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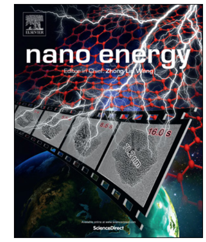

Theoretical systems of triboelectric nanogenerators

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Abstract
Triboelectric nanogenerator (TENG) technology based on contact electrification and electrostatic induction is an emerging new mechanical energy harvesting technology with numerous advantages. The current area power density of TENGs has reached 313 W/m^2 and their volume energy density has reached 490 kW/m^3. In this review, we systematically analyzed the theoretical system of triboelectric nanogenerators (TENGs). Starting from the physics of TENGs, we thoroughly discussed the fundamental working principle of TENGs and simulation method. Then the intrinsic output characteristics, load characteristics, and optimization strategy is in-depth discussed. TENGs have inherent capacitive behavior and their governing equation is their *V-Q-x* relationship. There are two capacitance formed between the tribo-charged dielectric surface and the two metal electrodes, respectively. The ratio of these two capacitances changes with the position of this dielectric surface, inducing electrons to transfer between the metal electrodes under SC condition. This is the core working mechanism of triboelectric generators and different TENG fundamental modes can be classified based on the changing behavior of these two capacitances. Their first-order lumped-parameter equivalent circuit model is a voltage source in series with a capacitor. Their resistive load characteristics have a “three-working-region” behavior because of the impedance match mechanism. Besides, when TENGs are utilized to charge a capacitor with a bridge rectifier in multiple motion cycles, it is equivalent to utilizing a constant DC voltage source with an internal resistance to charge. The optimization techniques for all TENG fundamental modes are also discussed in detail. The theoretical system reviewed in this work provides a theoretical basis of TENGs and can be utilized as a guideline for TENG designers to continue improving TENG output performance.

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Introduction

The tremendous development of portable electronics and sensor networks makes it an urgent requirement to develop sustainable and stable energy sources for them. Powering them entirely by batteries has become more and more unpractical and unfavorable, mainly for the limited battery lifetime, large scope of distribution of these kinds of electronic devices, and potential health and environmental hazards. Therefore, new technologies that can harvest energy from ambient environment as sustainable power sources are emerging research fields, called nano-energy research, which focuses on the applications of nanomaterials and nanotechnology for harvesting energy for powering micro/nanosystems. Recently, triboelectric nanogenerators (TENGs) based on contact electrification and electrostatic induction have become a promising technology in mechanical energy harvesting, which shows unique merits including large output power, high efficiency, low weight and cost effective materials, and simple fabrication [1]. Through 3 years research, the area power density of TENGs has reached 313 W/m^2 and their volume energy density has reached 490 kW/m^3 [2]. The current developed highest mechanical energy conversion efficiency has reached about 85% [3]. Triboelectric nanogenerators have been utilized as direct power source to charge a mobile phone battery [4] and worked as self-powered active sensors [5]. However, there are still requirements for continuing improving their output performance for more and more practical applications, which demands rational design and careful optimization of both materials and structures especially when the current TENG performance is already very high. Moreover, similar to the development of CMOS integrated circuits and systems, the fully-integrated energy harvesting systems that contain TENGs, power management circuits, signal processing circuits, energy storage elements, and/or load circuits are essential for the practical applications of the TENGs. Theoretical simulation plays a key role in understanding the working mechanism and analyzing the output performance of the entire system. Finally, from methodology point of view, simulation is always a necessary step in the whole device design process, because performing control experiments is usually time-consuming and not cost-effective. Thus a thorough theoretical understanding of TENGs is completely urgent in the whole research field. This knowledge can help choosing the appropriate TENG structure and materials, avoid designs which will greatly harm the output performance, and choose suitable system-level topologies for integrated energy harvesting systems.

The objective of this paper is to give a summary about the fundamental theory research of the triboelectric nanogenerator (TENG). First, we will discuss the governing equation, equivalent circuit model, and simulation method. Then, the basic output characteristics (open-circuit voltage, short-circuit transferred charges, and inherent capacitance) of four fundamental TENG modes are discussed in detail. Moreover, resistive load and capacitive load characteristics are shown. Finally, based on the above basic information, we will discuss some advanced TENG structures and optimization techniques for each fundamental TENG modes.

Basics of triboelectric nanogenerators

Inherent capacitive behavior and governing equations: *V-Q-x* relationship

The fundamental working principle of TENGs is a conjugation of contact electrification and electrostatic induction. Contact electrification provides static polarized charges and electrostatic induction is the main mechanism that converts mechanical energy to electricity. Since the most fundamental device based on electrostatics is a capacitor, fundamentally TENG will have inherent capacitive behavior [6].

An arbitrary TENG is analyzed to unveil its inherent capacitive behavior. For any triboelectric generators, there are pair of materials which are face to each other (called tribo-pairs). The distance (x) between these two triboelectric layers can be varied under the agitation of mechanical force. After being forced to get in contact with each other, the contact surface of the two triboelectric layers will have opposite static charges (tribo-charges), as a result of contact electrification. Besides the tribo-pairs layer, there are two electrodes that are carefully insulated inside the TENG system, which ensures the charges can only transfer between the two electrodes through external circuits. If we define the transferred charges from one electrode to another is Q, one electrode will have the transferred charge $-Q$ and the other electrode will have the transferred charge $+Q$.

The electrical potential difference between the two electrodes of any TENGs mainly contributes to two parts. The first part is from the polarized triboelectric charges and their contribution to the voltage is $V_{OC}(x)$, which is a function of separation distance x. Besides, the already transferred charges Q will also contribute to an electric potential difference. If we assume no triboelectric charges exist in this structure, this structure is completely a typical capacitor, so the contribution of these already transferred charges between the two electrodes is $-Q/C(x)$, where C is the capacitance between the two electrodes. Therefore, due to the electrical potential superposition principle, the total voltage difference between the two electrodes can be given by [6]

$$V = -\frac{1}{C(x)}Q + V_{OC}(x) \tag{1}$$

Eq. (1) (named as *V-Q-x* relationship) is the governing equation of any TENGs, clearly explaining its inherent capacitive behavior [6]. The separation of the polarized tribo-charges will generate an electrical potential difference between the two electrodes. If the external circuit exists between the two electrodes, this electrical potential will drive electrons to flow from one electrode to another. These already-transferred electrons can further screen the electrical potential between the two electrodes [7]. Under short-circuit conditions, these transferred charges (Q_{SC}) fully screen the electrical potential generated from polarized triboelectric charges. Therefore, the following equation can be easily derived for TENGs under short-circuit conditions [8]:

$$0 = -\frac{1}{C(x)}Q_{SC}(x) + V_{OC}(x) \tag{2}$$