, respectively. Besides, the TENG is tightly encapsulated, enabling it to avoid the influence of the external environment like humidity changes and harvest energy under water. Particularly, owing to the thin and soft properties of the encapsulation film, the device can respond to weak vibrations like the wrist pulse and act as a self-powered pulse sensor, which broadens its application prospects in the field of wearable energy harvesting devices and self-powered sensing systems. *Published by AIP Publishing.* https://doi.org/10.1063/1.5028478

Deformable and stretchable electronics have experienced a rapid development in recent years due to their potential in a number of new applications, such as wearable electronics, artificial electronic skins, implantable devices and prosthetics.[1–3] Consequently, a deformable energy source with similar properties is in high demand to continuously supply power to them.[4,5] To achieve this function, various types of energy harvesters have been explored to scavenge energy from an ambient environment, such as solar cells and nanogenerators based on piezoelectric, pyroelectric or triboelectric mechanisms.[6–9] Among them, a triboelectric nanogenerator (TENG) that can convert diverse types of mechanical energy into electricity is an attractive renewable power source due to its advantages of low cost, high efficiency in the low frequency and a vast choice of materials.[10–13] Besides, the output of a TENG is related to the characteristic of mechanical motion, which enables it to work as a self-powered sensor for monitoring changes in the external environment, such as pressure, contact location, acceleration and angle.[14–16]

Up to now, efforts have been made to develop stretchable and wearable TENGs, such as the fabric-based TENG being integrated with common clothes,[17] highly stretchable single-electrode TENGs based on conductive nanowires or liquid, and an ultrathin dual mode patch acting as a self-powered sensor.[18–20] However, the electrical output of a TENG is susceptible to humidity and the device will become invalid owing to the absence of triboelectric charges when the friction surface is covered by water or dust.[21] To make the device screened from the influence of undesired factors like sweat when working as a wearable device, it is necessary to protect the friction surface from the external environment.[22] For this purpose, a stretchable and encapsulated TENG is a choice since it can avoid the influence of external conditions while enabling the relative movement of friction layers.[23] In addition, the sensing ability of a TENG will be more stable when working as a self-powered sensor.

Here, we developed a fully encapsulated and stretchable TENG that is able to generate electric output under diverse mechanical motions and respond to different deformation degrees. The device has a simple airbag structure with a single electrode, which is composed of intrinsically stretchable polyurethane (PU) nanofibers and silver nanowires. To make the device stretchable and waterproof, micro-patterned polydimethylsiloxane (PDMS) is adopted as both the friction and encapsulation layers due to its hydrophobic property. Taking advantage of its self-recovery structure, the stretchable TENG is capable of harvesting body motion energy without contacting other objects when attached on body joints. Besides, by virtue of the thin and soft properties of the encapsulation film, the device can work as a self-powered bending sensor and a pressure sensor to monitor small vibrations like the wrist pulse. This work provides a practical approach for deformable power sources as well as self-powered sensors and has potential applications in various areas such as wearable health monitoring systems, robotics and human-machine interfaces.

The structure of the stretchable TENG is schematically depicted in Fig. 1(a), which integrates a stretchable electrode and a micro-patterned friction layer, separated by a thin PDMS frame. The whole device ($1.5\,\text{cm} \times 3\,\text{cm}$) is fully encapsulated and has an air gap of 2 mm between the electrode and the PDMS friction layer, enabling them to contact and separate, and thereby the generation of electric output. The schematic cross-section view of the device is shown in Fig. 1(b) to reveal its inner configuration. The electrode is fabricated by covering the electrospinning polyurethane nanofiber with silver nanowires through a dip coating process, and the SEM image of which is shown in Fig. 1(c). Figure 1(d) presents the SEM image of the micro-patterned PDMS, which is helpful to

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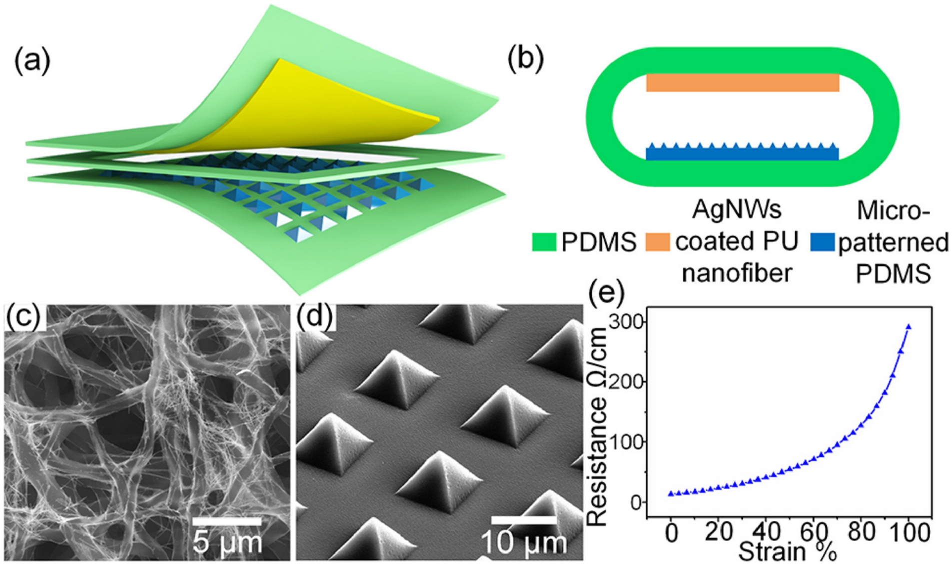

FIG. 1. (a) Structure schematic of the TENG. (b) Cross-section view of the device. (c) and (d) SEM images of the PU nanofibers (c) and a micro-patterned PDMS (d). (e) Resistance changes of the PU electrode with the increase of tensile strain.

increase the friction contact area and decrease the viscosity of the PDMS surface. The detailed fabrication method of the microstructure can be found in our previous report.[18] To verify the validity of the electrospinning nanofiber as a stretchable electrode, we measured its resistance changes as the variation of strain. As shown in Fig. 1(e), although the resistance of the as-fabricated electrode increases with the elongation, this increase is acceptable and will have little negative impact on the TENG's performance since the inherent impedance of the TENG is on the scale of MΩ.

The working mechanism of the stretchable TENG is described in Fig. 2, which is based on the triboelectric effect and electrostatic induction. As a typical single-electrode TENG, the device electrode is connected with a reference electrode (e.g., ground and body) through an external circuit to enable electrons to flow between them. After several rounds of contact and separation process, the surfaces of PDMS and the electrode are covered with opposite charges due to different electron affinities [Fig. 2(a)]. When the device is pressed or stretched, the air in the device will be squeezed to the side and the gap between the triboelectric couple will decrease. To achieve electrostatic equilibrium, positive charges will be attracted from the ground to the electrode, thus forming a positive current in the external load [Fig. 2(b)]. After getting to the maximum compression, electrostatic attraction is the strongest and most of the charges are transferred, as shown in Fig. 2(c). Finally, when the external force moves away, the device tends to recover to its original state owing to the elasticity of the encapsulation layer. Therefore, positive charges will flow back to the ground, generating a reverse current in the external load [Fig. 2(d)]. According to previous report, the relationship between the output voltage V, the transferred charge Q and the relative displacement of the triboelectric couple x can be expressed as[24]

$$\mathrm{V} = -1/C \times Q + V_{OC}(x),$$

where C is the capacitance between the working electrode and the reference electrode, which is almost a constant (C_0) with the increase of x. The equation of V_{OC} in the entire region of x can be obtained through the second-time interpolation method.[24]

Based on the above analysis, the stretchable TENG can generate electric output under any motion that can cause the relative displacement of the triboelectric couple, such as bending and stretching. Benefiting from the excellent flexibility and stretchability of the device structure, the TENG can operate under diverse deformation without any mechanical failure, as shown in Fig. 3(a). Under the pressing motion triggered by a vibrator at the frequency of 5 Hz, the device can generate a peak-to-peak voltage of 16.2 V and a short-circuit

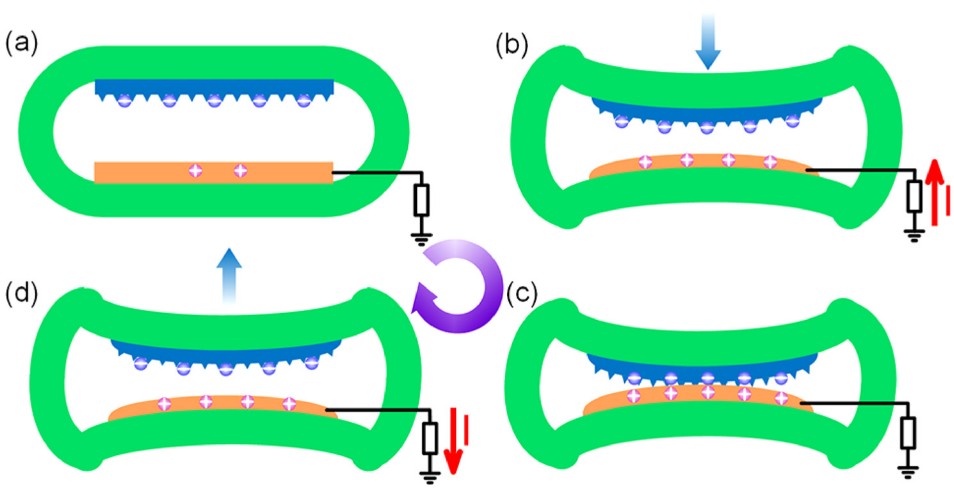

FIG. 2. Working principle of the stretchable TENG.

current of 257.5 nA [Figs. 3(b) and 3(c)]. Noting that the electrode area of the device is only 1 × 2 cm and the real contact area is much smaller than this, the peak current density can be calculated as 1.28 mA/m^2. For the stretching-releasing motion at the frequency of about 3 Hz, the device exhibits a peak voltage and a current of 8 V and 50.2 nA, respectively [Figs. 3(d) and 3(e)]. By periodically bending and releasing the device, it can generate voltage and current with peak values of 6.48 V and 33.5 nA, respectively [Figs. 3(f) and 3(g)]. The result that the TENG presents higher output under pressing motion than other kinds of motion can be attributed to two reasons. On the one hand, the contact area and the relative displacement of the two fiction layers under pressure are larger than that of other situations, contributing to more triboelectric charges on the surface and larger changes of induction potential. On the other hand, besides the PDMS friction layer, the surface charges on the force-applying object will also cause electrostatic induction on the TENG electrode during the pressing-releasing process.

Different from most of the previously reported stretchable TENGs that need to be pressed by hand or other materials, the device is able to generate triboelectric output under tensile strain without being touched by other objects. Due to the air-bag structure, the triboelectric couple in the device can separate automatically after removing the external force. Therefore, the application field of the device can be greatly extended. To demonstrate its feasibility as a stretchable energy harvester, we attach the device on the wrist to harvest energy from wrist rotation [Fig. 4(a)]. As can be seen in Fig. 4(b), the device can generate pulse signals with a peak current of 40 nA during the movement of the wrist. Particularly, the biggest advantage of the air-bag structure is that the encapsulation layer can protect the triboelectric charges from the influence of the external environment. To verify the waterproof ability of the device, we

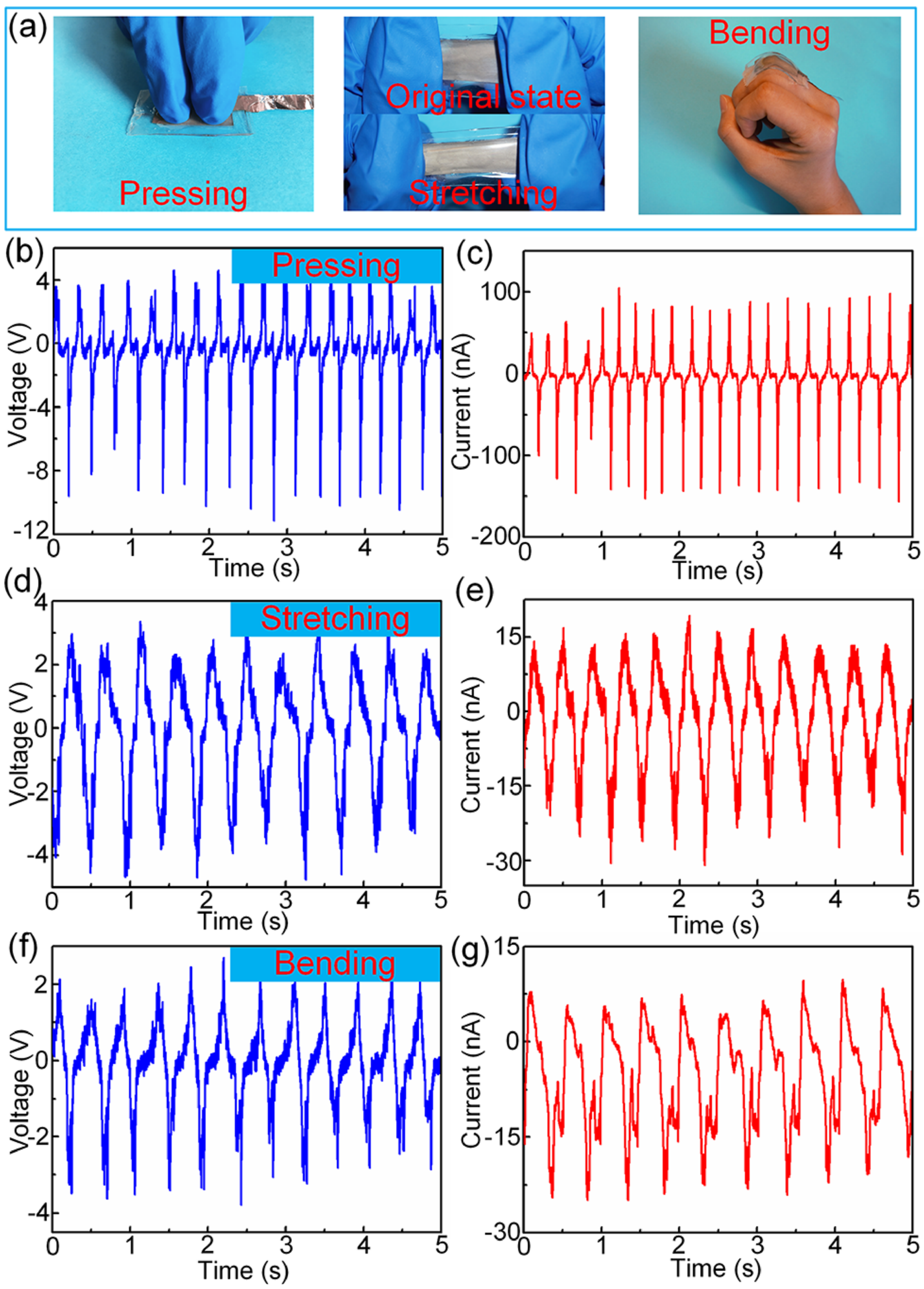

FIG. 3. (a) Photographs showing the device under different deformations. (b)–(g) Output voltage and current of the TENG when the device is under (b) and (c) pressing, (d) and (e) stretching and (f) and (g) bending motion.

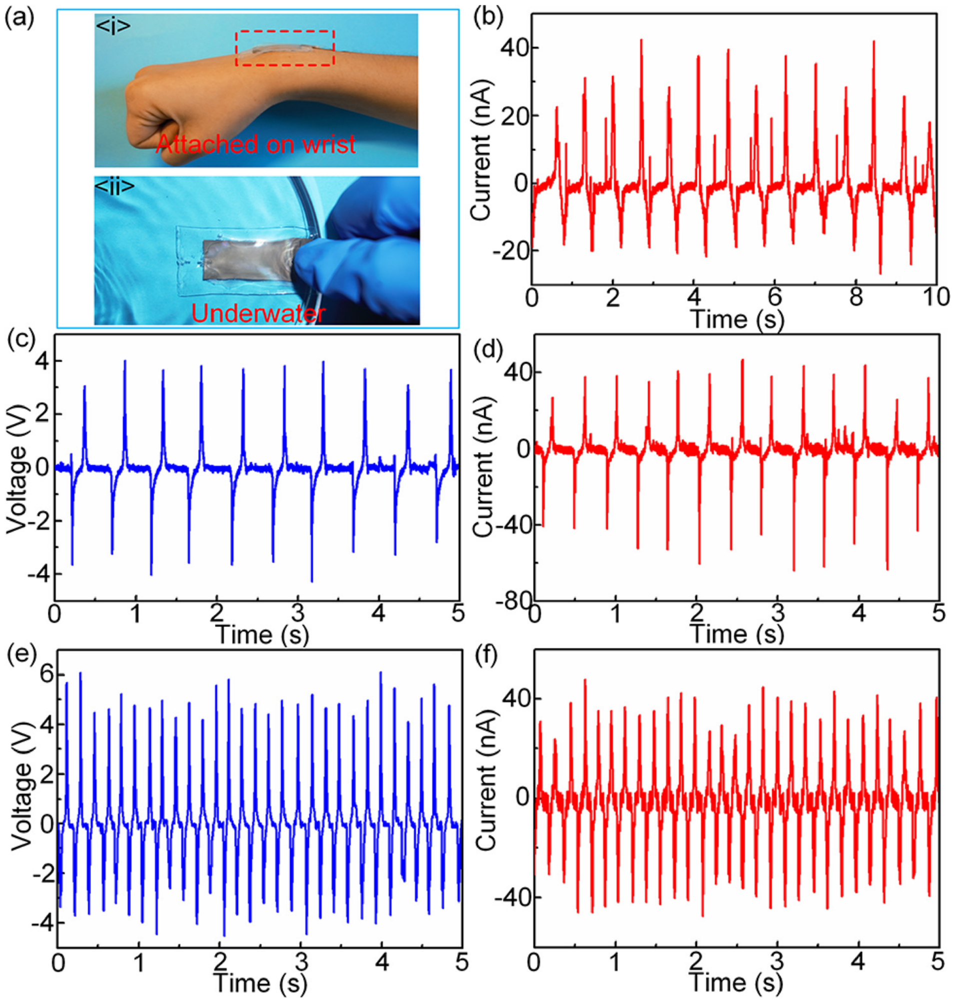

FIG. 4. (a) Photographs showing energy harvesting situations. (b) Output current of the TENG when attached on the wrist. (c) Output voltage and (d) current of the TENG when pressed under water. (e) Output voltage and (f) current of the device after being under water for 12 h.

measured the output by pressing the TENG under water, as shown in Fig. 4(a)⟨ii⟩. Thanks to the hydrophobic property of the PDMS, the stretchable TENG can work effectively under water, generating an average peak output voltage and a current of 3.6 V and 51.8 nA, respectively [Figs. 4(c) and 4(d)]. Moreover, owing to the low penetration rate of water molecules into PDMS, the device can work under water for a long period of time. As shown in Figs. 4(e) and 4(f), the device

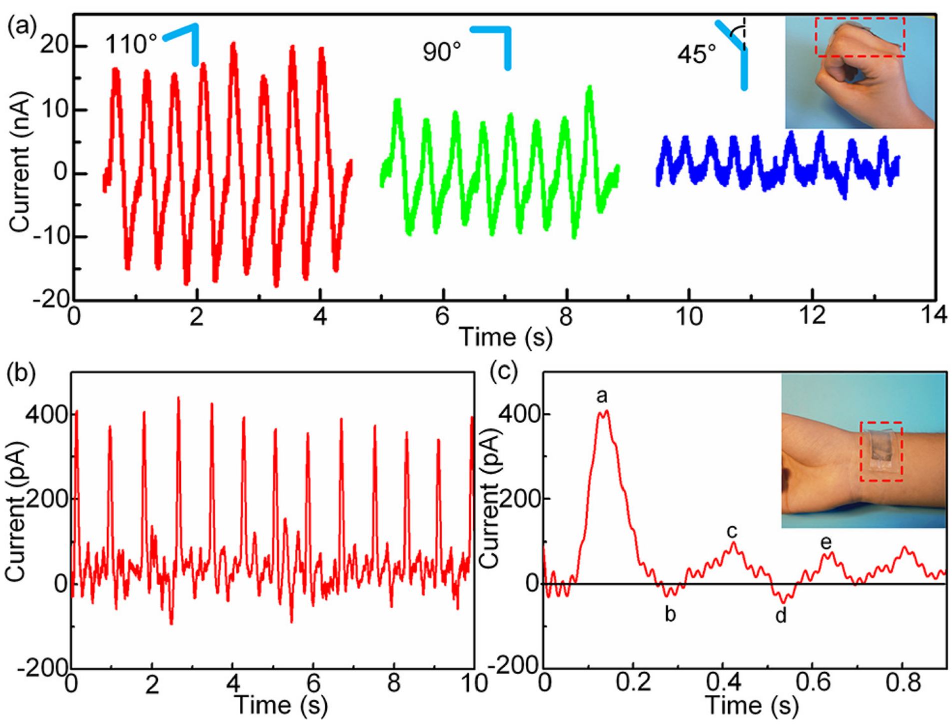

FIG. 5. (a) The output signal of the TENG at different bending degrees. (b) The real-time artery pulse signal measured by the TENG and (c) the enlarged pulse information for one cycle.

shows little decrease in the output performance after being placed under water for 12 h.

Since the output of the TENG is related to the contact area and the relative displacement of friction layers, the device can also be used as a self-powered sensor to reflect the degree of deformation. Here, we demonstrate the stretchable TENG attached on the finger joint to test the bending degree of the finger. With the increase of the bending angle, the output of the device increases obviously [Fig. 5(a)]. Moreover, the device is attached on the wrist to monitor the artery pulse in real-time. The current signal of pulse beats during 10 s of a young girl is shown in Fig. 5(b) and the enlarged view of one cycle is depicted in Fig. 5(c). The inset shows the photograph of the device attached on the wrist. As exhibited in the enlarged figure, detailed wave information can be clearly recorded by the device, showing its application potential as a real-time healthcare monitor.

In summary, we demonstrated a waterproof and deformable TENG based on a stretchable nanofiber electrode and a PDMS encapsulation layer for energy harvesting and self-powered sensing. The whole device is made of soft materials so that it can scavenge energy from diverse mechanical deformations. Due to the seamlessly airbag structure, the device can generate electricity under tensile strain without contacting with other object and is free from the influence of environment humidity. Moreover, by virtue of the thin and soft properties of the encapsulation layer, the device is able to work as a self-powered sensor for detecting the bending degree and monitoring the real-time human radial artery pulse, showing its potential applications in self-powered sensing systems.

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