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RAPID COMMUNICATION

Triboelectric nanogenerators as a new energy technology: From fundamentals, devices, to applications

Guang Zhu[a,*], Bai Peng[b], Jun Chen[b], Qingshen Jing[b], Zhong Lin Wang[a,b,]**

[a]*Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, China*
[b]*School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA*

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Abstract
Contact electrification is coupled with electrostatic induction in developing triboelectric nanogenerator as a new energy technology. The triboelectric nanogenerator has two basic operating modes that can be used to harvest a variety of mechanical energy. It provides not only a viable means of powering portable and wearable electronics, but also demonstrates a possible route towards power generation in large scale. This paper makes a comprehensive review on fundamentals, operating modes, device design and performance enhancement of this newly emerged technology.

Introduction

The advance of integrated circuits in the last decade has ushered in the age of miniaturized electronics that are becoming more portable, wearable, stand-alone and even implantable than ever before. They then require power solutions that are sustainable, maintenance-free and even perpetual, making the use of conventional power supplies such as battery limited. With this regard, energy harvesting techniques that can capture and convert ambient energy have emerged as a supplementary and even an alternative power solution [1-4]. Mechanical energy, due to its abundant availability, is an ideal source for energy harvesting. Well-established transduction mechanisms for mechanical energy harvesting include electrostatic, electromagnetic, and piezoelectric effects, which have been extensively studied for a few decades [5-13].

In the last several years, a new type of energy harvesting technology named as triboelectric nanogenerator (TENG) has emerged to harness ambient mechanical motions [14-17]. The TENG has a novel and unique mechanism by using the coupling between triboelectric effect and electrostatic

*Corresponding author.
**Corresponding author at: Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, China.
E-mail addresses: zhuguang@binn.cas.cn (G. Zhu), zlwang@binn.cas.cn (Z. Lin Wang).

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induction. It features unparalleled advantages over other developed existing technologies, including high power density, light weight, small size, low cost, flexibility and even transparency [18,19]. Since its first report in 2012, it has evolved very rapidly and attracted extensive research interests on a global scale. Basic principles and modes have been proposed; various device structures for harvesting a broad range of mechanical energy have been reported; output power has been dramatically promoted through advanced device designing; and attractive applications of this technology in energy and sensing have been demonstrated.

In this review, we will first have a concise discussion on fundamentals of the physical model of the TENG, which will be followed by an introduction of the basic operating modes. Then we will have detailed elaboration on how to develop high-performance devices. Our recent works will be shown to illustrate each designing strategy. Challenges and prospects will be presented in the end.

Fundamentals

Triboelectric effect is a type of charge transfer by which any two materials, after contact with each other, become electrically charged in opposite signs. The origin of this effect is still shrouded in unsettled questions; and the type of the charge species is still under debate [20-24]. However, it is known that the triboelectric charges are only confined on the surface of materials. They neither recombine nor get annihilated. Instead, they stay in a quasi-permanent way for an extended period of time although minor charge migration occurs [25,26]. The effect has been utilized in applications including electrostatic separations, self-assembly, photocopy and laser printing [27-29]. It is because triboelectric charges are immobile and difficult to be conducted away that triboelectric effect has not been applied in power generation, though it was used to produce high voltage.

The key innovation of the TENG is to incorporate electrostatic induction into an electricity-generating process. Conductive electrodes that can provide mobile charges are fabricated on the back side of the triboelectric charges. In a TENG, it is induced charges on the back electrodes instead of triboelectric charges that actually form the output current. When two pieces of materials carrying opposite triboelectric charges make relative motion, electric potential difference created between the two electrodes causes transient flow of induced charges. As a result, electric current is produced, delivering effective output power to a load if connected between the electrodes. In this process, mechanical energy is thus converted into electrical energy. The form of the relative motion can be diverse, making the TENG capable of harvesting various types of mechanical energy.

Device structures

Contact mode

Basic energy-generation process

The contact mode features a motion direction that is perpendicular to the charged surfaces in a TENG. Our work in 2012 was the first to propose an accurate and clear description of the energy-generation process [15]. Polymethyl methacrylate (PMMA) and polyimide (Kapton) were used as a pair of contact materials.

In an open-circuit condition, exchange of induced charges cannot occur between the two electrodes. Shown in Fig. 1, no triboelectric charges are generated in the original state

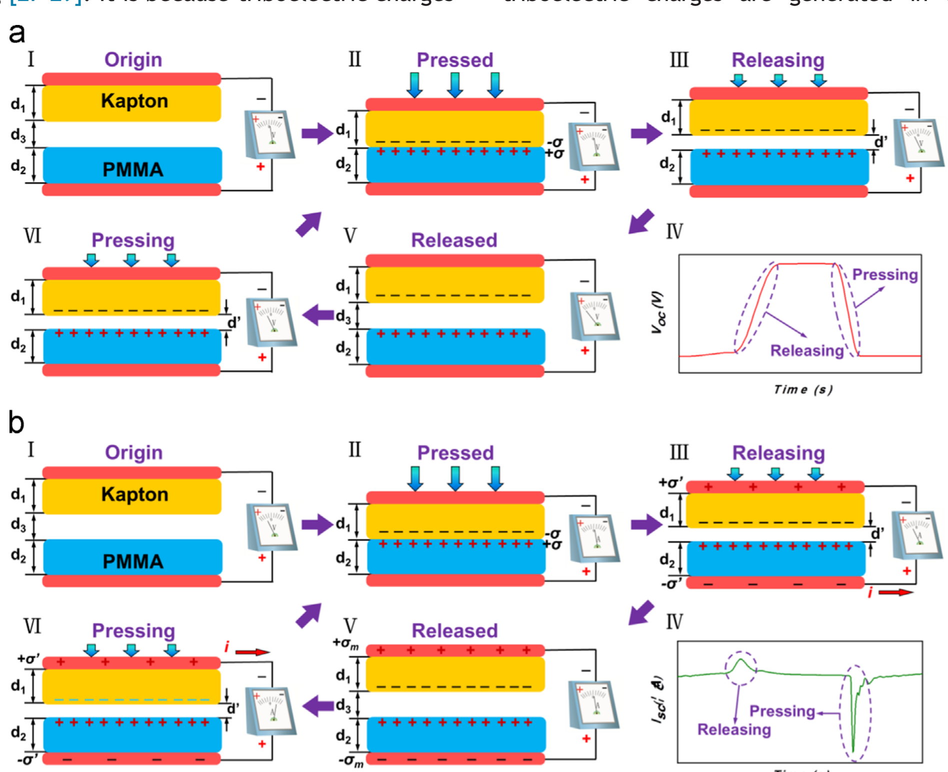

Fig. 1 Sketch that illustrates the operating principle of the contact mode. (a) Open-circuit condition. (b) Short-circuit condition.