

Energy Harvesting Devices: A Review of Triboelectric Nanogenerator and its Applications

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ABSTRACT

A portable or self-powered power source is required to meet the current energy demand. Conventional energy sources are depleting or resulting in an environmental impact. Energy sources such as wind, solar, and hydropower are much studied to harvest renewable energy and storage for future use. But with emerging wearable, smart devices, and health monitoring devices the need for self-powered devices is growing rapidly. These devices can be powered using traditional batteries, but it has certain limitations and concerns. Energy harvesting devices such as nanogenerators are booming as they can generate electricity from applications for self-powered systems, sensors, the Internet of Things (IoT), medical devices, and Biomechanical energy harvesting. The invention of nanogenerators paved the way for lightweight, flexible, easy-to-fabricate, and low-maintenance devices for applications such as energy harvesting and self-powered devices. In this paper, various types of nanogenerators, their fabrication techniques, and their applications are studied and outlined.

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Introduction

In recent times, Energy harvesting devices have gained much attention because of the ability of these devices to harvest energy from external sources such as mechanical, thermal, wind, and kinetic energy. The harvested energy is stored in small devices such as wearable electronics, monitoring, or sensor devices. With the growing demand for small wearable electronics, monitoring devices, or sensor devices, researchers are studying to identify a nanogenerator that meets the current need for a smaller device size, work life, weight, power, and cost of the energy harvesting devices to be widely used as low energy electronics.

Types of Energy Harvesting Devices

A Nanogenerator is an energy-harvesting device that produces electricity by converting mechanical or thermal energy. A nanogenerator uses three approaches to produce electric energy, they are piezoelectric, pyroelectric, and triboelectric nanogenerators. To convert mechanical energy into electricity, piezoelectric and triboelectric nanogenerators can be used. To convert thermal energy from time-dependent temperature fluctuation, pyroelectric nanogenerators can be used.

A. Piezoelectric Nanogenerators

A piezoelectric nanogenerator (PENG) converts kinetic energy into electric energy using a piezoelectric nanostructured material. A PENG is further classified based on the configuration of the piezoelectric nanogenerator, they are a Vertical nanowire Integrated Nanogenerator (VING) consisting of 3-D vertical stacking of piezoelectric material. The lateral configuration of the piezoelectric

nanostructure is classified as the Lateral nanowire Integrated Nanogenerator (LING). Nanocomposite Electrical Generators (NEG) have sandwich layers of piezoelectric nanostructure and polymer matrix that fill between the piezoelectric nanostructures. A fourth type of the PENG was suggested by Professor Zhong Lin Wang in 2008 where the piezoelectric nanostructures are grown on two microfibers in its radial direction and are twined to form a PENG [1].

A few piezoelectric materials such as ZnO, CdS, and GaN have been the primary research focus materials due to the wurtzite structure [1-2]. The advantages of these materials are facile, cost-effective hydrothermal synthesis at temperatures below 100°C, and the vertical crystalline growth making it easier to integrate PENG material with various substrates. A research focus is also on identifying a new material with a high piezoelectric constant, ideal composition, and orientation that shows a high piezoelectric response making it suitable for applications in smart wearable devices, flexible and self-powered devices.

B. Pyroelectric Nanogenerators

A pyroelectric nanogenerator uses pyroelectric nanostructured materials to convert thermal energy into electrical energy. The driving force for this type of device is the temperature difference between the two ends of the device [3-4].

C. Triboelectric Nanogenerators

A triboelectric nanogenerator (TENG) converts external mechanical energy into electricity using triboelectric materials [1]. The triboelectric materials show a combination of triboelectric effect and electrostatic induction that is converted into electric energy using energy harvesting devices such as TENG. A

triboelectric nanogenerator operates in 3 modes.

Vertical contact separation mode nanogenerator as shown in Figure 1 produces a triboelectric effect by periodic mechanical agitation applied onto a device to bend or press the inner surface of two sheets, with close contact of the surfaces producing charge transfer leaving opposite charges on both surfaces when separated generating an electric field. Having an insulator as one of the materials gives an advantage of triboelectric effects retaining on the surface for a long and cannot be conducted away [5-28].

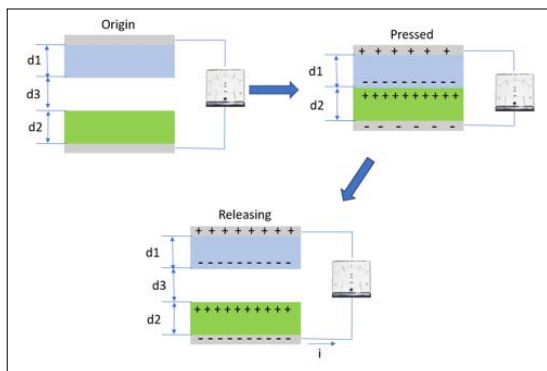


Figure 1: Vertical Contact Separation Mode

Figure 2 shows a Lateral or In-plane sliding mode nanogenerator uses a periodic change in the contact area by in-plane sliding between two surfaces creating a voltage drop that drives the flow of electrons in the external load. A periodic change in the contact area of two surfaces creates lateral change resulting in the voltage drop for driving electrons in the external load.

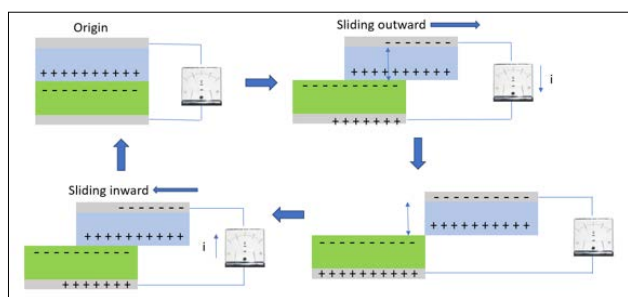


Figure 2: In-Plane Sliding Mode

Single electrode-based triboelectric nanogenerator generates charges by electrification and electrostatic induction as shown in Figure 3.

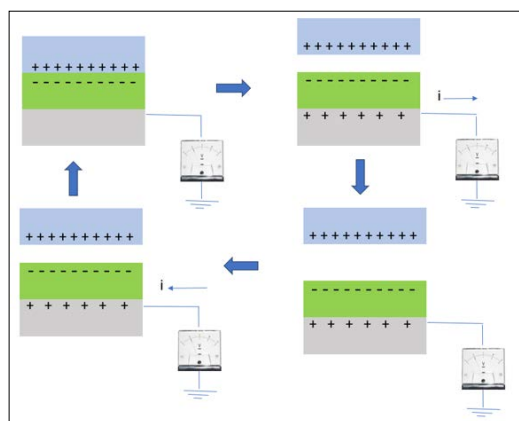


Figure 3: Single Electrode Mode

For applications of the TENGs in self-powered electronic devices, the energy efficiency is still considered low. The use of dielectric materials with higher electric charge capacity, high electronegative difference, and optimized material thickness could increase the energy efficiency of the TENG device. Researchers are evaluating various techniques to increase the performance of the TENG to develop a high-performing TENG with a low-cost, flexible, breathable, and readily scalable fabrication process. Table 1 lists several designs of TENGs, their main features, and applications.

Table I: TENG Fabrication Techniques

Design of TENG's	Features	Application	Research articles
Electrospun EN-TENGs	Breathable and high flexibility	Portable device power system, self-powered fabric-based electronics	[5-22]
Porous TENGs	Breathable, lightweight	Wearable electronic devices	[23-25]
Stretchable triboelectric nanogenerator SNF-TENG	Stretchable and breathable	power source for wearable applications, smart raincoats, self-powered e-skin, and tactile interactive interfaces	[26]
Rotary triboelectric nanogenerator	Harvests energy from all mechanical movements such as wind, water wave	Air filter, haze treatment, wound healing	[27-29]
Woven triboelectric nanogenerator (WS)-TENGs	Harvests energy from human motion	Integrated into human clothing or floor mat	[30,31]
Biodegradable triboelectric nanogenerator BD-TENG	Environment-friendly, High durability, high processability	IoT, wearable devices, implant devices	[32,33]

To harvest the mechanical energy from mechanical movements such as wind, wave, and so forth [29,35-37]. Attempts have been made to evaluate the woven triboelectric nanogenerator (WS-TENG) to effectively harvest mechanical energy from human motion [32,33]. A honeycomb-like nanostructure for a triboelectric nanogenerator is studied by et al [38]. A combination of piezo-triboelectric nanogenerators (PTNG) based on BCZT/PVDF-HFP composite nanofibers was studied [36].

Although most materials exhibit triboelectric effect, the choice of material is critical to increase the conversion energy of TENG. With surface modification techniques, and composites, the material can be chemically functionalized to enhance the triboelectrification effect. The inherent property of the material to gain electrons depends on the polarity. Various polymeric materials were used to Polyvinyl alcohol (PVA), Polyvinylidene fluoride (PVDF), Polyamide 66 PA66, PVDF-TrFE.

Recently biomaterial based TENGs have received huge attention for their great potential in the IoT, wearable devices, and implantable devices [33]. A fully biodegradable triboelectric nanogenerator

(BD-TENG) was studied which shows huge potential for a green micro-power source for environment monitoring and as biomedical implants with no adverse effects to the environment or human body [32]. A spongy parenchyma-like structure SP-TENG imparted on an electrospun mat was tested by for portable electronics and flexible sensors [34,38].

Applications

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- **Self-Powered Sensors**

A TENG generates energy once the mechanical motion is triggered from active sensors or motion sensors. Harvesting energy from human motion, environmental energy, and vibration energy. Nanogenerators can be employed to capture and convert waste energy from various sources, including industrial activities, and the automotive and transportation industries. The nanogenerator can be used to capture wasted mechanical or thermal energy into usable electricity, nanogenerators can contribute to more sustainable and efficient energy management practices.

- **Medical Devices**

Nanogenerators can be incorporated into implantable medical devices, including pacemakers, neurostimulators, or drug transport systems, to provide a continuous power source without the need for battery-substitute surgical treatment. TENGs can harvest energy from bodily functions, such as muscle movements.

- **Internet of Things (IoT)**

Nanogenerators can deliver strength to rigid as well as bendy IoT gadgets consisting of Wi-Fi sensors, and verbal exchange modules. The use of nanogenerators permits long-lasting and self-enough networks. Nanogenerators can help limit the maintenance and energy fees related to large-scale IoT deployments.

- **Consumer Electronics**

Nanogenerators may be integrated into electronic devices along with smartphones, or faraway controls, to extend battery lifestyles or maybe cast off the need for batteries. For example, a nanogenerator can be embedded into a tool's casing to seize strength from person interactions, like urgent keys or swiping video display units.

Conclusion

The application and technique of energy harvesting make nanogenerators unique but are currently limited to applications as supplementary battery devices. With a combination of technology from other energy harvesters such as solar or biochemical energy harvesters, the applications of nanogenerators are enhanced or widespread. This work provides an opportunity to review and summarize various nanogenerators, their fabrication techniques, and their applications as a sustainable power source for self-powered electronics and energy harvesting devices.

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