Single Electrode Sole Triboelectric Nanogenerator for Human Motion Energy Harvesting

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Abstract: Single-electrode triboelectric nanogenerator (TENG) exhibits significant potential applications in harvesting kinetic energy from human body movements due to its simple and flexible structure. In this work, we report a facile and low-cost external single-electrode sole triboelectric nanogenerator (TENG) for harvesting human motion energy dissipated in the environment. The sole TENG is assembled only by attaching the PTFE film to the sole. Different test scenarios are characterized to demonstrate the feasibility of the TENG. The characterization results of sole TENG exhibit excellent performance, especially the sole TENG under wood plate scenarios could obtain an output open-circuit voltage of 100 V, a short-circuit current of 6.5 µA, and an instantaneous power of 61 µW under external resistance of 20 MΩ. The excellent output of sole TENG could provide a sustainable power supply to directly drive more than 60 LEDs and power a calculator via a capacitor. The facile and low-cost assembling process and output characteristics indicate that the sole TENG has the potential for practical application.

1. Introduction

Nowadays, the emergence of new technologies, such as flexible and wearable electronics, has been driving the development of information technology, expanding the application of electronic products, and enriching human daily life around the world.[1–3] However, with the development of flexible and wearable electronics, the poor continuity of power supply to devices remains a challenge.[4] Furthermore, traditional batteries are still the main power source, which is unfavorable to the application of wearable electronics due to the potential pollution caused by the leakage of electrolyte solutions and poor flexibility.[5,6] The urgent and numerous demand for clean, excellent continuity, and flexible power supply is critical for driving these various wearable devices. Therefore, self-powered system can be a replacement for traditional battery-powered wearable electronics and be promising to be a widely used technology, improving the poor continuity of power sources.[7–9] Triboelectric nanogenerator (TENG) is an emerging and burgeoning energy-harvesting technology to effectively scavenge scattered energy such as human motion energy to convert electric energy, which is based on the triboelectrification and electrostatic induction effects.[10–13] The TENG has been intensively explored to harvest energy to power electronics due to the features of high energy conversion efficiency, excellent flexibility, lightweight, low cost, various materials selection, and easy to assemble.[14–17] TENG with four working modes:[18–21] contact-separation mode, lateral-sliding mode, free-standing mode, and single-electrode mode have been extensively studied in the application of energy harvesting and sensors, especially, the single electrode could better combine with the human body or the surrounding environment or both due to its flexible and simple structure.[22]

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The main way of energy dissipation in the human body is through human motion and dissipated in the environment with no gain. Among the human motions, the energy consumption of walking and running accounts for the majority of energy dissipation of the human body. Utilizing the features of contact and separation between the sole and the ground during walking and running, the single electrode mode TENG and sole can be integrated perfectly to assemble the single electrode external sole TENG.[23] Although previous works[23,24] have reported the sole TENG based on polytetrafluoroethylene (PTFE), testing in more scenarios such as wet testing conditions, is still lacking. Therefore, more practical tests are needed to better improve the sole TENG and may promote the development of practical application of sole TENG.

Herein, we reported an external single electrode sole TENG for human motion energy harvesting fabricated only by the PTFE film and copper foil. For practical application, we simulated different tests the sole faced in daily life including asphalt road, metal plate, brick, glass, concrete, ceramic, paper, and wood, which could be found in daily life. In particular, the TENG in contact with asphalt roads, concrete, wood, and ceramic exhibit excellent performance in open-circuit voltage, and short-circuit current. Furthermore, we measure the output performance of the TENG contact with the wood, which exhibits an instantaneous power of 61 μW under the resistance of 20 MΩ, an output open-circuit voltage of 100 V, and a short-circuit current of 6.5 μA. Based on this, application in driving electronics is exploited to demonstrate the feasibility of the TENG. More than 100 commercial green LEDs and a commercial calculator are powered successfully. This work may shed light on TENG in practical applications with low cost and high efficiency for energy harvesting from walking and motion.

2. Experimental section and characterization

PTFE has been widely applied in TENG due to its features of excellent triboelectric electronegative material, wear resistance, and corrosion resistance.[25,26] In this work, PTFE is selected as the triboelectric material. The TENG device is assembled by the following steps. Simply, the commercial PTFE film (thickness: 65 μm) is attached to copper foil and fixed on the 3 mm thickness laser cutting acrylic square with an effective working area of 5×5 cm2 to measure the electric output properties. For practical application in energy harvesting from human motion, the PTFE pasted on the copper foil is attached to the sole tightly, as shown in Fig. 1(b), and then sealed with silicone rubber thoroughly on the external sole. The copper wire is connected to the measurement system (Keithly 6514, USA) to acquire the output electric signals. The scanning electron microscope (SEM, thermo scientific Apreo 2C) is used to investigate the morphology of PTFE film. The hydrophobic property is tested by a contact angle machine (kruss DSA100). The shoes are purchased on the local market. The test materials of asphalt road, metal plate, brick, glass, concrete, ceramic, paper, and wood are obtained from the surrounding environment.

3. Results and discussion

Fig. 1(a) shows the diagraph of designed single electrode external sole TENG, which is composed of triple layers including PTFE film, Cu foil, and the sole, with features of facile to assemble and low cost. Fig. 1(b) shows the digital picture of sole TENG for testing. Fig. 1(c) shows the SEM image of PTFE with rough surface, providing great surface area and beneficiary to enhance the output of TENG. Fig. 1(d) shows the PTFE with good hydrophobic (contact angle = 119°) due to the rough surface, which could reduce water adhesion and relieve deterioration of TENG in humidity environment. Fig. 1(e) shows four typical measurement scenarios including ceramic, wood, concrete, and asphalt road, obtained from the surrounding environment the sole faced in daily life. The four scenarios are the most the scenarios that the sole can face. The testing of sole TENG in this work is also based on these four scenarios.

The electricity generation mechanism of the assembled single electrode[27] sole TENG is schematically explained in Fig. 1(f). When the PTFE comes into contact with the ground (different scenarios), the electrons are transferred from the ground to the surface of PTFE film owing to the triboelectrification effect. Once the PTFE separates from the ground, the triboelectric charges remain on the surface due to the insulation f PTFE. The negative charges on the PTFE induce the positive charges on Cu foil electrode due to the electrostatic induction effect to electric neutrality, and hence the induced charges flow to the ground to form the positive current. When the PTFE fully separate from the ground, the negative charges on PTFE are completely shielded from the induced charges on the Cu foil electrode, and the electrical equilibrium is obtained without output signals. When PTFE approaches the ground, the induced charges on the Cu foil electrode decrease, and hence the electrons flow back to Cu foil electrode, leading to the negative current. Thus, the alternating current (AC) is formed during the process of contact and separation.[28,29] Repeatedly, the sole TENG can output electric energy.

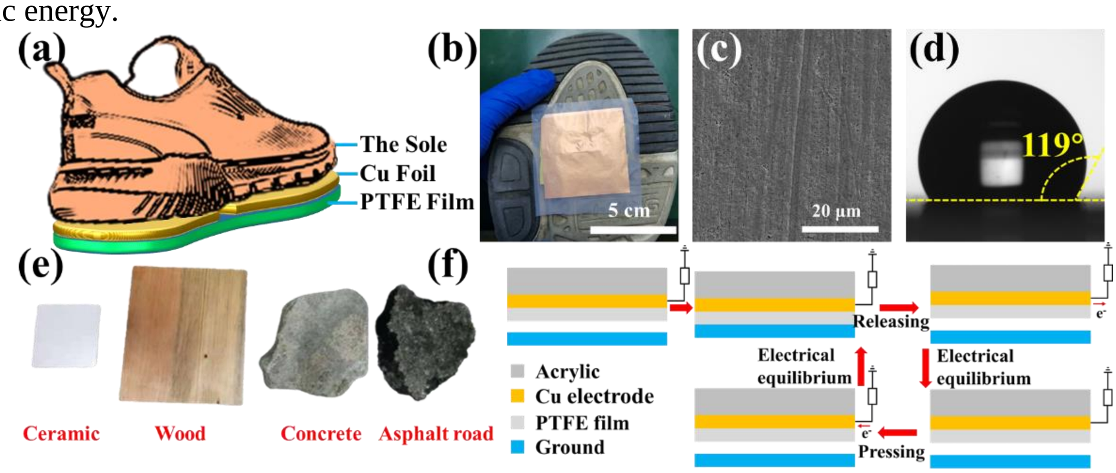

Fig. 1. (a) The diagram of the TENG. (b) The digital picture of assembled TENG. (c) SEM of PTFE film. (d) Hydrophobicity of the PTFE film. (e) Four typical practical application scenarios: ceramic, wood, concrete, asphalt road. (e) The mechanism of the electricity generation of TENG.

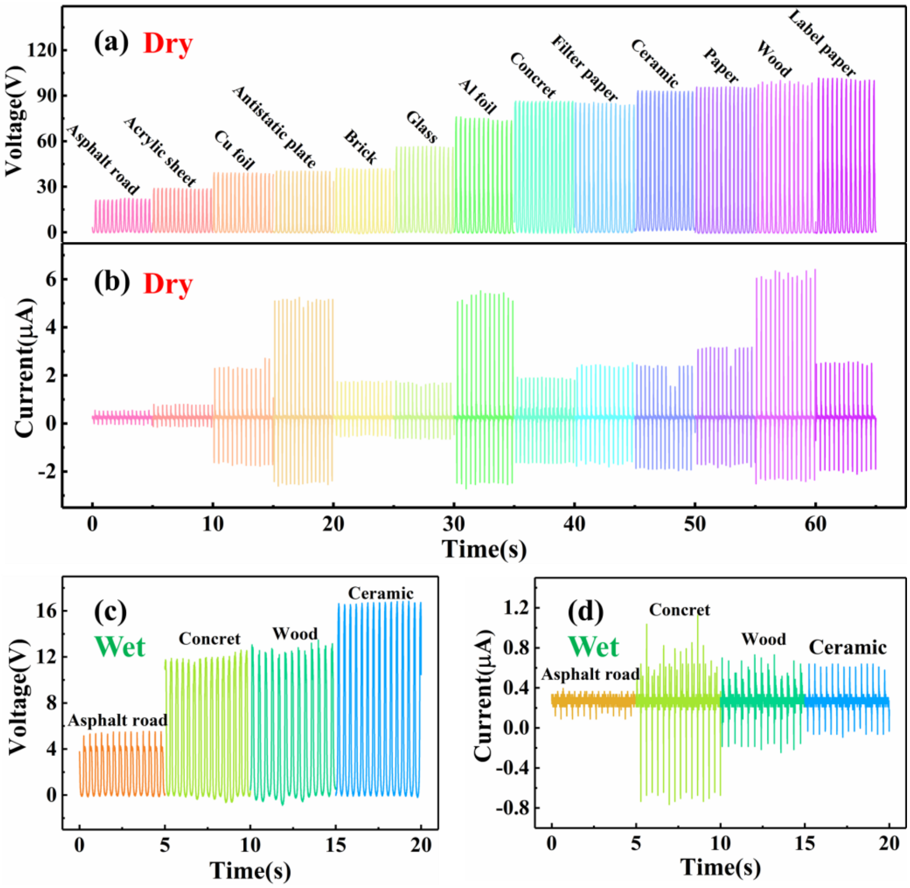

Fig. 2. (a, b) The output performance of open-circuit voltage and short-circuit current in dry scenarios and (c, d) wet scenarios.

More testing scenarios could exhibit the practical performance of the device. Fig. 2(a-d) shows the output performance of TENG under different contact surfaces under dry/wet surfaces condition. Fig. 2(a, b) shows the open-circuit voltage and short-circuit current of different contact surface in dry conditions, which is common to the sole in daily life including asphalt road, brick concrete, ceramic, paper, and wood. and could simulate almost the practical application scenarios of the sole faced. When the sole TENG come into contact and separate with asphalt road, the sole TENG exhibits the output performance of open-circuit voltage of 20 V and short-circuit current of 0.5 μA under 50 N at 3 Hz. The TENG display poorest performance compare to other scenarios. The hard asphalt road with many big pits decreases the effective contact area, leading to the poorest output performance. Smooth surface with more effective contact area such as acrylic, Cu foil, antistatic plate, glass, and Al foil ceramic exhibit better output performance, as shown in Fig. 2(a, b). The surface with porous hierarchical structures such as brick, concrete, filter paper, and wood plater also exhibit excellent output performance. To simulate practical application the sole faced in daily life, the output performance of TENG in wet conditions is also measured, as shown in Fig 2(c, d). When the sole TENG comes into contact with different wet scenarios, the TENGs exhibit poor output, that is to say, wet scenarios deteriorate output performance, which is similar to other ref.,[30] undermining the practical application. In short, TENG in dry scenarios are favorable to practical application.

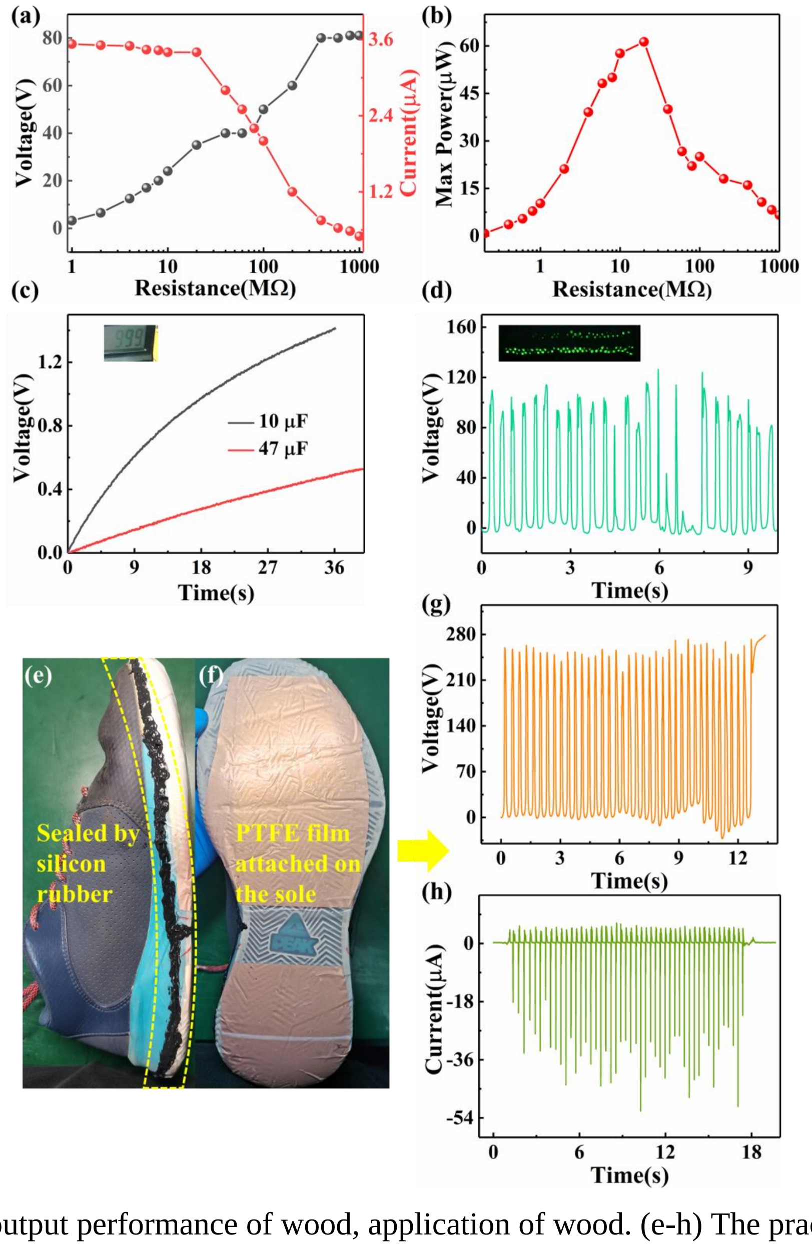

Fig. 3. (a-d) The output performance of wood, application of wood. (e-h) The practical application (tested in terrazzo floor) of the TENG.

The measurement indicates that the TENG in contact with the wood plate exhibits the best output performance, and hence is selected to measure the TENG performance. Fig. 3(a-d) shows the output power, charging, and application of wood plate-based TENG. Fig. 3(a) shows the instantaneous voltage and current measured under different external resistances of 0.1-1000 MΩ, in which the instantaneous peak voltage gradually increased to a constant value by increasing the loading resistances, on the contrary, the instantaneous current decreased gradually. Fig. 3(b) shows the instantaneous power of wood plate-based TENG, in which the power exhibits a steady trend of upward with increasing external resistances before getting to maximum power, and then presents a trend of downward for the peak power. According to the maximum power theory, the external resistor is equivalent to the internal resistor of the wood plate-based TENG. In view of this, the instantaneous peak power of wood plate-based TENG obtained a maximum power 61 μW under external resistance of 20 MΩ.

Finally, we demonstrate that the external single electrode sole TENG assembled only by the PTFE film and Cu foil could provide a power source for practical electronic devices. Fig. 3(c) shows that over 60 commercial green LEDs are powered by the wood plate-based TENG via a full-bridge rectifier circuit, which could convert AC to DC output signals. In addition, the TENG can be used as a stable output by exploring the capacitor, as shown in Fig. 4(d). Fig. 3(c) shows the charging curves of 10 and 47 μF capacitors, indicating that it takes 30 s to charge a 47 μF capacitor from 0 to 0.4 V. The inset of Fig. 3(d) shows that a commercial calculator can be powered by storing energy in 47 μF after charging for a while. The examples above show that the TENG can be used as a sustainable power source.

For practical application we attached a PTFE film and Cu foil to cover the whole sole and sealed with silicone rubber as shown in Fig. 3(e, f). The terrazzo floor surface is used to demonstrate the output performance of sole TENG, which exhibits excellent performance including open-circuit voltage over 240 V and short-circuit current over 36 μA, as shown in Fig. (g, h). In short, we believe that integrating the PTFE or other wear-resistant polymer with excellent negative triboelectric into the sole could greatly facilitate the practical application of TENG for powering wearable electronics.

4. Conclusion

In this work, a facile and low cost TENG for harvesting human motion energy is fabricated. The TENG is assembled only by attaching the PTFE film to the sole. Sole TENG under different measurement scenarios are characterized. The characterization results shows that the dry scenarios are favorable to the practical application of sole TENG, and wet scenarios may decrease the output. Among these scenarios, sole TENG under wood scenarios exhibits excellent output performance, resulting the instantaneous power of 61 μW under external resistance of 20 MΩ, an output open-circuit voltage of 100 V, a short-circuit current of 6.5 μA. The sole TENG under wood scenarios could directly light over 60 green LEDs in series instantaneously and successfully drive a commercial calculator work. The excellent output performance, facile and low cost assembled process indicate that the TENG has the potential for practical application with low cost. This work may pave the way to the practical application of single electrode external sole TENG.

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Data Availability Statement

All data included in this study are available upon request by contacting the corresponding author.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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