APPLIED SCIENCES AND ENGINEERING

Triboelectric nanogenerator for high-entropy energy, self-powered sensors, and popular education

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Triboelectric nanogenerator (TENG) has become a promising option for high-entropy energy harvesting and self-powered sensors because of their ability to combine the effects of contact electrification and electrostatic induction to effectively convert mechanical energy into electric power or signals. Here, the theoretical origin of TENG, strategies for high-performance TENG, and its applications in high-entropy energy, self-powered sensors, and blue energy are comprehensively introduced on the basis of the fundamental science and principle of TENG. Besides, a series of work in popular science education for TENG that includes numerous scientific and technological products from our science education base, Maxwell Science+, is emphatically introduced. This topic provides an angle and notable insights into the development of TENG.

INTRODUCTION

As the world enters the era of Internet of Things (IoT), sensor networks, big data, robotics, our lives are filled with various small electronic devices (*1*, *2*). Meanwhile, the field of artificial intelligence (AI) is currently experiencing a rapid growth, with thousands of electronic devices being developed each year (*3*, *4*). The construction of more energy-efficient, responsive, and miniaturized electronic devices has become a common objective. However, one thing is true for any technology: No electronics can work without electricity! Moreover, the distribution of energy in the IoT era can be understood in terms of entropy theory (*5*). Electricity from power plants is generated from centralized, high-quality sources such as coal and oil, which are nonrenewable fossil fuels. In contrast, the energy sources that power the IoT are widely distributed and lack organization because of their mobility and relatively low quality. Wang (*6*, *7*) has used entropy theory to characterize the distribution and power supply of small electronic devices in the IoT era. As a result, the high-entropy energy (HEE) is proposed, which is about the reutilization of the energy distributed in our living environment that is low-quality, low-density but huge amount, in the forms such as solar, wind, mechanical, heat, and even biomass. Recently, numerous energy harvesters have been developed with the objective of capturing a diverse range of HEE sources. Such thermoelectric devices are used for capturing low-grade waste heat energy. Since the discovery of the thermoelectric effect in materials, there has been a great deal of research conducted into the use of thermoelectric materials in thermoelectric devices (*8*, *9*). Nevertheless, the elevated cost of thermoelectric materials and the diminished efficiency of thermoelectric conversion have constrained the potential for commercialization. In recent years, piezoelectric nanogenerators constructed on the basis of piezoelectric materials that enable piezoelectric energy conversion have also been developing rapidly (*10*). However, it is noteworthy that most energy-harvesting devices rely on a limited range of specialized materials, including thermoelectrics, piezoelectrics, and photovoltaics for solar cells. These materials are often expensive and scarce, in contrast to the materials used to construct triboelectric nanogenerator (TENG), which are more widely available and economical. A TENG can be constructed using casual combination of two materials to produce a specific output. Thus, TENGs are one of the important technologies for HEE (*11*).

TENGs are a promising option for mechanical energy harvesting because of their ability to combine the effects of contact electrification and electrostatic induction (ESI) to effectively convert mechanical energy into electric power or signals (*12*, *13*). More specifically, triboelectrification or contact electrification generates static charges on material surfaces in contact, while ESI converts mechanical energy into electricity by inducing a change in electrical potential through mechanically agitated separation. In recent years, an increasing number of researchers have contributed to the study of TENGs. The development of TENGs has progressed rapidly from basic science to advanced technology and applications and has evolved with the trend of interdisciplinary cross-fertilization, including materials science, nanotechnology, biomedicine, and computer engineering (*14*, *15*). Moreover, research on TENGs has made remarkable progress in both theoretical knowledge and application markets, with more than 16,000 scientists distributed in 90 countries engaging in TENG research (*16*). It is worth noting that, in addition to the breakthroughs in a large number of research papers, more and more products developed on the basis of the TENG principle have been commercialized.

The triboelectric effect is a common physical phenomenon in our everyday life, and it is a result from two different materials coming into contact. It is generally regarded as a negative effect in industry given that the electrostatic charges induced from it can lead to ignition, dust explosions, dielectric breakdown, electronic damage, etc. However, Wang's group (*17*) first invented TENGs in 2012 by coupling the triboelectric effect with ESI to effectively use ambient mechanical energy. This has given people a positive understanding of the triboelectric effect. In this regard, we have done a lot of work in popular science education based on TENGs. Since establishing our first science education base, Maxwell Science+ (National Science Education Base) in Beijing, China in 2018, we have developed numerous scientific and technological products for popularizing science and its practical applications. This is highly notable for the advancement of TENGs and physics education, which will be emphasized in this review.

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BASIC THEORY OF TENG

Equivalent circuit model

The fundamental working principle of TENGs is a combination of contact electrification with ESI effects. Three theoretical models have been established to quantify the TENG's output characteristics (*18*), including the following: (i) the equivalent circuit model, including the capacitor model (Fig. 1A) and Norton's equivalent circuit model (Fig. 1B) (*19*–*24*); (ii) the universal dynamic simulation model that combines the quasi-electrostatic mode and electrical circuit model (*24*, *25*); (iii) the mathematical-physical model based on Maxwell's equations (*22*, *26*). As the most fundamental model of the TENG, the parallel-plate capacitor model is used to simulate the output of the TENG with a planar configuration, where a TENG is equivalent to a series connection between a voltage source and a variable capacitor (*20*, *27*). The accurate Norton's equivalent circuit model, which consists of a current source in parallel with a pure capacitive reactance, has been developed by the theory of a lumped-parameter equivalent circuit (*22*, *23*). It is therefore possible to demonstrate that the displacement current serves as a TENG's driving source because of the fact that the time-varying displacement current is determined under a short circuit state (*18*, *23*). This approach allows for the quantitative determination of the current passing between the internal equivalent capacitor and the external load resistor (*22*).

Expanded Maxwell's equations

The displacement current has been used to quantify the power output of TENGs (*23*, *28*, *29*). For media with defined borders and volumes, the standard Maxwell's equations are matched. However, the equations require to be extended for situations including moving material and time-dependent configuration. Wang started from the integral form of the Maxwell's equations, first derived the standard differential form of the Maxwell's equations by assuming that the media volumes and surfaces/interfaces are fixed, and then derived the expanded Maxwell's equations by assuming that the medium is moving as a rigid translation (Fig. 1C) (*30*). The expanded Maxwell's equations are further developed with including the polarization density term $\boldsymbol{P_s}$ in displacement vector owing to electrostatic charges on medium surfaces as produced by effect such as triboelectrification, based on which the first-principle theory for the TENGs is developed (*30*).

STRATEGIES FOR HIGH-PERFORMANCE TENG

Material design

The TENG consists of two triboelectric layers with different electronegativity and corresponding electrodes for outputting electrical power (*31*). Studies have shown that contact electrification can occur in a wide range of materials, such as ceramics, polymers, metals, semiconductors, etc. (*32*), and it can also occur in any state, such as

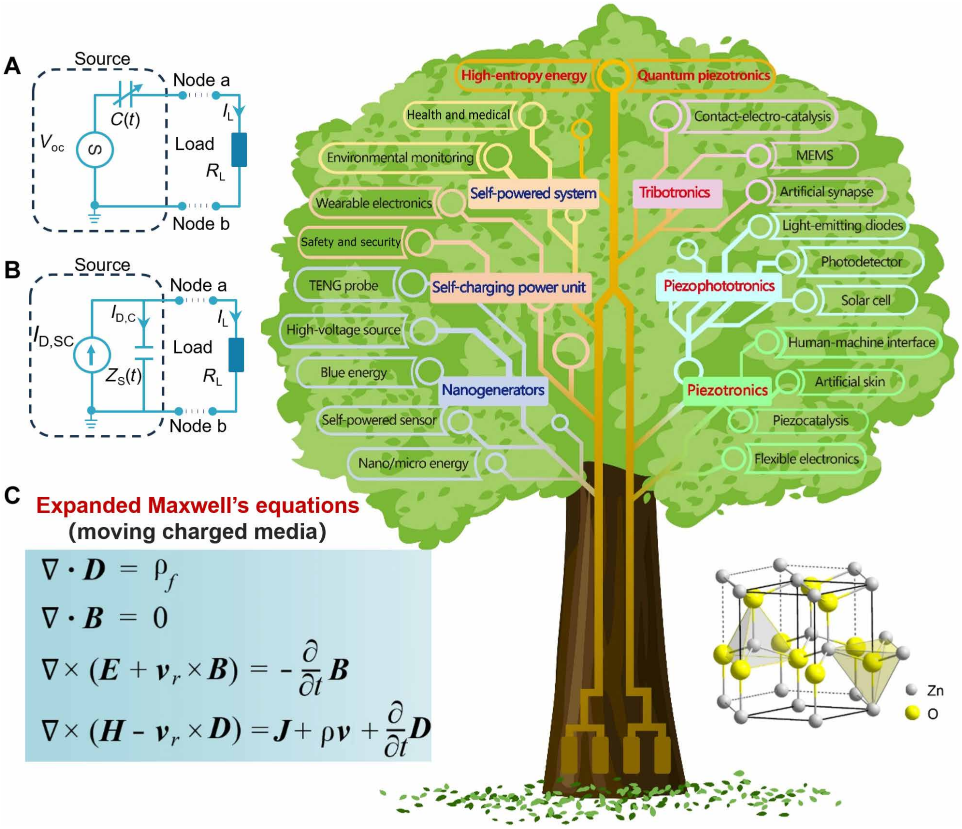

Fig. 1. Basic theory of TENG. Equivalent circuit models of TENGs. (**A**) The capacitance model of TENGs. (**B**) The Norton's equivalent circuit model (*18*). (**C**) The expanded Maxwell's equations (*30*).

solids, liquids, and gases (*33*). In general, the difference in electronegativity between the two triboelectric materials determines the triboelectric charge density. The design of triboelectric electrical materials was the first strategy that was used to improve TENG performance, mainly through material selection, surface modification, and internal filling.

Material selection

In terms of material selection, triboelectric series is an important tool for the selection of triboelectric materials. Further, Zou *et al.* (*34*) developed a general standard method for quantifying the triboelectric series of various polymers, using quantitative triboelectricity as an essential material property. In addition, they quantified the triboelectric charge densities of nearly 30 inorganic nonmetallic materials, confirming that contact electrification is an electronic quantum transition effect under environmental conditions, which helps us understand the internal mechanism of contact electricity (*35*). Recently, Yu *et al.* (*36*) proposed a universal set of material selection rules based on charge density, moisture resistance, and friction coefficient in low- and high-humidity environments. It is of direct significance and value to improve the electrical output of TENG and promote the long-term stability of TENG equipment. At the same time, it also provides more ideas and reference value for researchers in related fields.

Surface modification

Surface modification is also an effective method for improving the charge density of triboelectric materials, which mainly includes chemical surface functionalization and surface ion injection. Chemical surface functionalization can increase the surface charge density by introducing groups with strong ability to gain or lose electrons, which expand the selection range of materials. The existing methods of combining triboelectric materials in nature have been limited to some extent. Chemical functionalization can be used to improve the material's ability to gain or lose electrons, facilitating the development of TENG. Initially, Lin *et al.* (*37*) grew a layer of catechin-adsorbed TiO_2 nanomaterial arrays on the electrode surface. High sensitivity (detection limit of 5 μM) and selectivity were achieved through the strong interaction between Ti atoms of TiO_2 nanomaterial and catechin enadiol groups. The results of this study demonstrate the potential for chemical modification to improve the electrical output of TENG. Then, Feng *et al.* (*38*) designed a gecko-foot–like polypropylene nanowire material. By modifying the nanocellulose membrane with amino-silane, Nie *et al.* (*39*) greatly enhanced the positive charge on the surface of the cellulose membrane. Recently, it was reported that to improve the output performance of TENG, two triboelectric layer materials were treated: electrospun amino-functionalized reduced graphene oxide (A-rGO)/Nylon-12 and micropatterned molybdenum disulfide (MoS_2)/Ecoflex as highly tribopositive and tribonegative layers, respectively. After modification, the surface potential of positive and negative triboelectric layer is increased by 2.5 times and 3.1 times, respectively. Surface ion injection is another method of surface modification. Many ions can be used as charge sources, and their selection range is wide. The most common method is plasma treatment (*40*). Li *et al.* (*41*) proposed a surface modification method using low-energy ion irradiation to adjust the chemical structure of triboelectric polymers, which is very helpful in understanding the interactions between different chemical groups and the electrification properties. The films modified by ion irradiation not only set a record for the friction series but also provided a good demonstration for the regulation of chemical structure. This is a breakthrough for the production of triboelectric materials with diverse properties and can advance TENG research at a very fundamental level.

Internal filling

Filling some special fillers in the triboelectric layer to optimize the composition of the triboelectric material is also an effective way to improve the performance of TENG. In particle filling, the optimized triboelectric material can enhance surface electrification, resulting in more ESI (*42*). Jian *et al.* (*43*) prepared flower-like TiO_2 nanoparticles and filled them into polymethyl methacrylate. TiO_2 nanoparticles modify the surface of the film, enhancing the dielectric constant and space charge polarization. At present, metal–organic framework (MOF) as an active filler has also been applied to TENG. Wen *et al.* (*44*) designed a polydimethylsiloxane composite material TENG and systematically studied the effects of different functional fillers on the output properties of TENG. This work demonstrates a strategy to improve output performance by using functionally filled MOFs with large electron-absorbing functional groups and has guiding implications for how to select efficient triboelectric fillers. Existing fillers have a single function in capturing frictional charge, and researchers in related fields have worked hard to develop bifunctional composites with high charge induction and charge trapping capabilities. High-performance TENGs prepared by fluorinated MOF (F-MOF), $NiAlF_5(H_2O)\ (pyr)_2{\cdot}2(H_2O)$ (KAUST-8, AlFFIVE-1-Ni) as bifunctional fillers have been reported. On the one hand, F-MOF acts as a charge-trapping site similar to conventional fillers; on the other hand, it also increases the induced charge by introducing fluorine atoms and improving the surface roughness (*45*). There is still a lot of research space to improve the triboelectric properties by using filling method, and it is worth our greater efforts.

Structure design

The design of the structure is critical to the output performance and efficiency of the TENG, and in practical applications, the reliability and stability of the TENG are also very important. The space utilization and structural stability of the TENG device can be optimized through a reasonable structural design. In addition, the improvement of the structure also expands the application range of TENGs. In recent years, a variety of structural design methods for TENG have been reported in the literature, including multilayer/multipoint in a single TENG, TENG networks, and mechanical adjustment of low-frequency excitation (*46*). This section summarizes the innovative structure of TENG in recent years. Because of the limitation of high-voltage breakdown, the power density of TENG is severely restricted by the limited surface friction charge density. In view of this, Zhang *et al.* (*47*) developed a three-dimensional (3D) fractal structured nanogenerator. The device can efficiently collect spatially distributed Maxwell displacement currents. In addition, mechanical-electrical energy conversion using the semiconductor effect of materials is still limited. To solve this problem, Pan *et al.* (*48*) report a field-effect nanogenerator for mechanoelectrical energy conversion. The generator can output electrical waveforms closely related to the sliding speed of the gate, producing high voltage, high charge density, and a power density three times higher than that of a conventional TENG. At the same time, traditional TENG often faces challenges such as instantaneous pulse output, high crest factor, and insufficient output power, which makes it difficult to work stably and continuously. A disk-type multiphase dc TENG has recently been reported, which reduces the crest factor and improves performance by using an independent triboelectric layer mode (*49*).

The device has good output performance and durability, with a maximum average power of 10.38 mW after 80,000 rotation cycles and minimal friction layer wear, lifting the stability limits of the practical application of the TENG equipment, while reducing the environmental impact, which can also be expanded on the basis of related research. In addition, TENGs rely on rectifiers because of their pulsed ac output, which reduces the integrity and portability of the energy supply network. Most research on dc TENG focuses only on improving one-sided performance. Li *et al.* (*50*) established a set of comprehensive ternary dielectric evaluation rules based on coupled charge leakage effect and ternary dielectric tribo-charging effect to improve the overall performance of dc TENG. The TENG has three output modes: ac, dc, and ac/dc convertible output. Although a series of dual-mode TENGs has been developed by combining traditional ac and dc TENGs, there are still output deficiencies and strict material selection issues. To address these problems, Chen *et al.* (*51*) proposed a hybrid TENG to achieve a switchable dual-output mode. To obtain TENG with stable and continuous output capability, the researchers used the hysteresis and ordered charge migration behavior of dielectric polymers to propose a concept of constant current TENGs and realized constant-current output in ac form. This is a breakthrough from the limitations of traditional thinking (*52*). To improve the output, durability, and practical application of the TENG, equipment of various structures is constantly being improved and designed. We expect that the simplest, most practical, and economical devices will come out in the future, which requires continuous efforts and exploration by researchers.

Interfacial design

Over the past decade of TENG's development, the scientific community has recognized that interface design plays an integral role in driving the development of multiple disciplines, including physics (*53*), chemistry (*54*), and materials (*55*), which are key to building high-performance devices. The first TENG uses bulk dielectric materials to achieve charge transfer, forming a tribological potential layer in the interface region that acts as a charge "pump" to drive the flow of electrons in the external load when the system capacitance changes. Considering the general structure of TENG devices, interface design is an effective means of improving the performance of TENG devices. As shown in Fig. 2, this section mainly summarizes from four aspects, including the following: surface chemistry, interfacial lubrication, increase in interfacial electric field, and enhancement of the density of surface states.

Surface chemistry

The output performance of TENGs depends largely on the surface chemistry. Therefore, controlling the surface chemical properties through appropriate modification methods is one of the effective strategies for improving the output performance of TENGs (*56*). Functional group grafting is a simple and effective method to change the surface chemistry. By introducing electron acceptor and electron donor groups on the surface of triboelectric materials, it is superior to complex bulk engineering (*57*–*59*). This approach also overcomes the limitations of triboelectric material selection when designing high-performance TENG. Ion implantation technology is also a common means to change the chemical properties of the surface, which is suitable for various triboelectric polymers. Ion implantation and modification is the method of directly adding ions or unipolar charged particles on the surface or inside of triboelectric materials, which can effectively control the surface chemistry of the material and improve the output performance of TENGs (*41*, *60*–*63*). It is a simple and direct method for improving the performance of TENG by controlling the surface chemistry of triboelectric materials. This also broadens the selection of materials and expands the advantages of the TENG in various application scenarios. To advance the field of TENGs surface chemistry, there are many challenges to be overcome, such as functional group grafting occurs only at the surface, rather than deep into most of the triboelectric material, and long-term friction may lose effectiveness. While chemically modifying material surfaces to alter charge density has been studied, a more systematic understanding of this effect has not been elucidated

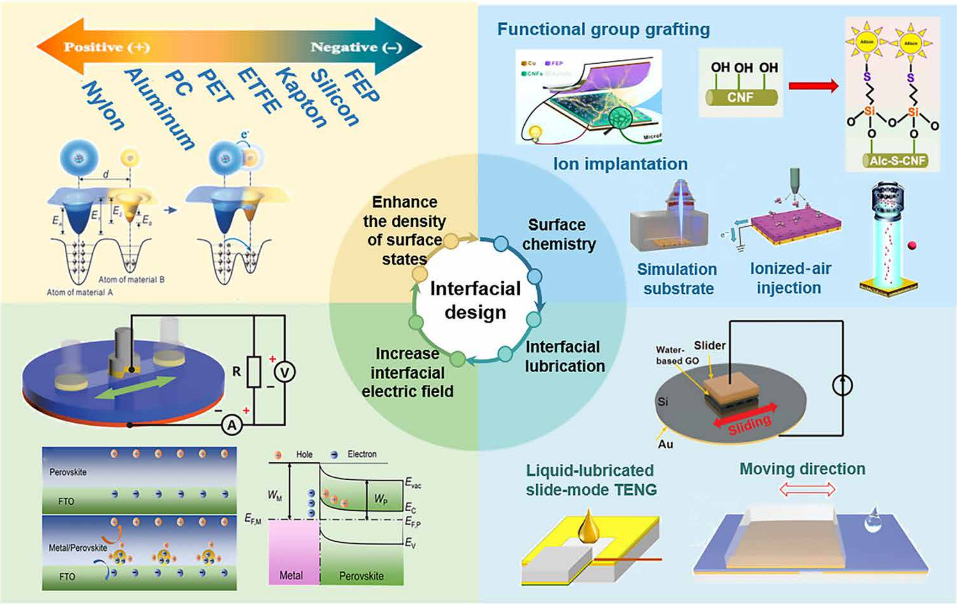

Fig. 2. Interfacial design for high-performance TENG. Representative structures based on (*41*, *58*, *59*, *62*, *63*, *65*, *66*, *70*, *71*, *73*).

in detail. A systematic and well-developed mechanism to elucidate the effects of chemical modifications on molecular surfaces to control the frictional charge density is critical. This is very necessary for the stability and practical application of TENG equipment, and it is worth more energy and efforts of researchers.

Interfacial lubrication

dc TENG has the characteristics of high dc current density and continuous output, which has great potential in solving the power supply problem of miniaturized electronic devices. However, the serious wear problem of dc TENG leads to rapid decay in current density, and it is difficult to achieve long-term operation with high output (*64*). Qiao *et al.* (*65*) proposed an effective strategy to simultaneously increase the dc current density and lifetime of dc TENG through interface lubrication. They used a water-based graphene oxide solution as a lubricant, which has good lubrication properties and can increase the sliding surface carrier, improve the current density, and ultimately reduce the wear between the copper and the silicon surface. In addition, to avoid the air breakdown effect, Wu *et al.* proposed interfacial liquid lubrication as a strategy to improve the TENG's power output and durability. The liquid lubricant inhibits the interface breakdown due to the high breakdown field strength requirement and the low electrostatic field strength of the microgap between the triboelectric layer and the electrode. Compared to the solid-solid contact TENG, the service life of the TENG can be greatly improved through interface lubrication, with no wear detected even after 36,000 cycles (*66*). Interface lubrication is an effective method to solve the wear problem of dc TENG and improve the dc current density at the same time, which will accelerate the practical application of dc TENG in the future, and opens an approach for extending the lifetime and stability of TENGs.

Increase in interfacial electric field

In 2018, several research teams manufactured the TENG using semiconductor materials, and experiments observed dc output, a phenomenon that differs from traditional TENG. Liu *et al.* (*67*) observed dc production by sliding a metal probe over a molybdenum disulfide film. They also determined the presence of electron tunneling in the metal-insulator-semiconductor triboelectric interface (*68*). In 2019, Wang *et al.* (*69*) first named this phenomenon the "tribovoltaic effect". Zhang *et al.* (*70*) proposed a mechanism based on interfacial electric field to explain the tribovoltaic effect, achieving high-performance dc TENG with ultrahigh voltage and power density. Their research shows that faster speeds, greater pressures, and smaller areas can increase maximum power density. This work not only extends TENG's candidate materials from organic polymers to semiconductors but also demonstrates an electrical energy conversion mechanism based on the tribovoltaic effect. Wang *et al.* (*71*) enhanced the interfacial electric field and the charge density by adjusting the metal/perovskite Schottky junction. The interfacial electric field may contribute to the electrical output of various dc TENG, but its direction is not necessarily consistent with the internal electric field. The direction of the dc TENG electrical output is determined by the total electric field superimposed by the interface electric field and the internal electric field (*72*). The interfacial electric field theory is a supplement to the internal electric field theory and plays an important role in the generation mechanism of dc TENG.

Enhancement of the density of surface states

The mechanism of triboelectrification has been controversial, and electron transfer may be the main reason of contact electrification. However, in some experiments, the charge density of the pairwise charge between the three materials cannot be fully explained by the difference in occupying energy levels. For example, when Kapton is rubbed with polyethylene terephthalate (PET), PET has a stronger negative charge capacity, but the triboelectric capacity of the two with copper indicates that Kapton has a stronger negative charge capacity, which cannot be explained by the occupation energy level difference alone. Recently, Y. Zi's team proposed an electron transfer model based on surface state density (DOSS) as another key factor in the generation of frictional charge. In the experiment, the surface charging density was regulated by applying an external bias voltage on the TENG in contact separation mode, and the real surface state density was measured by a series of derivations and calculations. The experimental results confirm the contribution of DOSS to friction charge generation, and the derived charge density is agreed with the measured results. The study provides another key factor for frictional charge generation (*72*). Wang's team synthesized FPPE copolymer films in which the position of the triboelectric sequence can be regulated. They found that FPPE-2 containing 25% 4-(4-hydroxylphenyl)(2H)-phthalazin-1-one (DHPZ) showed a particular negative shift compared to FPPE-1 without DHPZ, which was different from what was expected. This phenomenon can be attributed to a change in the surface state density caused by a specific crystallization effect of FPPE-2 (*73*). A unified model of contact separation TENG suitable for any combination of materials has been reported, showing that the triboelectrification output is a synergistic effect of ESI and dynamic junction modulation (DJM). The output contains four current/voltage peaks, two of which are attributable to ESI effects, determined by the surface state density and electron affinity difference of the material. The other two are related to the DJM effect and are determined by the charge exchange between the surface state and the depletion region (*74*). The study of surface state density may provide a more complete model for understanding the mechanism of contact electrification and guiding the selection of materials for contact electrification. This is also a solid step toward further understanding the mechanism of friction charge generation. The model based on the surface state density can provide guidance for the selection and modification of triboelectric materials and advanced triboelectric charge control in the future. This is of constructive significance to the high output, stability, and environmental friendliness of the TENG.

TENG FOR HEE

Entropy theory can be used to understand energy distribution in the IoT era. Conventional energy sources, such as coal and oil-generated electricity, are often viewed as centralized and high-quality sources of energy (*5*). However, it is important to note that these sources are nonrenewable and have irreversible environmental impacts. In contrast, the energy for powering the IoT would be widely distributed, disordered because of mobility, and of relatively low quality. The term HEE refers to the random, irregular, and micro-nano mechanical energy widely distributed across the surrounding environment (*6*). The IoT has led to an increase in the production of mobile objects and electronic products, resulting in a wider distribution of electronic components. Therefore, collecting random and irregular micro- nano mechanical HEE in self-powering electronic devices with disordered distribution has become a research hotspot.

TENG also called as Wang generator that has been invented by Wang in 2012 with the purpose of recycling and making use of micro-nano mechanical HEE in the environment. HEE exists in various forms, including biomechanical (*87*), wind (*88*, *89*), vibrational (*90*, *91*), thermal (*92*), and acoustic energy (*93*, *94*). TENG can effectively convert irregular, low-frequency, and low-amplitude mechanical energy into electric power by combining the effects of contact electrification and ESI. They are ideal for harvesting energy from the living environment and integrate multiple disciplines, including materials science, chemistry, physics, electrical engineering, and medicine. As energy-harvesting devices, TENG play a crucial role in various fields.

Figure 3A shows the variety of energy sources in our living environment. HEE can be understood as harvesting widely distributed disordered energy from the environment, such as solar energy and/or motion/vibration energy. Contrarily, the traditional energy model is presented as a power plant that converts high concentrations of energy, such as coal, into electricity and transmits it quickly and over long distances for use by people. Figure 3B demonstrates the potential for different materials to function as wearable devices that can harvest biomechanical energy from human motion. Hydrogel can be used as an electronic skin to harvest energy in biomechanics (Fig. 3Bi). Fibers can be used as wearable devices to harvest energy from human movement (Fig. 3Bii). Other special materials and devices, such as conductive liquids, can also be used to prepare wearable devices that harvest energy generated by human movement (Fig. 3Biii) (*95*, *96*). Wind energy is an HEE source that can be easily harvested, and the construction of a noncontact inductive constant voltage TENG based on a combination of power management and sensing modules can improve the energy output efficiency and real-time sensing. By constructing a noncontact inductive constant voltage TENG and combining it with a power management module and a sensing module, the efficiency of energy output and real-time sensing can be improved (Fig. 3C) (*78*). In addition, the introduction of soft contacts in the TENG structure or the design of specially constructed TENGs can greatly improve energy utilization. Furthermore, because of the challenging conditions of wind energy harvesting, there is ongoing research into wind energy-harvesting devices specifically designed for harsh environments (*97*). Vibration energy is also a widely distributed HEE source. TENG can efficiently collect ambient vibration energy while performing vibration monitoring, which is important in many construction and manufacturing

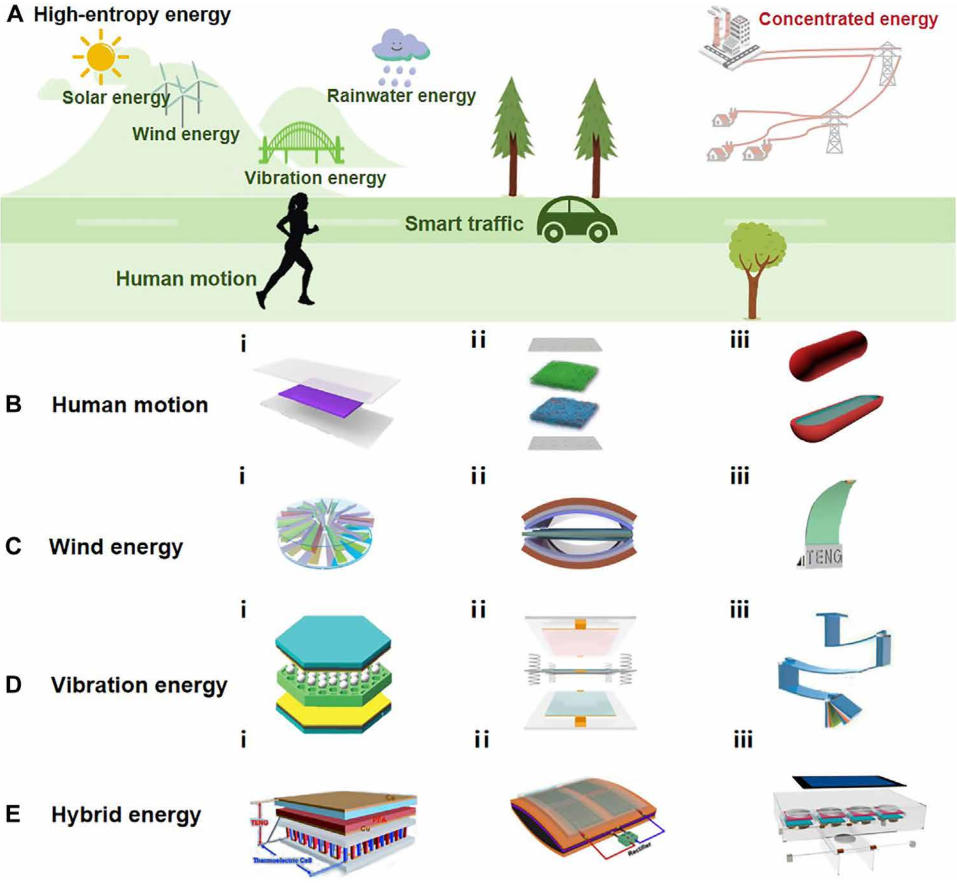

Fig. 3. TENG for HEE harvesting. (**A**) High-entropy and concentrated energy in the environment. (**B**) TENG for harvesting HEE from human motion (i) hydrogel-based TENG (*75*), (ii) fiber-based TENG (*76*), (iii) a shape-adaptive TENG (*77*). (**C**) TENG for harvesting HEE from wind. (i) A blade-based soft contact TENG with a charge space accumulation design for wind energy harvesting (*78*); (ii) an ultrastretchable TENG for harvesting breeze wind energy (*79*); (iii) a leaf-like TENG for harvesting gentle wind energy (*80*). (**D**) (i) A honeycomb structure inspired TENG for highly effective vibration energy harvesting (*81*); (ii) an all-in-one vibration sensor assembled with instantaneous discharge-boosted TENG and IR wireless communication (*82*); (iii) a multimode vibrational TENG for harvesting vibration energy (*83*). (**E**) (i) A hybrid energy cell integrated by a TENG, a thermoelectric cell and a solar cell (*84*); (ii) integrating micro supercapacitors with TENGs for a flexible self-charging power unit (*85*); (iii) multifunctional power unit by hybridizing contact-separate TENG, electromagnetic generator and solar cell (*86*).

processes. Figure 3D shows three different TENG structures for collecting vibration energy. TENG can be combined with other devices to harvest multiple energies. For example, thermoelectric and solar cells are commonly used to prepare hybrid energy batteries integrated with TENG. In addition, integrating micro-supercapacitors with TENGs allows for the assembly of flexible self-charging power devices. The current trend in achieving multiple energy harvesting is to connect TENG in series with other energy-harvesting devices to achieve more efficient HEE harvesting (Fig. 3E).

TENG AS SELF-POWERED SENSORS

In recent years, sensor technology has been applied to almost all areas of society, especially the IoT, flexible electronics, mobile communication electronics, and smart wearable devices, but the construction and maintenance cost of the entire sensor network is a huge budget. In the not-too-distant future, there will be more than 30 billion sensors linked to the internet, resulting in 120 GW of energy use, which means that traditional sensors powered by the grid or batteries will face enormous challenge (*98*). TENG self-powered sensor, which has advantages of additional power supply needless, simple preparation, low limitation, and high efficiency, is a reliable strategy to solve the problem of the horrible power consumption of traditional sensors. In addition, it has a compelling sensing performance compared with tradition sensors, including high sensitivity and short response time. For example, a force/pressure TENG sensor has a high sensitivity of 1.03 V N^{-1} and about 3.11 V kPa^{-1} (*99*), a TENG e-skin achieve a high sensitivity of 616.42 kPa^{-1} and a fast response time of 5.6 ms (*100*), and a humidity TENG sensor has a sensitivity of 80 nA RH^{-1} and an ultrafast response time of 0.6 ms (*95*). Hence, TENG self-powered sensors are wildly used to detect various parameters such as acceleration (*101*, *102*), vibration (*103*, *104*), pressure (*105*, *106*), strain (*107*, *108*), temperature (*109*, *110*), quality concentration in the environment (*111*, *112*), environment humidity (*113*, *114*), etc. What is more, TENG-based AI technology is an effective option for constructing smart self-powered sensor systems, such as robotics (*115*, *116*), human-machine interface system (*117*, *118*), intelligent security identification (*119*, *120*), intelligent sports (*121*, *122*), transportation (*123*, *124*), and intelligent health system (*125*, *126*). As shown in Fig. 4, we outline the main types of self-powered sensing systems including TENG self-powered sensors for human intelligent monitoring, smart city, traffic monitoring, safety monitoring, and marine monitoring, additionally look in the future research direction.

TENG self-powered sensors for human intelligent monitoring

As shown in Fig. 4A, TENG is trustworthy in physiological monitoring applications [such as body movement (*127*), breathing (*128*), and heart beating (*129*)] and offers various benefits, including being low cost, simple to build, lightweight, self-powered, and simple to build. The signal from TENG sensors can be integrated with AI (like machine learning and deep learning algorithms) and export feature signals for building Intelligent Medical Internet of Things systems (*130*, *131*). Wearable and implantable devices are two essential and main categories for TENG human monitoring. Wearable TENG sensors based on flexible material can attach to the skin or, by wearing them on the body, collect a variety of physiological and motor information, and scavenge energy from body motions as a power source for self-sustainable systems (*132*–*134*). As shown in Fig. 4Ai, a 3D-printed flexible TENG sensors and human-machine interfaces are printed and subsequently networked on a human body to sense comprehensive motion information; simple motion capture was achieved and six predefined movements were recognized with 94.85% accuracy with the application of Bluetooth wireless transmission and AI algorithms in this network (*135*). Implantable TENG can be used for self-powered cardiovascular health care that mainly includes self-powered cardiac monitoring devices (*107*, *136*), self-powered therapeutic devices (*137*, *138*), and power sources for cardiac pacemakers (*139*, *140*). As shown in Fig. 4Aii, a fully rubbery power management system composed of an elastic TENG, a rubbery diode–based full-wave bridge rectifier, and a capacitor was developed and can serve as a biointegrated self-sustained power source from organ motion (*141*).

TENG self-powered sensors for smart city, safety, and marine monitoring

Smart cities are devoted to offering a more convenient, efficient, and environmentally friendly lifestyle, which has become the norm in urban development, and sensors are an important technology for smart city building. As shown in Fig. 4B, TENG self-powered intelligent sensors can observe all aspects of the city, including people, buildings, traffic, air, and water and send the information to the city brain for analysis and processing. Safety is always the first priority, TENG self-powered sensors have been widely developed in safety monitoring, including intelligent transportation system, human motion safety monitoring, civil infrastructure safety monitoring, etc. In intelligent transportation system, overspeed wake-up alarm (*142*), driving behavior monitoring (*143*), real-time wheel monitoring (*144*), and smart pavement-integrated traffic monitoring (*145*) have been realized by TENG self-powered sensors. For civil infrastructure safety monitoring, TENG self-powered sensors, which can sense displacements, velocities, accelerations, and vibration types, have the potential in monitoring the structural health, such as the detection of vibration and crack in the bridges or buildings (*146*, *147*). Environmental monitoring is of great significance to environmental protection, health and safety, sustainable development, policy making, etc. Recently, wireless self-powered TENG sensor networks have been rapidly developed in water/liquid level sensing (*148*), environmental (water, air, and soil) quality monitoring (*149*), wind speed sensing (*150*), earthquakes ground motion detection (*151*), agricultural environment (*152*), etc. It is worth highlighting that ocean wave contains various marine information, wave-driven TENG self-powered sensors have an extremely outstanding application for marine environmental monitoring. An underwater TENG (UTENG) which can generate electricity from the kinetic energy of near-surface water waves, currents, and tides, the harvested power can be used to power pH and turbidity sensors for environmental monitoring of oceanic waters (*153*).

Summary and future perspectives for TENG self-powered sensors

In summary, TENGs self-powered sensor has been successfully used in many fields, including health monitoring, marine monitoring, and safety monitoring. In particular, AI technology can process parameters from TENG sensor, so smart TENG self-powered sensor systems based on AI and TENG have been developed rapidly and have shown a broad research and application prospect. In the era of IoT,

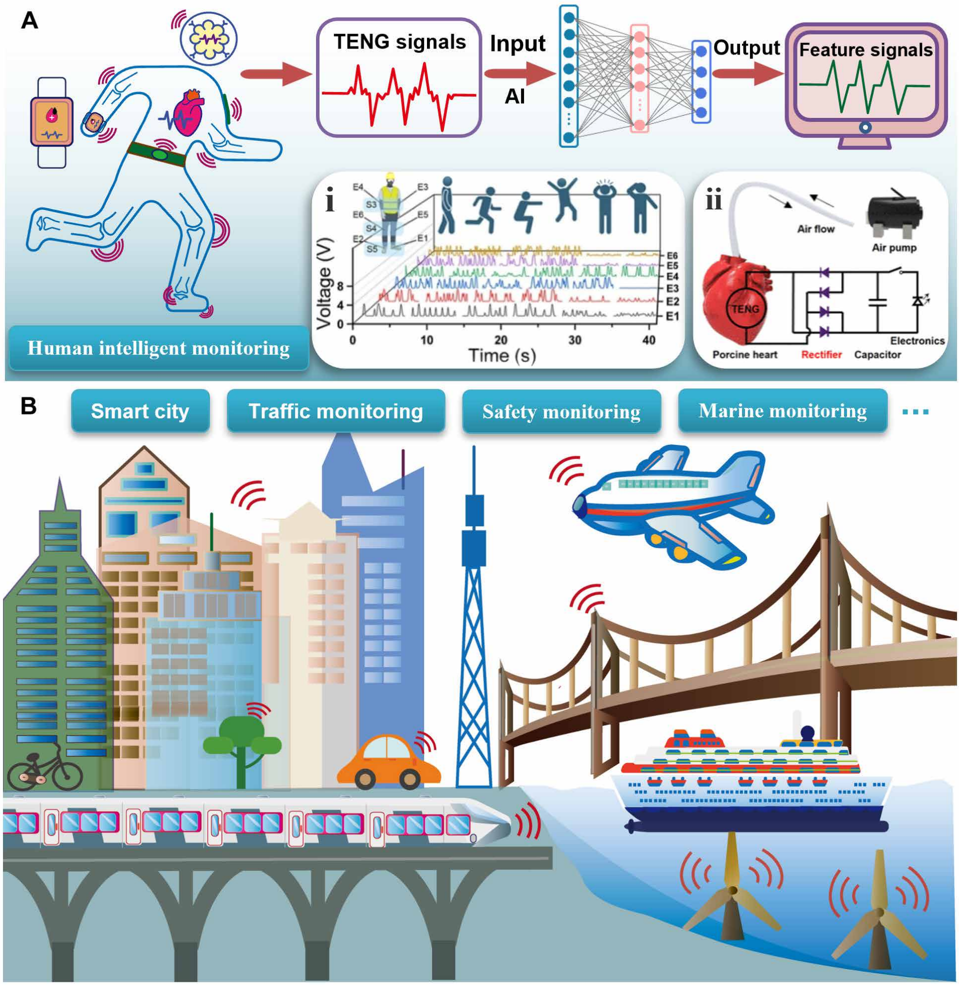

Fig. 4. TENG as self-powered sensors. (**A**) TENG self-powered sensors for human intelligent monitoring. (i) A 3D-printed flexible TENG sensors and human–machine interfaces (*135*); (ii) biointegrated self-sustained power source from organ motion based on a TENG power management system (*141*). (**B**) TENG self-powered sensors for smart city, traffic, safety, and marine monitoring.

information develops rapidly, and life is more convenient, ethical issues (including security, privacy, and moral hazard) brought by the IoT need to be considered. Compared with the traditional internet and sensor network, the TENG-IoT has a more thorough perception, and the boundary between people and objects is more blurred. Therefore, the future development should include the security technology research of the IoT, the nontechnical strategy research, and the construction of perfect ethics. Moreover, it is necessary to further improve the reliability and sensitivity of TENG from the aspects of material selection and structural design, etc., to enhance its service life and stability.

TENG FOR BLUE ENERGY

The ocean is rich in wave energy; finished wave energy refers to the kinetic energy and potential energy of the ocean surface waves, wave energy has the advantages of high energy density, wide distribution, and so on. It is the most direct to use, take inexhaustible, renewable, clean energy. TENGs provide a good way to convert wave energy into electric energy and have a broad application prospect. So far, various structural designs of TENG have been developed to achieve high output power, high flexibility, high stability, low cost, and other characteristics. This section reviews the latest research progress of wave energy harvesting in TENG from the perspective of various design structures and TENG network.

According to the reported research work, the TENG structures applied to blue energy harvesting can be divided into core-shell structures, wave structures, and bionic structures (Fig. 5). The spherical shell structure TENG has the advantages of lightweight, low resistance to water wave movement, and easy integration, and the coupled TENG network has been proved to be efficient in using water wave energy. Wang *et al.* (*154*) designed a spherical shell structure of TENG, which is a free-standing structure consisting of a rolling ball and two fixed electrodes. Driven by wave vibrations, the independent ball can roll back and forth between the two electrodes to provide alternating current to an external load. In the work of Liu *et al.* (*155*), a multilayered helical spherical TENG (MH-TENG) was designed. They explored a bidirectional complementary charge shuttle mechanism that effectively improved the overall output performance of the two units. Eccentric spherical shell structures have also

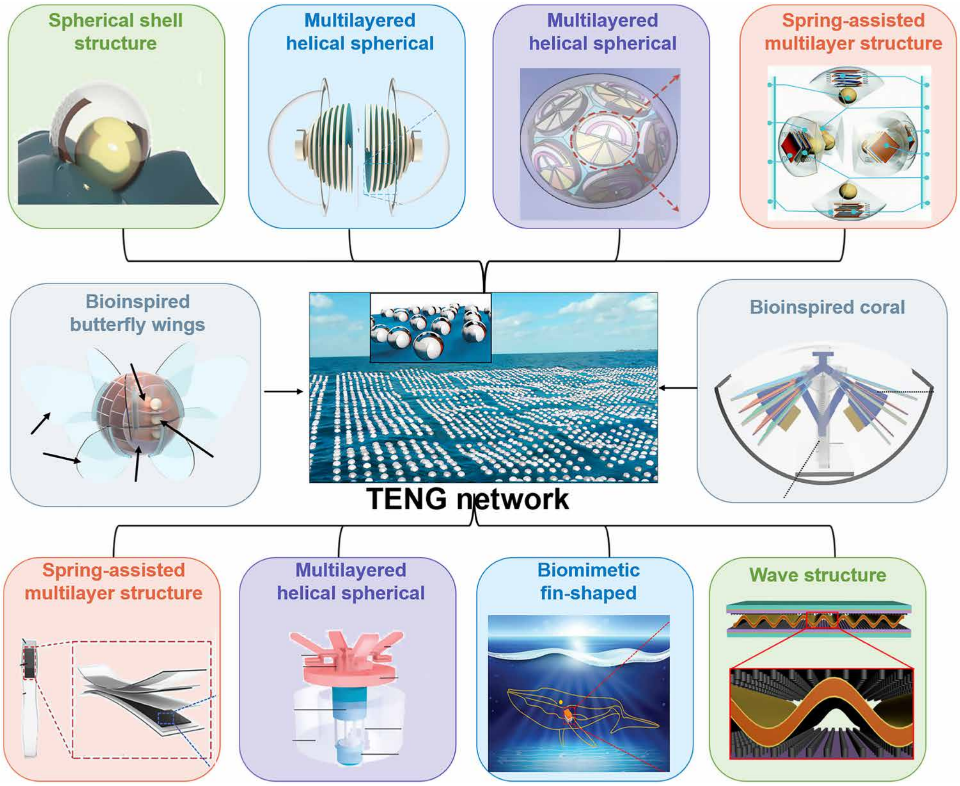

Fig. 5. Design of TENG for blue energy. Representative structures based on (*154*–*163*).

been designed to collect low-frequency water wave energy in random directions. The unique structure also provides an innovative and efficient way to harvest blue energy on a large scale (*156*). The wave structure was a popular structure used by TENG to collect wave energy in the early days. The wavy structure of the TENG can be easily packed to collect the impact energy of water waves, clarifying the principle of wave energy harvesting. A wavy Cu-Kapton-Cu sandwiched between two flat nanostructured PTFE films was first reported by Wen *et al.* This structural design allows the TENG to self-recover after impact without the use of additional springs and also converts direct impact into lateral slide (*157*). In addition, a spring can be introduced into the structure to store elastic potential energy. Liang *et al.* (*158*) designed and manufactured a spherical TENG with a spring-assisted multilayer structure for harvesting water wave energy from multiple trigger directions, more efficiently harvesting and using random energy in a regulated manner. Inspired by nature, many TENG devices with bionic structures have also been studied and reported, and these devices have superior performance in specific use environments. Inspired by bionic fins with excellent hydrodynamic properties. Zhang *et al.* (*159*) designed a biomimetic fin-shaped seafloor energy-harvesting device based on a multilayered TENG (BFM-TENG). Lei *et al.* (*160*) reported a butterfly TENG whose curved shell can effectively absorb the impact force of water waves, and an internal spring-assisted four-bar linkage can induce multiple contact separation motion of the TENG module. TENG, whose design was inspired by the poster's beard (*161*) and coral (*162*), were also reported. Wang *et al.* (*163*) reported a bioinspired butterfly wings TENG (BBW-TENG) consisting of a shell with bionic blades and the generation units. BBW-TENG is sensitive to multidirectional water wave excitation and shows the acquisition energy of multidirectional low-frequency water wave energy. The TENG network is composed of thousands of TENG units through certain connections, which can output high-power electricity. Chen *et al.* (*164*) creatively exploited the surface charging effect between a conventional polymer and an extremely thin metal layer as an electrode. The TENG is able to float on water and convert slow, random, high-intensity oscillating wave energy into electrical energy. On the basis of the measured output of a single TENG, the TENG network is expected to give an average power output of 1.15 MW from 1-km^2 surface area. Despite the advanced progress that has been acquired, more efforts are needed to further study this area to realize the practical application of TENG in blue energy harvesting.

TENG FOR POPULAR SCIENCE EDUCATION

Contact electrification was first recorded by Thales of Miletus around 600 BC, where he discovered that amber rods rubbed with wool could attract light and small objects and even generate electrical sparks (*165*). This phenomenon is now commonly referred to as the triboelectric effect or triboelectrification, in which the contact and separation of two materials creates an equal amount of net opposite charge. TENGs was invented by Wang and his colleagues in 2012 (*166*) and was originally intended to harness the energy generated in the triboelectric effect. Since then, numerous TENG designs have been reported and applied in various fields by optimizing their geometry and materials. According to the Scopus database, the analysis results of keywords related to "triboelectric" have increased exponentially after 2012 (*167*). Because of the multidisciplinary nature of the TENG and its wide range of applications, these may be unfamiliar to researchers and students in the field. Some experiments in the popularization of science and the research of teaching AIDS are of great significance to the future progress of this field. The aim of popular science is to teach students and general public with minimal or no experience of triboelectric effects and circuits.

Under the powerful support and leadership of Z.L.W., a team led by X.C. created a science education base, science popularization demonstration base, and science popularization practice base in Beijing, China, namely, Maxwell Science$^+$. Maxwell Science$^+$ aims to transform the scientific research achievements in TENG research into popular science products that are interesting, interactive, and informative and can be applied to popular science teaching. At present, the park has developed a number of global original science popularization exhibitions, including the TENG based on leaves and sandwich structure, as well as interesting smart masks, smart doors, smart floors, smart shoes, smart glasses, and so on. Through visits, interactions, and experiences, children can improve their creative, hands-on, and collaborative skills and develop a scientific attitude and a scientific worldview. Understanding the triboelectric series (*35*, *179*) of materials is the first step of science popularization. There are also some research teams working on it. Recently, Lin *et al.* (*180*) analyzed in depth the amino acids present in the stratum corneum of human skin and quantified the triboelectric polarization. They also analyze material sensing mechanisms, characterization methods, electron exchange relationships, and the effects of temperature changes, which contribute to a scientific understanding of sensing technologies (*181*). To do a better job of science popularization, education, and fun, the combination of TENG and toys is a good way, which also solves the power problem in electronic toys. By charging batteries with TENG, when children play with toys, the energy generated when exposed to electrification can drive the toys to work and power up the light-emitting diodes in the toys (*168*). Several research teams have successfully implanted the TENG into smart toys. As shown in Fig. 6, Chandrasekhar *et al.* (*169*) assembled the TENG from biocompatible materials and built it into toys, developing smart clapping toys and smart duck toys. They also made six TENG pieces as puzzle pieces and connected them into a simple logic circuit to form a self-powered smart puzzle (*170*). To enrich the stronger educational functionality of smart toys, our team has also made some efforts for TENG in this field. We designed a two-order Rubik's cube based TENG (RSC-TENG) to collect the internal sliding energy of the cube (*171*). RSC-TENG can not only be used as a power source to charge small commercial electronic devices and can be used as a self-powered sensor but also can be very beneficial to the intellectual development of children. We also take the accordion structure as inspiration and propose an array of parallel assembly TENG, so that more people can enjoy the music while also feeling the charm of TENG (*172*). Our research not only provides a way for the next generation of commercial toys, but more importantly, it has a great significance to promote the popularization of science.

Further, as an effective electromechanical energy conversion technology, TENG can be used not only as a power source but also as an active sensing device in many application fields, permeating every aspect of our lives. Allowing more people to use TENG-based devices is of great significance to the development of the field and the progress of The Times. Currently, TENG is involved in the fields of wearable devices, biomedical and health care, wearable devices, smart cities, smart transportation, human-machine interface, robotics, chemical

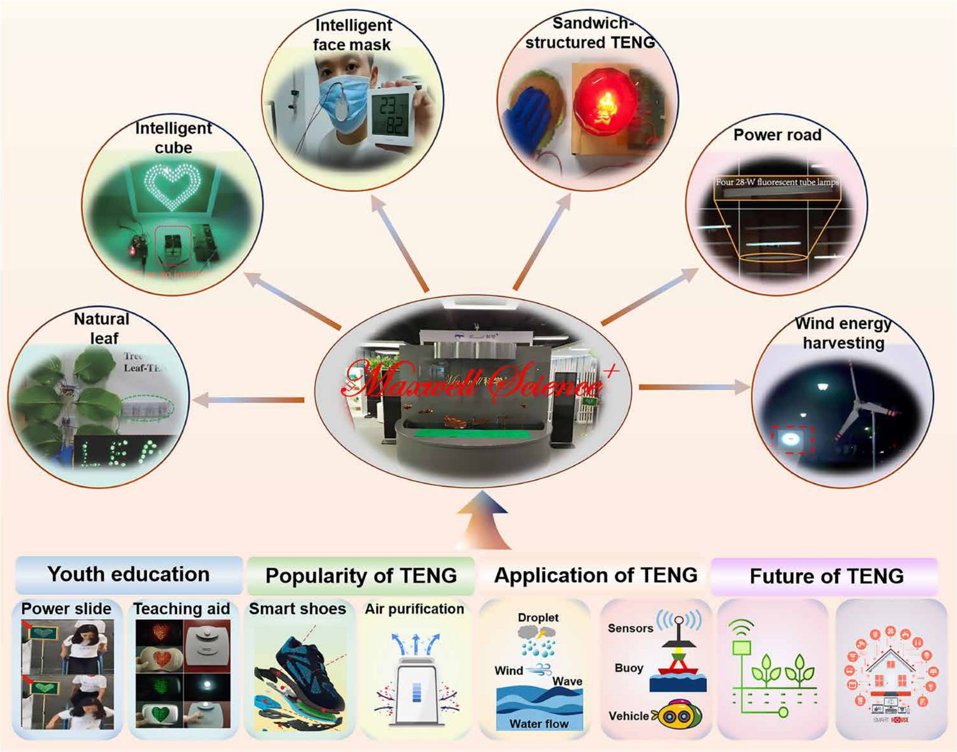

Fig. 6. Popular science education park based on TENG - Maxwell Science$^+$. Representative structures based on (*171*, *176*, *182*–*186*).

and environmental monitoring, fiber and fabric sensors, etc. (*173*). In recent years, more and more relevant studies have been conducted, as shown in Fig. 7. Gao *et al.* (*174*) recently proposed the TENG, a modular muscle sensor that can capture signals related to muscle stretching and trembling. Ryu *et al.* (*175*) report a commercial coin battery-sized high-performance inertia-driven TENG based on body motion and gravity. They demonstrated that the device successfully collected energy through real-time output voltage data monitored by Bluetooth, successfully integrated the pacemaker with the TENG, and determined the ventricular pacing and sensing operating mode of the self-charging pacemaker system. Ouyang *et al.* (*176*) also reported a TENG-based sensor that successfully identified abnormal vascular occlusion events in large animals (dogs). The TENG is also used to capture energy generated by constant friction between vehicles and roads (*177*), as well as wind energy generated by high-speed trains (*178*). Our living habits, social forms, entertainment, and so on are changing with the progress of The Times. In the future, with the progress of TENG technology, smart city, IoT, virtual reality, and so on gradually mature, the world will undergo earth-shaking changes.

CONCLUDING REMARKS

TENG fundamentals and application

By coupling contact electrification and ESI, a TENG device can convert mechanical energy into electric power or signal and the output current is produced by the Maxwell's displacement current. Using the electrostatic charges created on surfaces because of media contacts, a space variation in the arrangement of the electrostatic charges results in a displacement current that induces the flow of electrons connected to the two electrodes as driven by an external force (*188*, *189*). Because of this, TENG has a high output voltage although the mechanical triggering frequency and magnitude are rather low. TENG can convert any form of mechanical energy into electric power with a high energy-conversion efficiency especially at low frequency.

TENG was born at the right time that the world is marching into the era of AI and IoT. As a result, TENG has inspired worldwide research in energy-harvesting and self-powered sensing, simply because of its superior performance, cost-effective, and wide range choice of materials and broad applications, including but not limited to medical science, environmental science, wearable electronics, textile-based sensors and systems, IoT, security, and many more. Despite progress in the basic science and applications of TENG, there are still limitations and challenges that need to be addressed. These include improving surface charge density, current output, humidity resistance, durability, stability, packaging technology, etc. Future research aimed at specific applications. For example, creating more energy-efficient output and multiple energy-harvesting devices in HEE harvesting. In TENG-based self-powered sensors, how to improve the environmental stability and sensitivity of TENG is still the main goal of research. Blue energy requires further studies of the method and mechanism, in addition to analysis of material selection and structural design. In general, designing higher performance and more stable TENGs for various applications is a common objective of current TENG research.

Limitations and optimizations

It is evident that TENG demonstrates considerable potential for application in a number of fields, including HEE harvesting, self-powered sensing, blue energy, and even science education. However, challenges remain.

1) The necessity for the development of more efficient and convenient energy-harvesting devices. Despite wider and deeper develop-

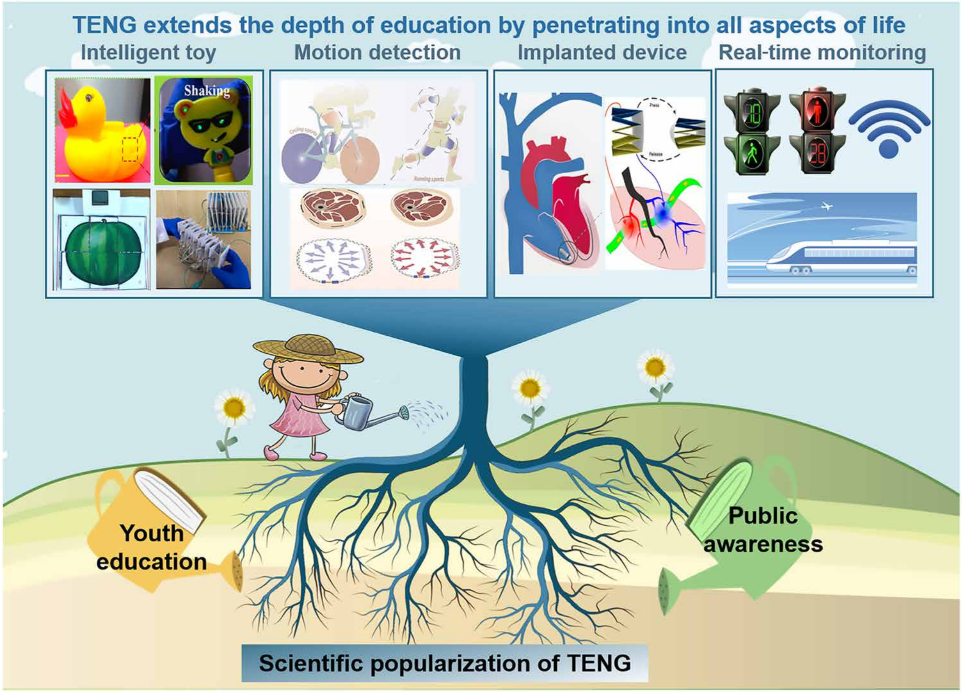

Fig. 7. TENG extends the depth of education by penetrating into all aspects of life. Representative structures based on (*169–172*, *174*, *187*).

ments in TENG harvesting and notable improvements in energy-harvesting efficiencies, the problem of lower conversion efficiencies persists. In particular, the intrinsic high impedance of TENG devices typically results in low current output with a pulse form. However, most electronic devices and energy storage units, including lithium batteries and supercapacitors, necessitate dc power. Consequently, efforts should be focused on the development of dedicated power management and energy storage circuits. Regardless of whether they are used for HEE harvesting or IoT self-powered sensing, this necessitates that TENGs have good stability, good packaging technology to enable TENG to operate in harsh environments. Sensitivity and stability are now commonly sought in self-powered sensors development.

2) The development of environmentally friendly and recyclable TENG is imminent. There is a wide range of materials used for TENG, but those with better and more stable performance are generally polymeric materials such as polyvinylidene difluoride and fluorinated ethylene propylene (FEP), which are environmentally harmful. Harvesting high-entropy or blue energy inevitably requires operating TENG in all kinds of environments. The potential environmental impact of TENG has prompted concerns and constraints on its development, underscoring the urgency for the advancement of green TENG.

3) A more profound ethical framework. As the development of TENG technology has accelerated across a range of industries, the ethical challenges associated with it have begun to attract increasing attention. This is particularly the case in the biomedical field, where TENG is being used in a range of applications, including implantable medical devices (such as self-powered pacemakers), wearable smart monitoring devices (for example, for monitoring sweat and blood glucose levels), drug delivery devices, and so on. It is imperative that attention be paid to human safety and ethical issues throughout the process of research and development, as well as promotion. Furthermore, standards and systems must be formulated to evaluate the safety and environmental protection of TENG. Conversely, the popularization of TENG should be actively encouraged, with the aim of fostering a more profound comprehension of the underlying principles, preparation, and applications of TENG, thereby facilitating the advancement of TENG.

Emerging potential areas

Fundamental physics of triboelectrification

Since the invention of TENG, the principle of coupling contact electrification has been widely studied. In practice, contact electrification involves an unexpected number of scientific disciplines, such as the Wang model for the electric double layer, contact electrification-induced interface light emission (*190*), and contact electro-catalysis (*191*). The usage of semiconductor materials in a contact electrochemical process produces direct current under external mechanical excitation. This phenomenon is known as the tribovoltaic effect (*192*). Originating from this effect, several multiphysics phenomena have arisen, including the tribovoltaic thermoelectric effect (*193*) and the tribo-photovoltaic effect (*194*), which was observed in dynamic metal/semiconductor Schottky systems.

The combination of TENG and AI

The fast development of AI provides possibility for data analysis through machine learning to reinforce the application of TENG in IoT (*195*). These subtle features hidden behind the real-time signal spectrum could be automatically extracted for AI applications, such as gesture recognition (*196*), texture recognition (*197*), and smart home (*198*). Besides, machine learning also provides an important data analysis tool for processing/analyzing the sensing signals detected by TENG, inspiring a promising research and development direction to the IoT applications.

Broader popular education based on TENG

The popularization of science is crucial for the development of future smart cities, IoT, and virtual reality. To achieve this, more experts in the field are required to promote science. The publicity and promotion of science should be increased to penetrate all aspects of life. Meanwhile, the development of more TENG-based science products is crucial for the future construction of the TENG-based IoT.

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Acknowledgments

Funding: This work was financially supported by the National Key R & D Project from Minister of Science and Technology (2021YFA1201601), the National Natural Science Foundation of China (52192610), and the Key Research Program of Frontier Sciences, CAS, China (ZDBS-LY-DQC025). **Author contributions:** Z.L.W. and X.C. conceived the review. H.X., L.P., and Q.Y. cowrote the initial draft. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the cited materials.

Submitted 5 August 2024
Accepted 28 October 2024
Published 29 November 2024
10.1126/sciadv.ads2291