

Triboelectric Nanogenerators: From Basic Mechanisms to Sustainable Energy Applications

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Abstract. Triboelectric nanogenerators, as an emerging mechanical energy collection technology, provide sustainable energy solutions for the Internet of Things and wearable devices through the synergistic effect of contact charging and electrostatic induction. This technology can efficiently collect low-frequency mechanical energy in the environment and has advantages such as diverse material selection and flexible structural design. TENG has developed four typical working modes: the vertical contact separation mode is suitable for vibration energy collection, the sliding friction mode realizes rotational energy conversion, the single-electrode mode is convenient for wearable integration, and the independent friction layer mode provides high output stability. However, the practical application of TENG still faces challenges such as unclear contact charging mechanism, environmental sensitivity, and large-scale preparation. Through material modification, surface engineering, TENG has demonstrated great potential in fields such as environmental energy harvesting, self-powered sensing and medical electronics. Future research should focus on the development of wide-temperature range materials, machine learning-assisted structural design, and breakthroughs in energy management technologies to promote the transition of TENG from the laboratory to industrial application.

Keywords: Triboelectric nanogenerator, Contact electrification, Charge transfer efficiency, Wearable electronics, Self-powered systems.

1. Introduction

With the rapid development of the Internet of Things and wearable electronic devices, the limitations of traditional battery-powered systems in terms of sustainability and maintenance costs have become increasingly prominent [1-3]. Triboelectric nanogenerators (TENG), as a novel energy harvesting technology, offer an innovative solution to this challenge by converting environmental mechanical energy into electrical energy [4-6]. The core advantage of this technology lies in its efficient low-frequency mechanical energy collection capability (<5Hz), wide range of material selection, and excellent flexible integration characteristics, making it an important breakthrough in the field of distributed energy supply [7,8].

The working principle of TENG is based on two key physical effects: the contact electrification effect and the electrostatic induction effect. When two materials with different electron affinities

come into contact, the phenomenon of interfacial charge transfer occurs. The subsequent separation process generates current through the external circuit driven by electrostatic induction [9,10]. At present, researchers have developed four typical working modes, including the vertical contact separation mode suitable for vibration energy collection, the sliding friction mode for rotational energy conversion, the single-electrode mode convenient for integration in wearable devices, and the independent friction layer mode with high output stability [4]. These innovations in working modes have greatly expanded the application scope of TENG in the field of energy harvesting.

Although TENG technology has made remarkable progress in basic research and application development, its large-scale practical application still faces several key challenges. Firstly, a deeper understanding of the mechanism of contact electrification still needs to be enhanced, especially the processes of generation, transfer and dissipation of interface charges are not yet fully understood [11,12]. Secondly, environmental factors such as humidity, temperature and surface contamination can significantly affect device performance, causing fluctuations in output power [13,14]. Finally, there are still technical bottlenecks in large-scale production and cost control, and more sophisticated material preparation processes and packaging methods need to be developed [15,16].

As a green energy technology with broad prospects, TENG has demonstrated great potential in the fields of micro-energy harvesting and self-powered systems. Through continuous material innovation, structural optimization and multi-mode energy conversion design, this technology is expected to be widely applied in fields such as environmental energy harvesting, self-powered sensing and wearable medical electronics. This article aims to systematically summarize the latest research progress of TENG technology, deeply analyze the challenges it faces and its future development direction and provide theoretical guidance and practical references for promoting this technology from the laboratory to industrial application.

2. Working principle of TENG

2.1. Operating mechanism

TENG's energy conversion relies on the synergistic effect of contact electrification and electrostatic induction [17,18]. Contact electrification is its core principle, where charge transfer occurs between two different materials during contact or friction [17,19]. When in contact, the interatomic distances at the interface shrink to the chemical bond scale, reducing the potential barrier between electron clouds and facilitating electron transfer from the material with higher electrochemical potential to the one with lower electrochemical potential until dynamic equilibrium is reached [20]. After separation, polar charges remain on the material surfaces, forming triboelectric charges. This process can occur in solid, liquid, and gas media, with electron transfer considered the primary mechanism for electrification between dielectric materials.

The presence of triboelectric charges further induces electrostatic induction, where the static charges on the dielectric surface drive the flow of free electrons in the electrode through electrostatic coupling, generating instantaneous current and converting mechanical energy into electrical energy [21,22]. However, the microscopic mechanism of contact electrification remains controversial, with core scientific questions including: (1) Whether ion or molecular contributions are involved in interfacial charge transfer; (2) The regulatory mechanisms of environmental factors (humidity, temperature) on transfer efficiency; (3) Quantum effects of charge distribution at the nanoscale. Related research is significant for elucidating the essence of triboelectric charging and optimizing TENG performance [23,24].

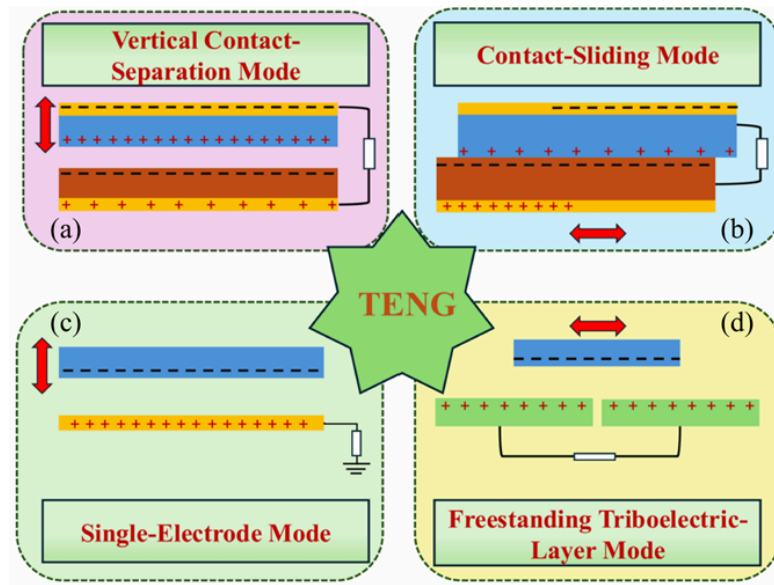


Figure 1. Schematic diagram of four kinds of TENGs

2.2. Four typical working modes

TENG primarily comprises four basic operating modes: vertical contact-separation mode (CS) [25], sliding friction mode (LS) [26], single-electrode mode (SE) [27], and freestanding triboelectric layer mode (FT) [28] (Fig. 1). The CS mode generates potential changes through vertical contact-separation, thereby outputting current ; the LS mode utilizes parallel interface sliding displacement to generate a potential difference; the SE mode uses the ground as a reference electrode to directly harvest mechanical energy from moving objects; the FT mode introduces symmetric dual electrodes based on the SE mode, achieving energy harvesting by inducing asymmetric charge distribution through movement. In practical applications, different modes are often combined to enhance output performance and adaptability.

2.2.1. Vertical contact-separation mode

Wang et al. were the first to propose that, in a vertical contact-separated mode, TENGs can achieve energy conversion through the synergistic effects of the triboelectric effect and electrostatic induction [25]. This structure consists of two electrodes, one at the top and one at the bottom of a stacked device (Fig. 1a), with a tiny air gap between them. In the initial state, there is almost no significant charge accumulation or potential difference between the electrodes. When external force causes the two electrodes to come into contact, the triboelectric effect between different materials triggers electron transfer from one side to the other, resulting in opposite charge distributions at the interface and thus generating a potential difference [29].

This energy conversion process exhibits distinct periodicity, dependent on the alternating cycle of contact and separation. Its performance is influenced by various factors, including the material's triboelectric sequence, surface roughness, dielectric properties, and charge transfer mechanisms. During multiple cycles, the accumulation and release of triboelectric charges repeatedly occur, enabling the TENG to stably convert mechanical input into usable electrical energy. Azad et al. validated the performance based on the classic triboelectric sequence (aluminum as the positive terminal, polytetrafluoroethylene as the negative terminal), and the results showed that this

configuration exhibits outstanding output efficiency: a 10uF capacitor can be charged to 24.04 V within 300 seconds, corresponding to a maximum energy density of 2800 uJ cm⁻³ [29].

2.2.2. Sliding mode

Since the current output from CS-TENG typically exhibits intermittent pulses, researchers have proposed a sliding friction mode SM-TENG to obtain a more continuous and stable electrical signal. This mode achieves energy conversion through relative lateral sliding between electrodes. Fig. 1b illustrates that when two materials with different triboelectric properties move relative to each other in a parallel direction, the interface contact area undergoes triboelectric charging, causing electrons to transfer on the material surface and form a potential difference [26]. This potential difference drives free charges to flow through an external circuit, thereby converting the input mechanical energy into electrical energy. The energy conversion efficiency is closely related to the differences in triboelectric properties of the materials, the instantaneous contact area, and the sliding speed. Among these factors, the greater the difference in triboelectric properties, the more significant the charge transfer at the interface, and the higher the output current [30].

In contrast, SM-TENG outperforms CS-TENG in charge transfer efficiency, but its practical application is limited by energy loss due to air breakdown and insufficient durability caused by friction wear. Therefore, the key to improving the performance of sliding-mode TENG lies in optimizing the contact interface materials to reduce wear, designing a reasonable electrode structure to stabilize the contact area, and enhancing the long-term operational stability of the device [31].

2.2.3. Single-electrode mode

Although CS mode and SM mode have made significant progress in improving TENG output performance, their reliance on a dual-electrode structure limits their application in wearable, flexible electronics, and environmental energy harvesting scenarios. To address this, the single-electrode mode TENG was developed [27]. SE-TENG relies solely on a single working electrode to harvest energy through electrostatic coupling with the environment. Its operating mechanism is based on changes in potential difference caused by the interaction between the friction layer and external objects. As shown in Fig. 1c, the basic structure of this mode consists of a fixed friction layer and a movable electrode. When an external object moves relative to the friction layer, the triboelectric effect at the interface creates a difference in charge distribution on the surface, disrupting the electrostatic equilibrium of the electrode and promoting the directed flow of free electrons in the external circuit, thereby converting mechanical energy into electrical energy [32].

Compared to traditional dual-electrode modes, SE-TENG no longer requires paired electrodes, thereby achieving structural simplification, ease of integration, and high adaptability to complex environments. This design is particularly suitable for energy harvesting in wearable electronics and moving objects. Its principle lies in a single electrode directly contacting the environment or human body, while the other end senses changes in the electric field through electrostatic induction. This simplification not only enhances the device's flexibility and portability but also effectively reduces system size and manufacturing complexity. Yu et al. further developed an SE-TENG based on flexible, stretchable cotton fabric, which can stably output approximately 0.3V voltage at a frequency of 2.5 Hz and under a force of 4N, while maintaining excellent breathability and cycling stability [33].

2.2.4. Freestanding triboelectric layer mode

To overcome issues such as fixed electrodes, structural asymmetry, and inconvenient dual-electrode wiring in traditional TENG configurations, researchers proposed the Freestanding Triboelectric Layer Mode (FT-TENG) to better accommodate applications requiring large-scale relative motion, non-contact friction, and stable high output. Fig. 1d illustrates that this structure places the two electrodes on the same plane, with a gap in between forming the basic electrode unit. An independent friction layer is vertically positioned above electrode 1, with dimensions identical to those of electrode 1 [28]. For dielectric-type FT-TENG, the independent layer consists solely of a single layer of dielectric material; in metal-type FT-TENG, a metal film is typically deposited on the back of the dielectric layer to enhance conductivity and charge collection efficiency.

Under the influence of an external tangential driving force, the FEP friction layer periodically slides between the two electrodes. The triboelectric effect at the interface induces charge transfer between the electrodes and the dielectric layer, generating a transient potential difference. As the FEP layer repeatedly slides back and forth, charges continuously redistribute between the two electrodes, driving current flow through an external load and enabling AC output [34]. This mechanism efficiently converts external mechanical energy into electrical energy, making it particularly suitable for providing stable power to low-power or miniature electronic devices.

3. Key parameters affecting TENG performance

The output performance of TENG is influenced by multiple factors, which can be categorized into three main types: material surface characteristics, charge transfer efficiency, and environmental conditions. In terms of material surface characteristics, surface roughness significantly affects the charge transfer process by altering the effective contact area and the strength of interfacial interactions; the triboelectric sequence reflects the differences in electron affinity between materials and serves as an intrinsic parameter determining the magnitude of the output potential. In terms of charge transfer efficiency, the electron gain/loss tendencies and interface state characteristics of different material combinations directly affect energy conversion efficiency.

Environmental factors also play a crucial regulatory role in TENG output. Temperature changes affect material conductivity and charge relaxation time, thereby altering charge retention capability; humidity modulates output stability through water molecule-mediated surface charge reorganization effects; and atmospheric pressure can influence charge separation efficiency by affecting interfacial mechanical stress and contact states. These factors interact synergistically, forming a “material-structure-environment” multi-parameter coupled regulatory mechanism for TENG performance, which provides important guidance for device design and optimization.

3.1. Surface characteristics of materials

The surface roughness, charge density, and surface polarity of triboelectric materials are the core parameters determining the energy conversion performance of TENG [35]. Among these, roughness influences charge generation efficiency by adjusting the actual contact area [36]; charge density directly determines output voltage and current intensity [37], while surface polarity affects the strength of the triboelectric effect by regulating the charge transfer process at the interface [38]. Optimizing these surface characteristics can significantly enhance the overall output performance of the device.

Surface roughness plays a significant role in the triboelectric effect. In actual operation, the surface morphology of the material affects the effective contact between the positive and negative friction layers, thereby altering the power generation efficiency. For liquid-solid TENGs, the roughness of the solid friction layer is particularly critical [39]. Previous studies have shown that moderately increasing surface roughness can enhance triboelectric charge generation, as rough surfaces increase the actual contact area and enhance the mechanical effects of interfacial friction, enabling the surface to carry more charge and thereby increasing electron transfer [40]. However, excessively high roughness can result in highly uneven surface morphology, leading to unstable charge distribution and reducing the sustainability and output stability of the triboelectric effect [41].

Surface polarity is also a key factor influencing triboelectric performance, primarily determined by the material's chemical composition and molecular structure. The surface charge density is directly proportional to the material's dielectric constant, while interfacial polarization can effectively enhance the dielectric constant, thereby improving triboelectric performance [42]. Additionally, surface charge density is a direct indicator of triboelectric potential energy: the higher the charge density, the stronger the electric field per unit area, and the greater the intensity of the triboelectric effect. When a material possesses both excellent charge retention capability and charge transfer capability, its surface charge density is typically high, thereby achieving superior output performance.

3.2. Charge transfer efficiency

The charge transfer processes one of the core mechanisms of energy conversion in TENGs. This process typically occurs during the contact and separation stages between the surfaces of two friction materials. Due to differences in electron affinity between the materials and imbalances in surface charge density, electrons spontaneously transfer from one surface to the other [43]. During the contact phase, physical and chemical interactions at the interface synergistically inject part of the charge into the opposing surface. During the separation phase, these charges cannot be instantly neutralized, leading to the generation of a potential difference between the interfaces and the formation of an electrostatic field [44]. This electrostatic field drives the redistribution of charges in the external circuit, thereby generating current and achieving efficient conversion of mechanical energy into electrical energy.

In the triboelectric effect, the efficiency of charge transfer is influenced by various factors, including surface charge density, contact area, surface chemical properties, and the electronic structure of the material [45]. First, surface charge density is a key parameter determining the scale of charge transfer: the higher the charge density, the greater the electric field strength per unit contact area, thereby increasing the amount of charge transferred [46]. Therefore, enhancing the surface charge density of materials is an important approach to improving charge transfer efficiency. On the other hand, surface roughness also significantly affects transfer efficiency. The complexity of surface microstructures can increase the actual contact area, thereby promoting more charge exchange.

Additionally, the chemical composition and surface polarity of materials play a central role in charge transfer. Materials with higher electron affinity are more likely to accept electrons during friction, while materials with stronger charge-receiving capabilities can effectively absorb charges from another material [47]. Therefore, when designing TENG electrode layers, thin films with significantly different surface polarities are typically selected to achieve more efficient electron transfer. By regulating material surface polarity or chemical composition, such as introducing polar

groups into polymer-based materials or adjusting molecular arrangement structures, electronic affinity can be further enhanced, thereby improving charge transfer efficiency [48].

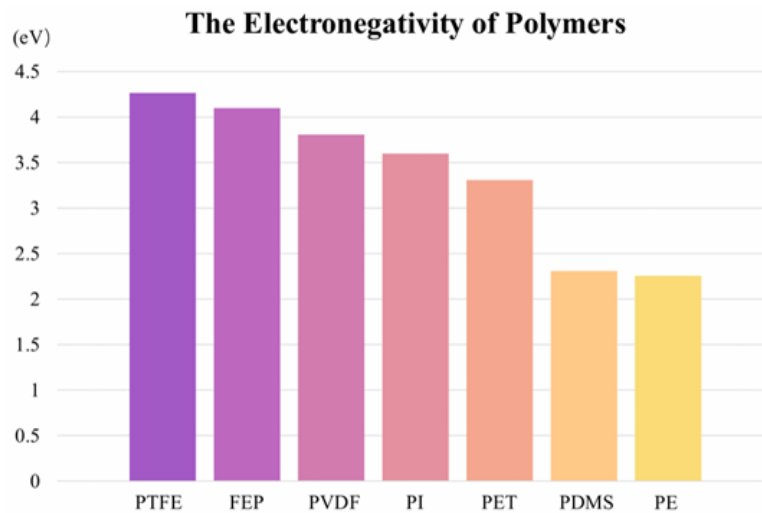


Figure 2. The electronegativity diagram of different polymers

To further enhance TENG output power, in addition to optimizing the material's inherent properties, surface modification techniques are widely employed to enhance charge transfer efficiency. Common methods include plasma treatment, laser etching, nanocoating, and surface functionalization [49,50]. These techniques alter the microstructure of the material's surface or introduce new chemical functional groups, thereby enhancing surface electron affinity and charge acceptance capability. For example, plasma treatment can regulate surface energy and increase the density of polar groups, thereby promoting efficient charge transfer. Laser etching technology, on the other hand, constructs micro- and nanostructures on the surface to increase contact area and enhance charge accumulation capacity.

3.3. Impact of environmental conditions

In recent years, researchers have found that environmental factors such as temperature, relative humidity, and external pressure significantly affect the stability and long-term performance of TENGs, potentially producing positive or negative effects.

Temperature is one of the most critical environmental factors. Traditional TENGs are typically tested for contact electrostatic generation at room temperature, so device designs are often based on room-temperature operation [51]. Xu et al. used TENG output to quantitatively analyze the real-time charge transfer mechanism, confirming that electron transfer is the dominant process in CE. They also found that high temperatures reduce the triboelectric properties of materials, accelerate charge decay, and consequently lead to a decrease in output power [28].

Relative humidity primarily refers to the moisture content in the ambient atmosphere and exhibits significant dependence on the triboelectric effect. Some studies have shown that high-humidity environments can reduce TENG output performance, as moisture adsorbed on the material surface can dissipate triboelectric charges [52]. Yang et al. found that by controlling RH (relative humidity), as RH decreases, the surface charge of the TENG increases, indicating that low-humidity environments are conducive to charge retention [53]. Additionally, Hu et al. found that different types of TENGs exhibit varying friction and charging performance under different humidity

conditions. For example, in sliding-type TENGs, the friction coefficient, open-circuit voltage, and short-circuit current first increase and then decrease with increasing RH [54].

External pressure includes atmospheric pressure and mechanical pressure applied to the interface. Environmental atmospheric pressure primarily regulates charge accumulation processes by influencing the evaporation of surface-adsorbed water layers. Nguyen V et al. found that when the pressure inside the experimental chamber was below atmospheric pressure, the charge accumulation rate of the TENG decreased; under high-humidity conditions, the optimal operating pressure of the TENG was slightly below atmospheric pressure. Additionally, by controlling the pressure inside the enclosure, device performance can be effectively enhanced [55]. Furthermore, applying interfacial pressure can alter the polymer-metal contact area, thereby regulating the output voltage. Seol et al. found that as contact pressure increases, the surface charge density of TENGs significantly increases, leading to improved output performance [56].

Due to its highly efficient low-frequency mechanical energy harvesting capability, self-powered sensing characteristics, and excellent biocompatibility, the TENG demonstrates broad application potential across multiple fields. First, in terms of energy harvesting and storage, TENG can efficiently convert dispersed low-frequency mechanical energy from human movement, wind energy, and ocean waves, and can be integrated with energy storage devices such as supercapacitors, micro-nano energy systems, and lithium-ion batteries to achieve effective storage and utilization of mechanical energy.

4. Application

In the field of self-powered sensing, TENG can be developed into high-sensitivity pressure sensors, humidity sensors, and biomechanical monitoring devices, enabling real-time dynamic signal acquisition without the need for an external power source. This self-powered characteristic gives it a distinct advantage in mobile monitoring, smart wearables, and environmental monitoring.

In biomedical applications, TENG not only provides continuous power for implantable medical devices but can also be used in high-precision health monitoring, wearable physiological sensing, and electrical stimulation therapy. Its excellent flexibility and biocompatibility make it suitable for both in vivo and in vitro applications.

Table 1. The application of TENG

Application fields	Examples	References
Energy harvesting	Human kinetic energy	[57,58]
	Wind energy	[59,60]
	Wave energy	[61,62]
Energy storage	Supercapacitors	[63,64]
	Micro-nano systems	[65,66]
	Li-ion batteries	[67]
Self-powered system	Pressure sensor	[68]
	Biosensor	[69,70]
	Humidity sensor	[71,72]
Biomedical application	Therapeutics	[73]
	Drug delivery	[74]
	Health monitoring	[75,76]

In summary, TENG can be used as both a distributed energy harvesting device and a highly sensitive self-powered sensor, playing an important role in many fields such as medicine, human-computer interaction, and industrial monitoring. With the optimization of material design, the development of surface modification technology, and the improvement of system integration, the application scope of TENG is expected to be further expanded and commercialized in more practical scenarios.

5. Conclusion

TENG, as an emerging mechanical energy harvesting technology, has evolved from fundamental theoretical research to engineering applications. Its energy conversion efficiency primarily depends on the synergistic effect of triboelectric charging and electrostatic induction. Among these, CS-TENG stands out as a typical model for fundamental research due to its high output voltage and energy conversion efficiency. SE-TENG enhances device flexibility and adaptability to wearable applications through simplified structural design. FT-TENG, meanwhile, employs a non-contact charge transfer mechanism to effectively address interface wear issues associated with traditional sliding modes, offering a novel approach for efficient harvesting of rotational mechanical energy.

The influence of material surface characteristics on the triboelectric effect exhibits a nonlinear relationship. Moderate surface roughness can increase the actual contact area, thereby enhancing charge transfer efficiency; however, excessive roughness leads to uneven charge distribution, reducing output stability. Additionally, environmental factors significantly regulate TENG performance: humidity affects interfacial charge dissipation through water molecule adsorption, while high-pressure environments enhance device output energy density by suppressing air breakdown effects.

Future research directions should focus on developing composite triboelectric materials suitable for wide temperature ranges, combining machine learning and other intelligent algorithms to optimize multi-layer structure design, and achieving precise control of charge transfer efficiency; exploring integration strategies between TENG and energy storage devices to address stability issues caused by intermittent mechanical energy output. These efforts will help advance the large-scale application of TENG in fields such as marine energy harvesting, smart sensor networks, and wearable electronics. Through interdisciplinary innovation, TENG has the potential to become a key component of future distributed energy systems, providing critical technological support for achieving global carbon neutrality goals.

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