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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

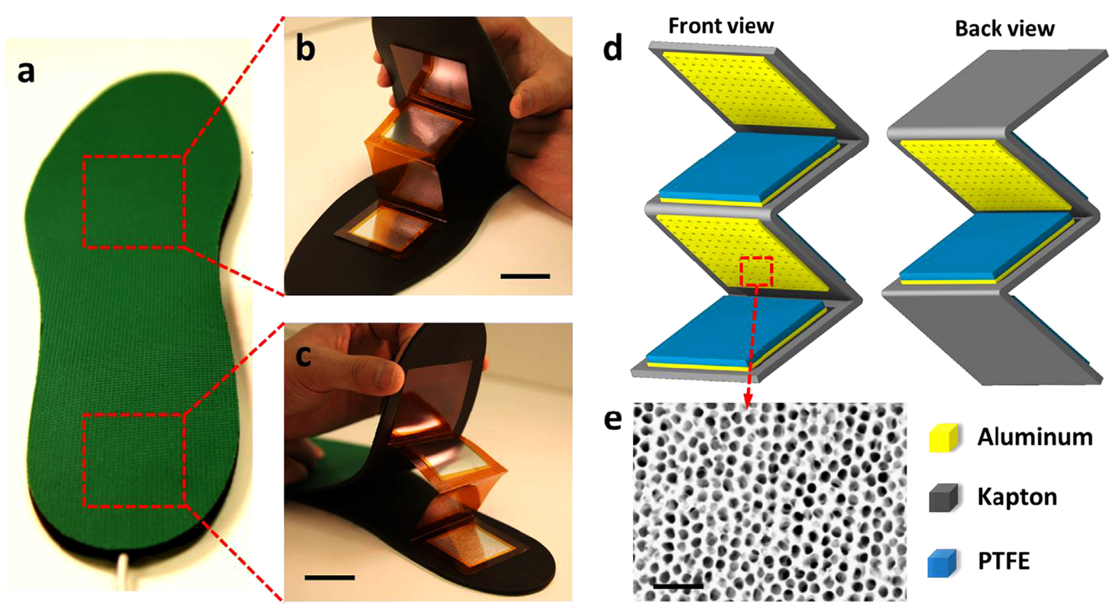

Figure 1 Structural design of the power-generating shoe insole based on flexible TENGs. (a) Photograph of a fully packaged power-generating shoe insole. (b) Photograph of the inner structure of the insole, showing a TENG installed at the front section of the insole. The scale bar is 2 cm. (c) Photograph 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.