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RAPID COMMUNICATION

Theory of freestanding triboelectric-layer-based nanogenerators

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Abstract
Triboelectric nanogenerator technology is emerging as a promising candidate for mechanical energy harvesting from ambient environment. Freestanding triboelectric-layer-based nanogenerators (FTENGs) are one of the fundamental operation modes with many advantages. In this paper, the first theoretical model of FTENGs is proposed with thorough analysis of their operation principle. Both contact-mode and sliding-mode FTENGs are discussed to fully uncover their unique characteristics. Contact-mode FTENGs have superior linearity, which is highly beneficial for both energy-harvesting and self-powered sensing applications. Sliding-mode FTENGs have two subcategories based on the material of their freestanding layer. For both of the two subcategories, the coupling effect of the height of the freestanding layer and the electrode gap on their output characteristics are discussed in detail to obtain the strategy for their structural optimization.

1. Introduction

Energy harvesting from natural environment has long been considered as a promising supplement to the traditional fuel sources. It can not only contribute to the hugely increased electricity demand of modern society, but also solve the energy source problem for mobile electronics when the traditional energy source is unreachable. Among all of the energy sources, mechanical energy has attracted much attention, mainly for its wide availability and high operability. Effects such as the electromagnetic, [1,2] electrostatic, [3-6] and piezoelectric effect [7] have already been utilized in mechanical energy harvesting, but each of them has its own limitations. Heavy magnets and pre-charging

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process are indispensable for electromagnetic generators and electrostatic electret generators, respectively. In addition, the low output of piezoelectric generators still limits their applicability. Recently, triboelectric nanogenerators (TENGs) based on the coupling effect of contact electrification [8-11] and electrostatic induction have been invented to overcome the above limitations and have exhibited their unique merits, such as large output power, high efficiency, cost effective materials, low weight, and simple fabrication [12]. Several operation modes of TENGs have already been developed to adapt them to different applications [12-17]. Among all of the operation modes, freestanding triboelectric-layer-based nanogenerators (FTENGs) have the following unique advantages [16-19]. First, compared to traditional attached-electrode TENGs, the moving triboelectric layer in FTENGs is not necessary to be attached with an electrode and a lead wire, which makes this device applicable to harvest mechanical energy from any arbitrary moving objects, such as a walking human and a moving automobile [16]. Second, compared to single-electrode TENGs with similar advantage discussed above, [20] FTENGs effectively avoid the electrostatic shield effect, so the limit of the charge transfer efficiency of FTENGs can be close to 100%, much larger than that of single-electrode TENGs (50%). Finally, FTENGs can work in the non-contact mode without significant degradation of the output, which can tremendously increase the energy conversion efficiency due to the large reduction of energy loss from both friction and inelastic collision in the system. However, until now fundamental understandings of FTENGs are still missing to reveal unique characteristics of their output performance. First, their operation principle and the fundamental physics need to be uncovered. Second, their unique output characteristics need to be thoroughly studied to assist the rational design of this structure. Finally, the influence of the structural parameters and how to optimize them to obtain the highest performance is unclear yet. Therefore, a comprehensive theoretical analysis of this structure is necessary.

In this paper, the first theoretical models of two types of FTENGs: contact-mode FTENGs based on vertical charge separation and sliding-mode FTENGs based on in-plane charge separation are discussed in detail. Contact-mode FTENGs are observed to have superior linear characteristics, which give rise to unique applications in vibration energy-harvesting and sensing. Sliding-mode FTENGs have two subcategories based on the material of the freestanding layer. Their output characteristics are carefully studied and the coupling effect of two important design parameters, freestanding height and electrode gap, on the output characteristics of these two sub-categories is investigated. In addition, structural optimization strategies are provided to maximize the power output for both contact-mode and sliding-mode FTENGs. This paper thoroughly elucidates the core working principle and unique characteristics of FTENGs and systematically investigates the influence of different structural parameters, which can serve as an important guideline and pave the way for their rational design and optimization towards real applications.

2. Contact-mode freestanding triboelectric-layer-based nanogenerators

2.1. Theoretical model of the contact-mode freestanding triboelectric-layer-based nanogenerator

We start our discussion from the contact-mode freestanding triboelectric-layer-based nanogenerators (CFTENGs). Two typical structures of CFTENGs are shown in figure 1. figure 1a shows a typical structure for dielectric-freestanding-layer CFTENGs. A dielectric plate (thickness: d_1, relative dielectric constant: ε_{r1}) and two metal plates are stacked face to face, forming two triboelectric pairs. The two metal plates also serve as two electrodes. The total air gap thickness between these two metal plates is defined as g. After the dielectric plate being forced to contact with the two metal plates, both the top and the bottom surfaces of Dielectric 1 will have static triboelectric charges (tribo-charge) due to contact electrification. For simplicity, we assume the triboelectric charge density of both surfaces is the same ($-\sigma$). At the same time, the two metal plates will have the same amount of positive charges in total because of charge conservation.

The concept of nodes is utilized to analyze this electrostatic system, which can fully show its inherent physics and working behavior [20]. In practical applications, the size of the metal electrode is always much larger than the air gap. Therefore, the area size of the freestanding contact-mode TENG (S) is seen as infinitely large and the edge effect can be ignored. As a result, the electric potential on metal 1, metal 2, the top and bottom surface of dielectric 1 are all

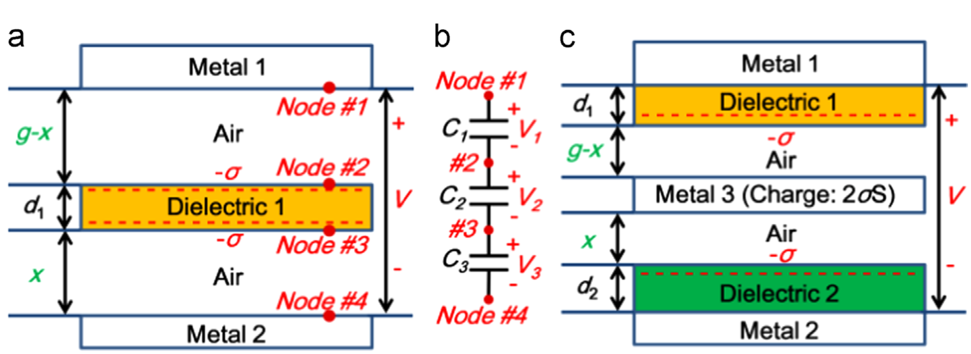

Figure 1 Theoretical models of CFTENGs. (a) Model of a typical dielectric freestanding layer CFTENG. (b) Equivalent circuit model of the dielectric CFTENG electrostatic system. (c) Model of a typical metal freestanding layer CFTENG.