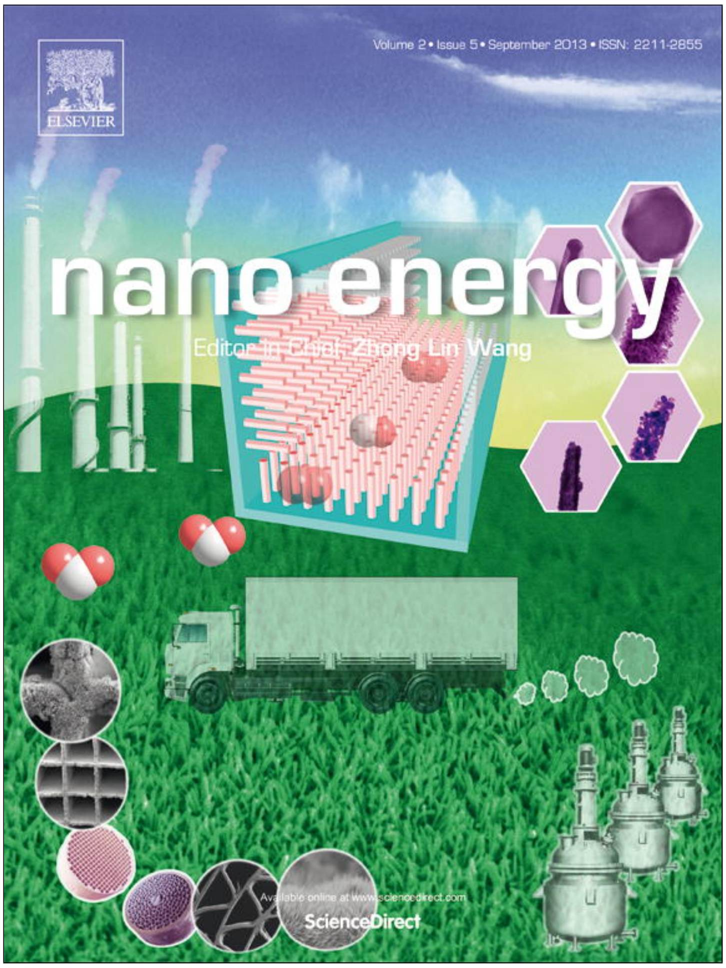
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RAPID COMMUNICATION

Power-generating shoe insole based on triboelectric nanogenerators for self-powered consumer electronics

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Abstract
A major application of energy-harvesting technology is to power portable and wearable consumer electronics. We report a packaged power-generating insole with built-in flexible multi-layered triboelectric nanogenerators that enable harvesting mechanical pressure during normal walking. Using the insole as a direct power source, we develop a fully packaged self-lighting shoe that has broad applications for display and entertainment purposes. Furthermore, a prototype of a wearable charging gadget is introduced for charging portable consumer electronics, such as cellphones. This work presents a successful initial attempt in applying energy-harvesting technology for self-powered electronics in our daily life, which will have broad impact on people's living style in the near future.

Introduction

In the past decade, the interest in energy harvesting technologies has grown substantially [1–4]. Traditional power supplies such as batteries have inherent limitations including immobility, limited lifetime, maintenance difficulty, and toxic hazards [5]. With proliferation of wireless sensors and consumer electronics, those problems become prominent. For example, over 1.7 billion cellphones were sold worldwide in 2012 alone. However, the need of frequent battery charging poses a major problem especially for users who are in long-distance travel and who have heavy usage of their cellphones. Therefore, it is highly desirable to develop a miniaturized portable power source for charging consumer electronics whenever and wherever needed. A perpetual power source through the addition of energy harvested from the environment would serve as a proper solution [6,7].

In 2012, a new type of technology called triboelectric nanogenerator (TENG) was invented for harvesting ambient mechanical energy [8]. It operates in a unique principle by coupling triboelectric effect with electrostatic induction [9]. The TENG brings together high performance, miniaturization,

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low cost, scalability, and applicability [10–12]. Since then, two basic operating modes have been developed, i.e. contact mode and friction mode, which have been utilized in a variety designs to harvest mechanical motions under different circumstances [13,14].

Herein, we developed a power-generating shoe insole with built-in flexible multi-layered TENGs. The TENGs were enclosed in the insole to harvest energy from foot pressure during normal walking. Each of the TENGs is composed of three layers that are fabricated on a single flexible substrate that has zigzag shape. Through parallel connection, electricity simultaneously produced from all of the three layers could add up together. Under pressure exerted from human body, each TENG could generate maximum open-circuit voltage of 220 V and short-circuit current of 600 μA. Equipped with this insole, a fully packaged self-lighting shoe was developed. Commercial LED bulbs were directly powered during normal walking. Moreover, we introduced a prototype of a new class of battery-charging gadget for charging cellphones by walking, making it possible to charge portable and wearable consumer electronics whenever and wherever needed. This work presents an initial effort of applying TENG in commonly used products, which enables self-powered technology in our daily life.

The structure of the power-generating insole is presented in Figure 1. Previous studies on dynamic foot pressure revealed that vertical pressure during walking concentrate on the heel and the forefoot [15]. Given the pressure distribution, two TENGs are positioned at two ends of the insole to make most use of the mechanical force (Figure 1a). The TENG has a multi-layered structure based on a single flexible substrate (Figure 1b and c). Every layer is fabricated on a facet of the zigzag-shape substrate (Figure 1d). Through the rational design, all layers are stacked together in vertical direction. Since they are electrically connected in parallel, electricity produced from each one can add up together, which enables multiple-fold enhancement in electric output without increasing the area of the TENG.

A single layer is essentially an independent energy-generating unit that operates in contact mode [9]. One contact surface is polished aluminum foil, which also serves as an electrode. The other contact surface is PTFE thin film. Copper is prepared at the back of the PTFE film as another electrode. Surface morphology modification was performed on the aluminum foil through wet chemical etching, creating dense nano-pores (Figure 1f) for enhancing charge transfer with the PTFE film [12]. Detailed fabrication process of the TENG was presented in a previous report [12].

The TENG operates through the coupling between triboelectric effect and electrostatic induction. Driven by external force, intimate contact between PTFE and aluminum induces surface charge transfer due to contact electrification. Negative triboelectric charges are generated on the PTFE surface since it has stronger tendency to obtain electrons in comparison to aluminum. As a reciprocating force is applied, the induced electrons are driven back and forth between two electrodes by the triboelectric charges. As a consequence, alternating-current is produced. The process of electricity generation was extensively discussed in details in previous reports [9,10].

To characterize the performance of the insole with built-in TENGs, gentle impact from human finger was applied onto the insole, generating maximum pressure between 50–60 KPa that is comparable to ground pressure of a human foot during walking. A single TENG could generate short-circuit current (I_{sc}) up to 600 μA (Figure 2a). A diode bridge was utilized to rectify the alternating current, generating signals that had only one direction. Open-circuit voltage

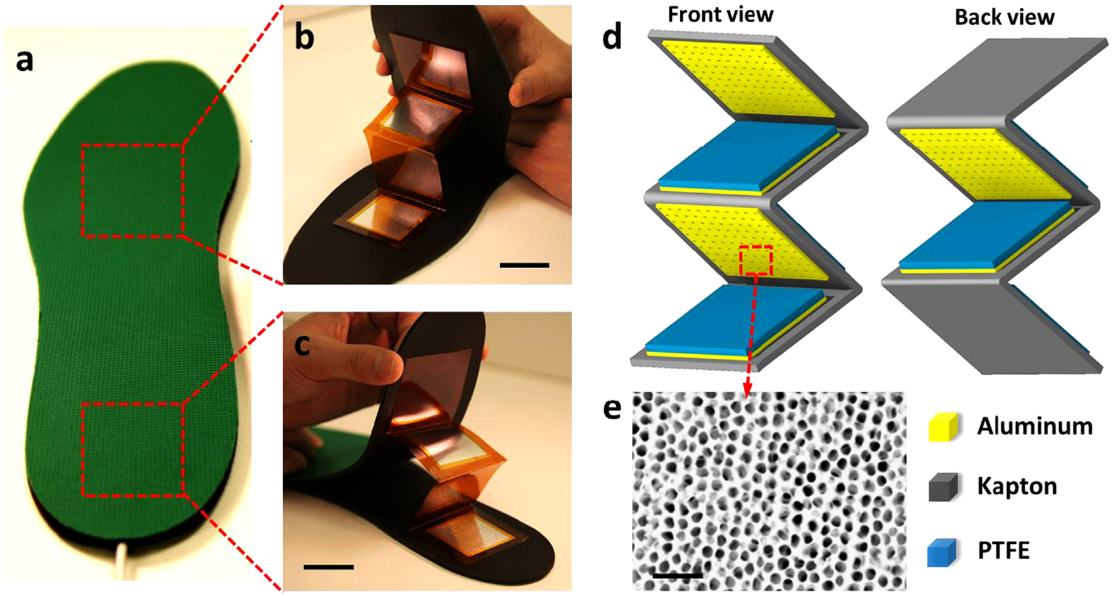

Figure 1 Structural design of the power-generating shoe insole based on flexible TENGs. (a) Photograph of a fully packaged power-generating shoe insole. (b) Photograph of the inner structure of the insole, showing a TENG installed at the front section of the insole. The scale bar is 2 cm. (c) Photograph of the inner structure of the insole, showing another TENG enclosed at the rear section of the insole. The scale bar is 2 cm. (d) Schematics from two different angles that reveal the structure of a multi-layered flexible TENG. The zigzag structure of the substrate accommodates 3 layers in a single TENG. (e) SEM image of nano-pores created at the surface of the aluminum foils. The scale bar is 200 nm.

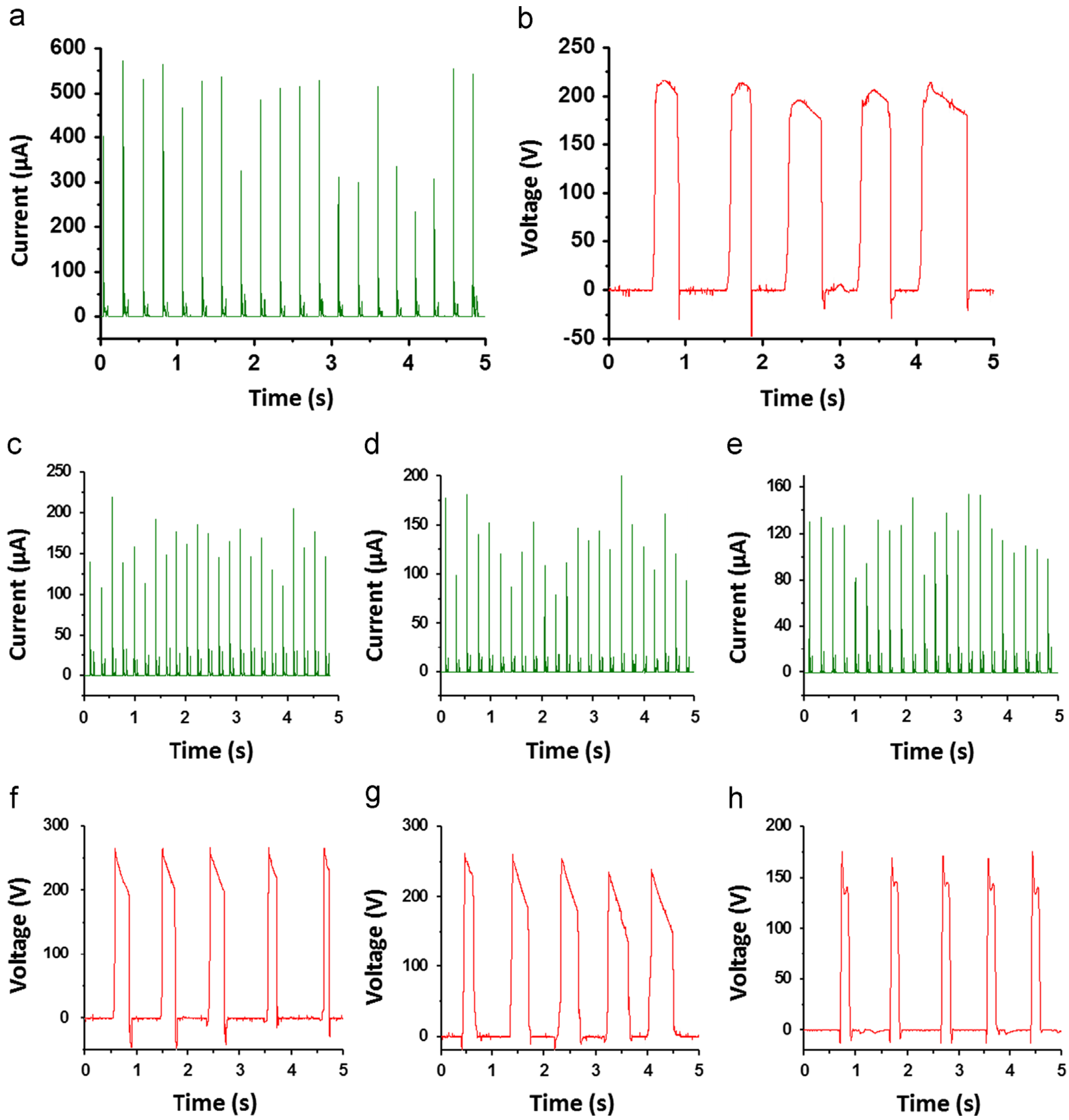

Figure 2 Electric output of a TENG that is installed inside of the insole. Impact from human fingers was used to trigger the TENG. (a) Short-circuit current of the TENG. The current was rectified through a rectifying bridge, generating current output that has only one direction. (b) Open-circuit voltage of the TENG. Slower impact compared to the current was applied to clearly show the quasi-square pattern of the voltage output. (c–e) Short-circuit current of the three layers in the TENG from the top layer to the bottom layer, respectively. Mechanical damping leads to slightly reduced current output of the bottom layer. The overall current output in (a) is the sum of all three layers. (f–h) Open-circuit voltage of the three layers in the TENG from the top layer to the bottom layer. Liner superposition does not apply to the voltage output because they are in parallel connection.

(V_{oc}) reached over 220 V (Figure 2b). The impact frequency was deliberately reduced compared to the current in order to clearly display the quasi-square pattern of the V_{oc} [9]. To further investigate the electric output of the TENG, the three layers that compose a TENG were characterized in a sequence from the top layer to the bottom layer. The I_{sc} from all of the three layers that are in parallel connection follows linear superposition, contributing to the overall current output in Figure 2a. The slightly reduced current of the bottom layer (Figure 2e) compared to the top layer (Figure 2c) can be attributed to mechanical damping in the multilayered structure. Since all three layers are connected in parallel, the V_{oc} of each layer cannot be built up. Instead, each one has amplitude that is comparable to that of the overall TENG (Figure 1b). Again, mechanical damping leads to smaller amplitude of V_{oc} from the bottom layer (Figure 2h) in comparison to other layers (Figure 2f and g).

To demonstrate the capability of the insole in powering electronics, it was utilized as a direct power source for commercial LED bulbs. Two rows of LEDs were connected with opposite polarities. Once human fingers pressed the insole with a TENG installed underneath, electricity generated from the TENG powered a row of LEDs (Figure 3a). When the pressure was withdrawn, electricity in an opposite direction is

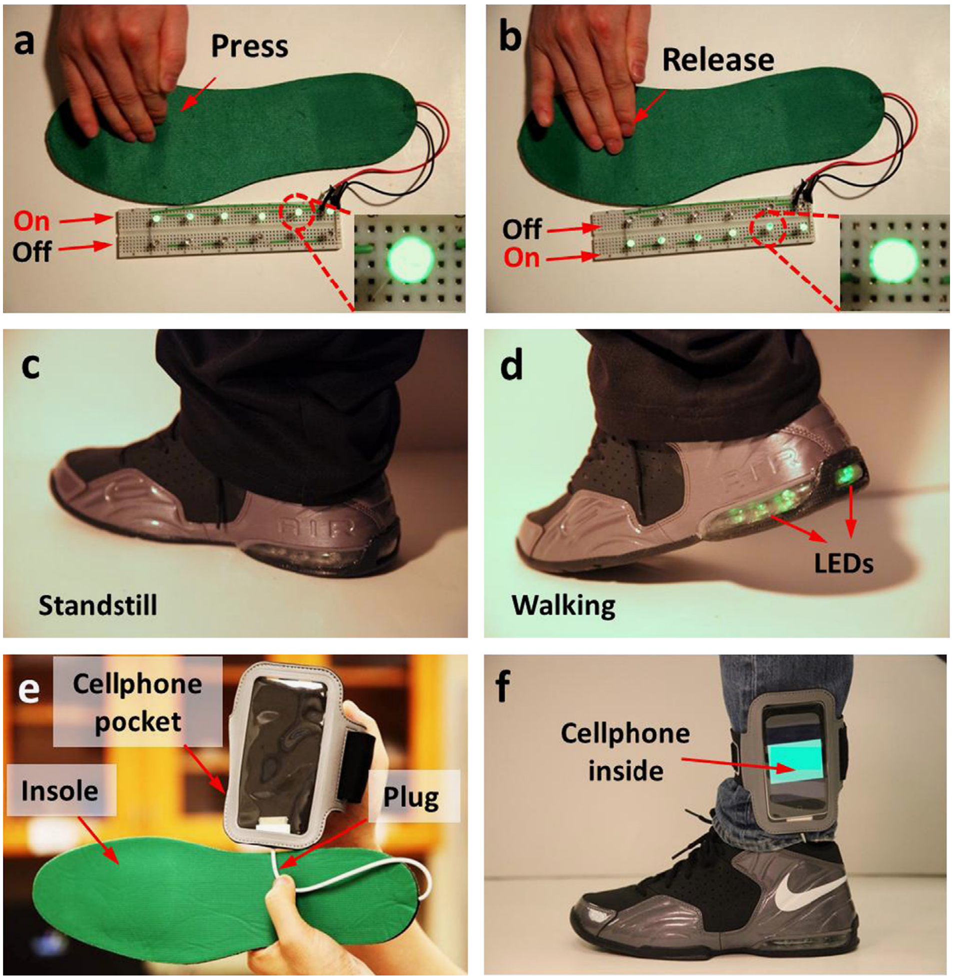

Figure 3 Applications of the power-generating insole as a power source for portable and wearable consumer electronics. (a) Photograph of lighted commercial LED bulbs as driven by the TENG when pressure is applied by human fingers. (b) Photograph of lighted commercial LED bulbs as driven by the TENG when pressure from human fingers is withdrawn. The two rows of LEDs are purposely connected with opposite polarities. Since alternating current from (a) and (b) has opposite directions, only one row can be powered at a time. (c) Photograph of a fully packaged self-lighting shoe that incorporates the power-generating insole and LED bulbs. (d) Photograph of the self-lighting shoe during normal walking, showing lighted LED bulbs in the air cushion. (e) Photograph of a prototype for charging cellphone by the power-generating insole. (f) Photography of the cellphone-charging gadget that is worn on the bottom leg with a cellphone plugged in.

produced, driving another row of LEDs (Figure 1b), which clearly visualized alternating current from the TENG (Supplementary Movie 1).

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.nanoen.2013.08.002.

Based on the insole with the built-in TENGs, the first fully packaged self-lighting shoe was developed. The insole was slid into a sneaker as an ordinary shoe insole. LED bulbs were installed inside of the air cushion with electrical connection to the insole. At standstill status, the shoe looks no difference to other sneakers. However, normal walking induces periodically applied pressure on the insole, powering all LEDs installed in the sneaker (Figure 3d, Supplementary Movie 2). This product prototype has immediate applications not only for entertainment purpose but also for display purpose. For people who have outdoor activities at night, such as construction works and street runners, the self-lighting shoe provides an important value proposition in preventing accidents and thus in protecting their safety.

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Moreover, the insole can be potentially utilized as charging source for portable and wearable consumer electronics, such as cellphones. A prototype of a cellphone-charging gadget was shown in Figure 3e, which consists of a power-generating insole, a cellphone pocket, and a plug that makes connection. The gadget can be easily worn on the bottom leg in a convenient way without introducing any discomfort (Figure 3f). It is a portable and handy power source, which enables charging for consume electronics whenever and wherever needed and thus solves the problems of the conventional charging method.

In summary, we develop an easy-implemented power-generating insole for shoes. It is based on a recently developed technology called triboelectric nanogenerator that converts ground pressure into electricity. The TENG has a thin-filmed multi-layered structure, which not only enables high power output density but also offers flexibility. Trigger by pressure from human body, a TENG produces open-circuit voltage of 220 V and short-circuit current of 600 μA. Based on the power-generating insole, a fully packaged self-lighting shoe was developed. LED bulbs installed in the shoe can be directly powered during normal walking. Besides, we introduced a wearable charging gadget, which provides a convenient technique in charging consumer electronics without any restriction on time and location. This work demonstrates that TENG is a practical and implementable technology that can be used to develop self-powered products for people's daily life.

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