Literature Review on Triboelectric Nanogenerator

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Abstract: A literature review that discussed about the triboelectric nanogenerator. Different modes and mechanism of triboelectric nanogenerator has been discussed. Materials which shows triboelectric actions are discussed here. Different application of triboelectric nanogenerators has also been discussed.

1. Introduction

A triboelectric nanogenerator is an energy harvesting device that converts the external mechanical energy into electricity by a conjunction of triboelectric effect and electrostatic induction. This new type of nanogenerator was firstly demonstrated in Prof. Zhong Lin Wang's group at Georgia Institute of Technology in the year of 2012. As for this power generation unit, in the inner circuit, a potential is created by the triboelectric effect due to the charge transfer between two thin organic/inorganic films that exhibit opposite tribo-polarity; in the outer circuit, electrons are driven to flow between two electrodes attached on the back sides of the films in order to balance the potential. Since the most useful materials for TENG are organic, it is also named organic nanogenerator, which is the first of using organic materials for harvesting mechanical energy.

Ever since the first report of the TENG in January 2012, the output power density of TENG has been improved for five orders of magnitude within 12 months. The area power density reaches 313 W/m², volume density reaches 490 kW/m³, and a conversion efficiency of ~60% has been demonstrated. Besides the unprecedented output performance, this new energy technology also has a number of other advantages, such as low cost in manufacturing and fabrication, excellent robustness and reliability, environmental-friendly, and so on.

The triboelectric nanogenerator can be applied to harvest all kind mechanical energy that is available but wasted in our daily life, such as human motion, walking, vibration, mechanical triggering, rotating tire, wind, flowing water and more.

The triboelectric nanogenerator has three basic operation modes: vertical contact-separation mode, in-plane sliding mode, and single-electrode mode. They have different characteristics and are suitable for different applications.

2. Basic modes and mechanisms

2.1. Vertical Contact-Separation Mode

The working mechanism of the triboelectric nanogenerator can be described as the periodic
change of the potential difference induced by the cycled separation and re-contact of the opposite triboelectric charges on the inner surfaces of the two sheets. When a mechanical agitation is applied onto the device to bend or press it, the inner surfaces of the two sheets will get into close contact and the charge transfer will begin, leaving one side of the surface with positive charges and the other with negative charges. This is just the triboelectric effect. When the deformation is released, the two surfaces with opposite charges will separate automatically, so that these opposite triboelectric charges will generate an electric field in between and thus induce a potential difference across the top and bottom electrodes. In order to screen this potential difference, the electrons will be driven to flow from one electrode to the other through the external load. The electricity generated in this process will continue until the potentials of the two electrodes get back to even again. Subsequently, when the two sheets are pressed towards each other again, the triboelectric-charge-induced potential difference will begin to decrease to zero, so that the transferred charges will flow back through the external load, to generate another current pulse in the opposite direction. When this periodic mechanical deformation lasts, the alternating current (AC) signals will be continuously generated[1][2].

As for the pair of materials getting in contact and generating triboelectric charges, at least one of them need to be an insulator, so that the triboelectric charges cannot be conducted away but will remain on the inner surface of the sheet. Then, these immobile triboelectric charges can induce AC electricity flow in the external load under the periodic distance change.

2.2. Lateral Sliding Mode

There are two basic friction processes: normal contact, and lateral sliding. We demonstrated here a TENG that is designed based on the in-plane sliding between the two surfaces in lateral direction.[3] With an intensive triboelectrification facilitated by sliding friction, a periodic change in the contact area between two surfaces leads to a lateral separation of the charge centers, which creates a voltage drop for driving the flow of electrons in the external load. The sliding-induced electricity generation mechanism is schematically depicted in the figure. In the original position, the two polymeric surfaces fully overlap and intimately contact with each other. Because of the large difference in the ability to attract electrons, the triboelectrification will leave one surface with net positive charges and the other with net negative charges with equal density. Since the tribo-charges on the insulators will only distribute in the surface layer and will not be leaked out for an extended period of time, the separation between the positively charged surface and negatively charged surface is negligible at this overlapping position, and thus there will be little electric potential drop across the two electrodes. Once the top plate with the positively charged surface starts to slide outward, the in-plane charge separation is initiated due to the decrease in contact surface area. The separated charges will generate an electric field pointing from the right to the left almost parallel to the plates, inducing a higher potential at the top electrode. This potential difference will drive a current flow from the top electrode to the bottom.
electrode in order to generate an electric potential drop that cancels the tribo-charge-induced potential. Because the vertical distance between the electrode layer and the tribo-charged polymeric surface is negligible compared to the lateral charge separation distance, the amount of the transferred charges on the electrodes approximately equals to the amount of the separated charges at any sliding displacement. Thus, the current flow will continue with the continuation of the ongoing sliding process that keeps increasing the separated charges, until the top plate fully slides out of the bottom plate and the tribo-charged surfaces are entirely separated. The measured current should be determined by the rate at which the two plates are being slid apart. Subsequently, when the top plate is reverted to slide backwards, the separated charges begins to get in contact again but no annihilation due to the insulator nature of the polymer materials. The redundant transferred charges on the electrodes will flow back through the external load with the increase of the contact area, in order to keep the electrostatic equilibrium. This will contribute to a current flow from the bottom electrode to the top electrode, along with the second half cycle of sliding. Once the two plates reach the overlapping position, the charged surfaces get into fully contact again. There will be no transferred charges left on the electrode, and the device returns to the first state. In this entire cycle, the processes of sliding outwards and inwards are symmetric, so a pair of symmetric alternating current peaks should be expected.

The mechanism of in-plane charge separation can work in either one directional sliding between two plates\textsuperscript{[4]} or in rotation mode\textsuperscript{[5]}. In the sliding mode, introducing linear grating or circular segmentation on the sliding surfaces is an extremely efficient means for energy harvesting. With such structures, two patterned triboelectric surfaces can get to fully mismatching position through a displacement of only a grating unit length rather than the entire length of the TENG so that it dramatically increase the transport efficiency of the induced charges.

2.3. Single-Electrode Mode

A single-electrode-based triboelectric nanogenerator is introduced as a more practical and feasible design for some applications such as fingertip-driven triboelectric nanoagenerator\textsuperscript{[25-26]} The working principle of the single-electrode TENG is schematically shown in the figure by the coupling of contact electrification and electrostatic induction. In the original position, the surfaces of skin and PDMS fully contact with each other, resulting in charge transfer between them. According to the triboelectric series, electrons were injected from the skin to the PDMS since the PDMS is more triboelectrically negative than skin, which is the contact electrification process. The produced triboelectric charges with opposite polarities are fully balanced/screened, leading to no electron flow in the external circuit. Once a relative separation between PDMS and skin occurs, these triboelectric charges cannot be compensated. The negative charges on the surface of the PDMS can induce positive charges on the ITO electrode, driving free electrons to flow from the ITO electrode to ground. This electrostatic induction process can give an output voltage/current signal if the distance separating between the touching skin and the bottom PDMS is appreciably comparable to the size of the PDMS film. When negative triboelectric charges on the PDMS are fully screened from the induced positive charges on the ITO electrode by increasing the separation distance between the PDMS and skin, no output signals can be observed, as illustrated. Moreover, when the
skin was reverted to approach the PDMS, the induced positive charges on the ITO electrode decrease and the electrons will flow from ground to the ITO electrode until the skin and PDMS fully contact with each other again, resulting in a reversed output voltage/current signal. This is a full cycle of electricity generation process for the TENG in contact-separation mode.

Fig 4. Single-electrode mode of triboelectric nanogenerator.

3. Applications

TENG is a physical process of converting mechanical agitation to an electric signal through the triboelectrification (in inner circuit) and electrostatic induction processes (in outer circuit). This basic process has been demonstrated for two major applications. The first application is energy harvesting with a particular advantage of harvesting mechanical energy. The other application is to serve as a self-powered active sensor, because it does not need an external power source to drive.

Fig 5. Triboelectric nanogenerator built inside shoe insole for harvesting walking energy.

3.1. Harvesting vibration energy

Vibration is one of the most popular phenomena in our daily life, from walking, voices, engine vibration, automobile, train, aircraft, wind and many more. It exists almost everywhere and at all the time. Harvesting vibration energy is of great value especially for powering mobile electronics. The following Based on the fundamental principles of triboelectric nanogenerators, various technologies have been demonstrated for
harvesting vibration energy. This application of triboelectric nanogenerator has been demonstrated in the following aspects: 1. Cantilever-based technique is a classical approach for harvesting mechanical energy, especially for MEMS. By designing the contact surface of a cantilever with the top and bottom surfaces during vibration, TENG has been demonstrated for harvesting ambient vibration energy based on the contact-separation mode[6]. 2. To harvest the energy from a backpack, we demonstrated a rationally designed TENG with integrated rhombic gridding, which greatly improved the total current output owing to the structurally multiplied unit cells connected in parallel[7]. 3. With the use of 4 supporting springs, a harmonic resonator-based TENG has been fabricated based on the resonance induced contact-separation between the two triboelectric materials, which has been used to harvest vibration energy from an automobile engine, a sofa and a desk[8,9]. Recently, a three-dimensional triboelectric nanogenerator (3D-TENG) has been designed based on a hybridization mode of conjunction the vertical contact-separation mode and the in-plane sliding mode. The innovative design facilitates harvesting random vibration energy in multiple directions over a wide bandwidth. The 3-D TENG is designed for harvesting ambient vibration energy, especially at low frequencies, under a range of conditions in daily life, thus, opening the applications of TENG in environmental/infrastructure monitoring, charging portable electronics and internet of things.

3.2. Harvesting energy from human body motion

Since there is abundant mechanical energy generated on human bodies in people's everyday life, we can make use of the triboelectric nanogenerator to convert this amount of mechanical energy into electricity, for charging portable electronics and biomedical applications. This will help to greatly improve the convenience of people's life and expand the application of the personal electronics. A packaged power-generating insole with built-in flexible multi-layered triboelectric nanogenerators has been demonstrated, which enable harvesting mechanical pressure during normal walking. The TENG used here relies on the contact-separation mode and is effective in responding to the periodic compression of the insole. 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. A TENG can be attached to the inner layer of a shirt for harvesting energy from body motion. Under the generally walking, the maximum output of voltage and current density are up to 17 V and 0.02 μA/cm², respectively. The TENG with a single layer size of 2 cm×7 cm×0.08 cm sticking on the clothes was demonstrated as a sustainable power source that not only can directly light up 30 light-emitting diodes (LEDs), but also can charge a lithium ion battery by persistently clapping clothes.

3.3. Self-powered active strain/force sensors

An triboelectric nanogenerator automatically generates an output voltage and current once it is mechanically triggered. The magnitude or the output signal signifies the impact of the mechanical deformation and its time-dependent behavior. This is the basic principle of the TENG can be applied as a self-powered pressure sensor. The voltage-output signal can reflect the applied pressure induced by a droplet of water. All types of TENGs have a high sensitivity and fast response to the external force and show as a sharp peak signal. Furthermore, the response to the impact of a piece of feather (20 mg, ~0.4 Pa in contact pressure) can be detected. The sensor signal can delicately show these details of the entire process. The existing results show that our sensor can be applied for measuring the subtle pressure in real life[9].
In a case that we make a matric array of the triboelectric nanogenerators, a large-area, and self-powered pressure map applied on a surface can be realized[10]. The response of the TENG array with local pressure was measured through a multi-channel measurement system. There are two types of output signals from the TENG: open circuit voltage and short circuit current. The Open circuit voltage is only dictated by the final configuration of the TENG after applying a mechanical triggering, so that it is a measure of the magnitude of the deformation, which is attributed to the static information to be provided by TENG. The output current depends on the rate at which the induced charge would flow, so that the current signal is more sensitive to the dynamic process of how the mechanical triggering is applied.

The active pressure sensor and the integrated sensor array based on the triboelectric effect have several advantages over conventional passive pressure sensors. First, the active sensor is capable of both static pressure sensing using the open-circuit voltage and dynamic pressure sensing using the short-circuit current, while conventional sensors are usually incapable of dynamic sensing to provide the loading rate information. Second, the prompt response of both static and dynamic sensing enables the revealing of details about the loading pressure. Third, the detection limit of the TENG for dynamic sensing is as low as 2.1 Pa, owing to the high output of the TENG. Fourth, the active sensor array presented in this work has no power consumption and could even be combined with its energy harvesting functionality for self-powered pressure mapping. Future works in this field involve the miniaturization of the pixel size to achieve higher spatial resolution, and the integration of the TEAS matrix onto fully flexible substrate for shape-adaptive pressure imaging.
3.4. Self-powered active chemical sensors

As for triboelectric nanogenerators, maximizing the charge generation on opposite sides can be achieved by selecting the materials with the largest difference in the ability to attract electrons and changing the surface morphology. In such a case, the output of the TENG depends on the type and concentration of molecules adsorbed on the surface of the triboelectric materials, which can be used for fabricating chemical and biochemical sensors. As an example, the performance of the TENG depends on the assembly of Au nanoparticles (NPs) onto the metal plate. These assembled Au NPs not only act as steady gaps between the two plates at strain free condition, but also enable the function of enlarging the contact area of the two plates, which will increase the electrical output of the TENG. Through further modification of 3-mercaptopropionic acid (3-MPA) molecules on the assembled Au NPs, the high-output nanogenerator can become a highly sensitive and selective nanosensor toward Hg$^{2+}$ ions detection because of the different triboelectric polarity of Au NPs and Hg$^{2+}$ ions. With its high sensitivity, selectivity and simplicity, the TENG holds great potential for the determination of Hg$^{2+}$ ions in environmental samples. As different ions, molecules, and materials have their unique triboelectric polarities, we expect that the TENG can become either an electrical turn-on or turn-off sensor when the analytes are selectively binding to the modified electrode surface. We believe this work will serve as the stepping stone for related TENG studies and inspire the development of TENG toward other metal ions and biomolecules such as DNA and proteins in the near future[11].

4. Choice of materials and surface structures

Almost all materials known exhibit the triboelectric effect, from metal, to polymer, to silk and to wood, almost everything. All of these materials can be candidates for fabricating TENGs, so that the materials choices for TENG are huge. However, the ability of a material for gaining/losing electron depends on its polarity. John Carl Wilcke published the first triboelectric series in a 1757 on static charges. A material towards the bottom of the series, when touched to a material near the top of the series, will attain a more negative charge. The further away two materials are from each other on the series, the greater the charge transferred. Beside the choice of the materials in the triboelectric series, the morphologies of the surfaces can be modified by physical techniques with the creation of pyramids-,
square- or hemisphere-based micro- or nano-patterns, which are effective for enhancing the contact area and possibly the triboelectrification. However, the created bumpy structure on the surface may increase the friction force, which may possibly reduce the energy conversion efficiency of the TENG. Therefore, an optimization has to be designed for maximizing the conversion efficiency.

The surfaces of the materials can be functionalized chemically using various molecules, nanotubes, nanowires or nanoparticles, in order to enhance the triboelectrification effect. Surface functionalization can largely change the surface potential. The introduction of nanostructures on the surfaces can change the local contact characteristics, which may improve the triboelectrification. This will involve a large amount of studies for testing a range of materials and a range of available nanostructures.

Besides these pure materials, the contact materials can be made of composites, such embedding nanoparticles in polymer matrix. This not only changes the surface electrification, but also the permittivity of the materials so that they can be effective for electrostatic induction. Therefore, there are numerous ways for enhancing the performance of the TENG from the materials point of view. This gives an excellent opportunity for chemists and materials scientists to do extensive study both in the basic science and in practical application. In contrast, materials systems for solar cell and thermal electric, for example, are rather limited, and there are not very many choices for high performance devices.

![Triboelectric Series Material](image)

Fig 8. Triboelectric series material.

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6. References


