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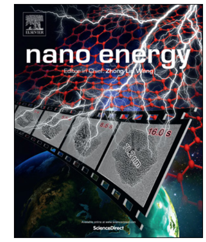

RAPID COMMUNICATION

An unmovable single-layer triboloelectric generator driven by sliding friction

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Abstract
In this paper we present a flexible single layer triboelectric generator (S-TEG). The device consists of two fixed intedigital electrodes on the top and bottom surfaces of a polyimide substrate. In operation, the S-TEG is a fixed surface. Electricity is generated by sliding friction with external objects. In comparison to traditional TEGs with movable electrodes, the fixed electrodes on S-TEG simplify packaging process. Charges of hundreds nC can be generated by a rod sliding on the S-TEG. Due to the interdigitated shape of the electrodes energy harvesting is still possible regardless of the material of the scratching rod. Various materials can be utilized to generate electricity free of the limitation of triboelectric properties, which greatly broadens the S-TEG's application field. In addition, the output voltage can be greatly enhanced by using the slippage of two S-TEGs. When one S-TEG slides on another, the maximum peak output voltage can reach 342.8 V and more than 1000 nC charges are transferred in each sliding cycle. Owing to the simple fabrication process, S-TEG devices using this structure are suitable for mass production. A demonstration was conducted to illustrate the potential of this S-TEG device to harvest energy from sliding surfaces encountered in daily life. An S-TEG integrated in a computer mouse pad can sufficiently drive 20 LEDs and a LCD screen.

Introduction

The development of energy harvesting technology to power miniature electronic devices and systems without charging or replacing batteries remains a great challenge. Research on miniature devices to convert other forms of energy such as solar energy, [1] mechanical energy, [2] heat [3] and so on into electrical energy has continued for decades. Among the techniques studied, harvesting mechanical energy from the environment is an effective and low cost energy scavenging technique [4]. Based on the working mechanism, traditional energy harvesters are classified into electrostatic, [5,6]

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piezoelectric, [7,8] and electromagnetic [9,10] devices. However, due to relatively low output and complex fabrication processes, these energy harvesters still cannot satisfy the needs of most electronic devices. Recently, generators based on the triboelectric effect, which can achieve high output and low cost of fabrication, have attracted significant attention [11]. The triboelectric effect is a mechanism of charge transfer. When two materials contact each other, different charges will be generated on the contacting surface of each material.

In previous studies, different structures for triboelectric generators (TEGs) have been proposed. There are two major types of TEGs. The first type utilizes motion in the vertical direction [12–17]. The second type makes use of horizontal movement, such as sliding and rotating TEGs [18–21]. However, the electrodes of these traditional TEG structures are located on two separate friction plates. The electrodes on one separate friction plate can move vertically or horizontally relative to the electrodes on the second friction plate. The moving electrodes reduce the reliability of the structure and bring many difficulties for integration and packaging. Single-electrode-based TEG [22–24] can to some extent solve the problem, but approximately half of the generated charges are wasted, leading to low energy conversion efficiency. To solve the problem some new kinds of generators are proposed, such as the freestanding-triboelectric-layer (FTENG) [25] and the free-rotating disk triboelectric nanogenerator [26].

In this work we also present a triboelectric generator integrating all the electrodes and friction components in a single flexible film, which remains fixed in operation. In this fully-integrated single-layer TEG (S-TEG), the electrodes double as one of the friction surfaces. Due to the interdigitated structure of the electrodes, power output is possible regardless of the material used to rub the S-TEG. With either a copper rod or a polyimide rod sliding on the S-TEG surface, current can be generated between the electrodes on the top and bottom of the polymer film. The working principle is discussed in more details in a subsequent section. Additionally, if one of these S-TEG devices slides on another, the output voltage will be dramatically increased. The S-TEG developed in this work was fabricated from a commercial flexible copper clad laminate (FCCL) which is simple and suitable for mass production. The influences of electrode position, geometry and nanostructuring of the polyimide surface have been investigated and the improved S-TEG design resulting from this testing has excellent performance. The S-TEG can be attached onto the surface of various objects to harvest energy. Since the fabrication process is simple, a large area of S-TEG can be fabricated easily. As an example, an S-TEG fixed onto a mouse pad, can harvest energy from the mechanical energy of moving the mouse on the pad to light up 20 LEDs and an LCD.

Experiments

The device consists of a polyimide film with interdigital-shaped copper electrodes on its both sides. Figure 1(a) gives a schematic view of the proposed TEG. Polyimide and copper are the triboelectric materials. According to the triboelectric sequence, polyimide and copper have different ability in constraining electrons [27]. Besides, the friction surface area is increased by making nanostructures on polyimide (shown in Figure 1(c)) to improve the output of S-TEG.

The S-TEG was fabricated using a FCCL substrate, which is flexible and suitable for mass production. The thickness of the polyimide and copper layers is 25 μm and 18 μm, respectively. The interdigital electrodes on both sides were patterned and etched with $FeCl_3$ solution. To increase the friction area of the polyimide surface, the device was treated by inductively coupled oxygen plasma. The details of the fabrication process are provided in Figure S1 of the Supporting information. The integrated electrodes, friction materials and simple fabrication process make this S-TEG more suitable for mass production.

Working principle

Unlike traditional TEGs, in this device electric power is obtained by a single rod or similar objects sliding on the interdigital electrodes. Regardless of the position of

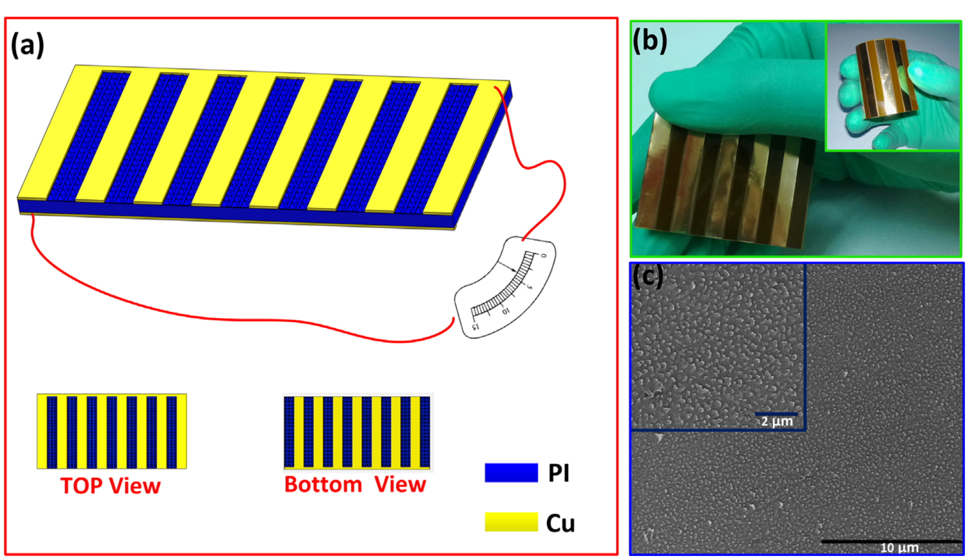

Figure 1 (a) 3D view of the proposed triboelectric generator. (b) Photograph of the fabricated triboelectric generator. (c) SEM image of the nanostructures on polyimide film.