Chapter

Small-Scale Energy Harvesting from Environment by Triboelectric Nanogenerators

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Abstract

The increasing needs to power trillions of sensors and devices for the Internet of Things require effective technology to harvest small-scale energy from renewable natural resources. As a new energy technology, triboelectric nanogenerators (TENGs) can harvest ambient mechanical energy and convert it into electricity for powering small electronic devices continuously. In this chapter, the fundamental working mechanism and fundamental modes of a TENG will be presented. It can harvest all kinds of mechanical energy, especially at low frequencies, such as human motion, walking, vibration, mechanical triggering, rotating tire, wind, moving automobile, flowing water, rain drops, ocean waves, and so on. Such variety of energy harvesting methods promises TENG as a new approach for small-scale energy harvesting.

Keywords: mechanical energy harvesting, triboelectric nanogenerators, biomechanical energy, vibration energy, wind energy, water energy, self-powered system

1. Introduction

With the rapid development of science and technology, Internet of Things (IoT) plays an increasingly important role in the next evolution of the Internet through turning data into information, knowledge, and wisdom [1]. More recently, multiple type applications based on IoT have been developed, including health testing, safe home, intelligent transportation, logistics supply, environmental protection, infrastructure testing, and security [2]. Sensor nodes in the IoTs are widely distributed and require independent, mobile, sustainable, and maintenance-free capabilities. Under the current technologies, most sensors require an external power source to drive their operation, wherein the battery is extensively applied. However, the life cycle of the battery is limited, and replacing the battery for the massive sensors is a huge project, which consumes a lot of manpower and material resources and increases the maintenance cost. In addition, the regularly replaced battery generates a large amount of harmful substances, which seriously endangers the environment and human health. Therefore, a clean and sustainable power source should be provided to satisfy the requirement of driving these small electronic devices sustainably.

Harvesting of the ambient environment energy, as an eco-friendly and renewable collecting energy method, is regarded as a promising and effective strategy to realize continuous powering for these small electronic equipment [3]. Some possible technologies have been exploited for collecting energy from surrounding environment, such as solar cells that collect energy from sunlight [4] and thermoelectric generators that harvest energy from temperature difference [5]. However, as constrained by the intermittency nature of sunlight, the low output of thermoelectric generators, these energy harvesting technologies cannot ensure the continuous operation of electronic devices. Owing to its abundant reserves and widespread, mechanical energy are increasingly utilized to extract and convert into electricity based on different mechanisms, including electromagnetic generator (EMG) [6], piezoelectric nanogenerator (PENG) [7, 8], and triboelectric nanogenerator (TENG) [9]. Considering the large-scale power generation of EMG and low output power of PENG, TENG has been demonstrated as a promising approach for harvesting ambient mechanical energy due to the desirable features of simple structure, flexibility, low cost, light weight, high efficiency, and high power density at low frequency [10]. The operation of TENGs is depended on triboelectrification (or contact electrification) and electrostatic induction [11], and the fundamental theory is according to Maxwell's displacement current and change in surface polarization [12]. Since the first invention of TENG in 2012, it has been extensively investigated and well confirmed that the potential of wide application is ranging from powering small electronic devices for self-powered systems, functioning as active sensors for medical, infrastructural, human-machine, environmental monitoring, and security [13–20]. Various types of wasted mechanical energies in our daily life, such as human motion, vibration, wind, and flowing water can be utilized by different TENG structures. Based on these characteristics, TENG can be utilized as a small-scale energy harvester for driving mass electronic equipment continuously.

2. Fundamental working modes of the TENG

TENGs are derived from the coupling effect of contact electrification and electrostatic induction. Contact electrification, as known as static electricity and contact charging, is a common phenomenon in many manufacturing environments and has been known for thousands of years. During the process of contact electrification, the dissimilar material/surface becomes charged after contacting with each other. After contacting, the opposite's triboelectric charge is produced on the surface of dissimilar materials with different electron affinities. Driven by external mechanical motion, the materials will be separated resulting in potential difference between the two electrodes on the back side of the materials. To maintain the electrostatic equilibrium, the free electrons in the electrodes will be driven to flow in external circuit to balance the induced potential difference, thus converting mechanical energy into electrical energy. According to the different structure designs of electrodes or moving manners of the triboelectric layer in TENGs, four different modes of TENGs have been build [9], as elaborated as follows.

2.1 Vertical contact-separation mode

The mechanism of vertical contact-separation mode can be elaborated largely by an example. As shown in **Figure 1a**, the simplest structure of TENG includes

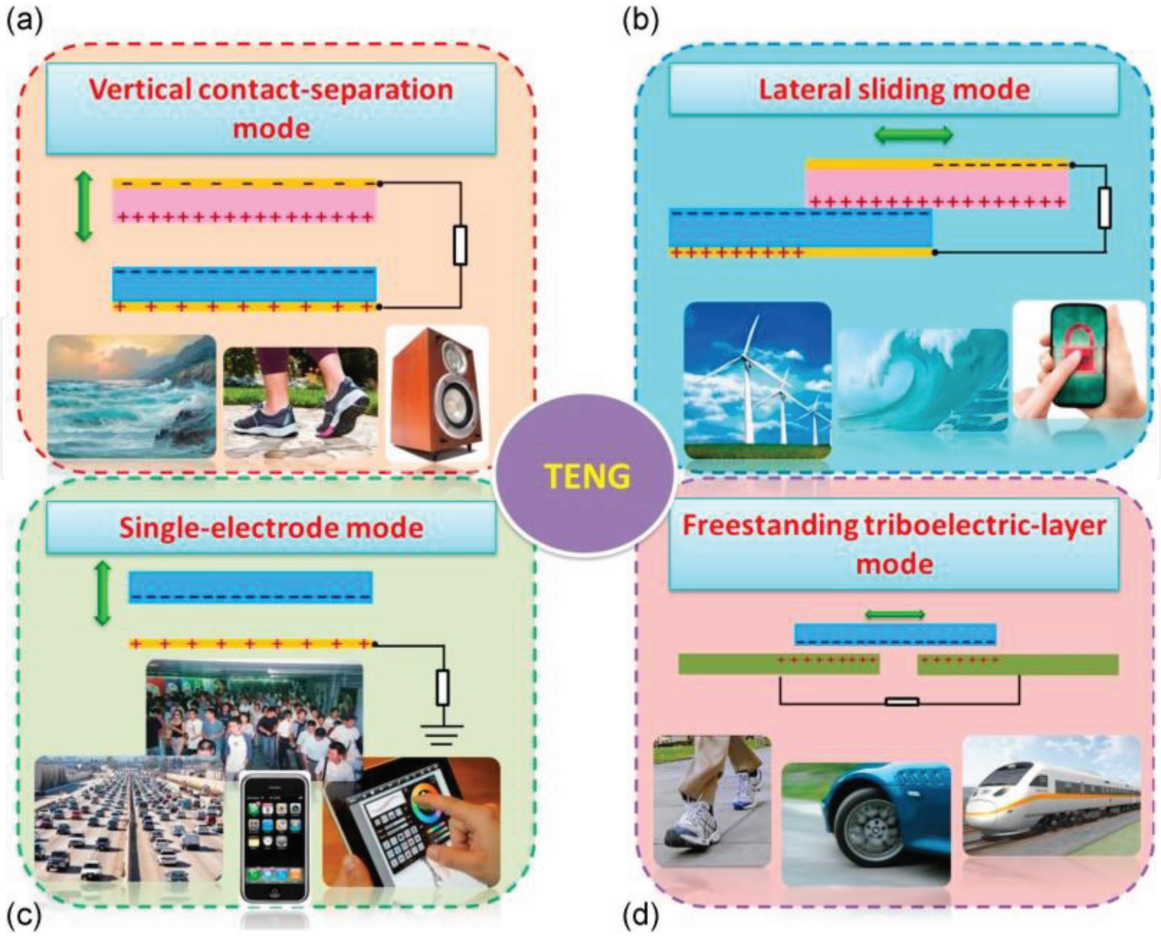

Figure 1.
The four fundamental modes of triboelectric nanogenerators: (a) vertical contact separation mode, (b) in-plane contact-sliding mode, (c) single-electrode mode, and (d) freestanding triboelectric-layer mode [9].

two metal electrodes and a dielectric film, in which two metal films work as top electrode and back electrode attached to dielectric film, respectively [21, 22]. When mechanical movement is applied in the unit, the top electrode and dielectric film will contact with each other, and thus the dielectric layer and electrode will get positively charged and negatively charged, respectively, due to the triboelectrification. Once they are separated by a short distance, the potential difference between the two electrodes will be induced, which will drive electrons to flow from the back electrode to the top electrode, resulting in a pulse current with an external circuit connected. If they are brought into contact again, the electrons will flow back and the current will be reversed.

2.2 Lateral-sliding mode

The basic structure of TENG in this model is the same as that of the vertical contact-separation mode. The difference is from the motion mode of the top electrode (**Figure 1b**). In the original state, the top electrode and dielectric film fully overlap and intimately contact with each other, leading to the oppositely charged surfaces. With the top electrode sliding outward, the contact surface area will decrease gradually until the complete separation of the two surfaces. The separated surface creates a potential difference across the two electrodes, generating a current flow from the top electrode to the bottom electrode. When it slides backward, then there will be a reversed current flow to balance the potential difference [23, 24].

2.3 Single-electrode mode

As displayed in **Figure 1c**, the single-electrode mode TENG has only one bottom electrode connected to the ground [25, 26]. After contact with the top material, the two surfaces will get charged owing to the triboelectric effect. During the process of an approaching and departing of top material, the local electrical field distribution caused by charged surfaces will change. Then, there will be potential difference change between the bottom electrode and the ground, and electrons exchange between them to maintain the potential change.

2.4 Freestanding triboelectric-layer mode

As for the freestanding triboelectric-layer mode, it is the only one that the motion part is a dielectric layer [10], as shown in **Figure 1d**. The dielectric layer and two electrodes are in the same order, and the gap distance between the two symmetric electrodes should much smaller than the size of dielectric layer. At the original position, the state of dielectric layer and electrode is the same as what is in the lateral-sliding mode. The dielectric layer and electrode will get oppositely charged, respectively, once the motion occurs as before mentioned. When the dielectric layer is sliding forward and backward, there will be a potential difference between the two electrodes due to the change of overlapped area, which drives the electron exchanges between them.

3. TENGs as small-scale power source

In order to satisfy the requirement of harvesting mechanical energy from multiple type motions, various TENGs have been fabricated based on the four modes illustrated above.

3.1 TENGs harvesting energy from biomechanical

Given the collection features of small scale, low frequency, and irregularity, human biomechanical motions are considered to be accessible, renewable, and the most abundant energy sources. TENG can collect this energy and convert it into electricity. Since it is first reported in 2012, TENG harvesting mechanical energy from human biomechanical movements has been fully developed.

Compared to the discrete devices, complex integrated TENGs can perform multiple functions with the merits of higher output performance, better adaptability, and sustainably. Based on the high-efficient and sustainable TENGs, various integrated TENGs have been developed for harvesting energy from human biomechanical movements. Zhu et al. introdued a packaged power-generating insole with built-in flexible multi-layered TENGs that harvested mechanical pressure during normal walking to power portable and wearable consumer electronics [27]. Bai et al. developed a flexible multilayered TENG by intergrating five layers of units on a zigzag-shaped Kapton substrate to gain pressure from normal walking [28]. Because of the unique structure and nanopore-based surface modification on the metal surface, the instantaneous short-circuit current (Isc) and the open-circuit voltage (Voc) can reach 0.66 mA and 215 V with an instantaneous maximum power density of 9.8 mW/cm^2 and 10.24 mW/cm^3. Triggered by press from normal walking, the TENG attached onto a shoe pad was able to instantaneously drive multiple commercial LED bulbs.

For improving the output current, Yang et al. designed an integrated rhombic gridding-based TENG to harvest vibration energy from natural human walking [29]. The newly designed TENG consists of PTFE nanowire arrays and aluminum nanopores with the hybridization of both the contact-separation mode and sliding electrification mode. Herein, Voc of the TENG could be up to 428 V, and Isc was near 1.395 mA with the peak power density of 30.7 W/m^2. Moreover, based on the TENG, a self-powered backpack was developed with a considerably high vibration-to-electric energy conversion efficiency of 10.62(±1.19)%. When a person walks naturally carrying the designed backpack with a total weight of 2.0 kg, the power harvested from the body vibration is high enough to simultaneously light all the 40 LEDs.

Based on a high-output TENG, Niu et al. developed an universal self-charging system exclusively driven by random body motion for sustainable operation of mobile electronics [14]. In this system, a multilayered attached-electrode contact-mode TENG is utilized to effectively collect the energy from human walking and running (**Figure 2a**). The basic working principle of attached-electrode contact-mode TENGs is shown in **Figure 2b**. The structure of multi-unit TEMG, shown in **Figure 2c**, consists of 10–15 layered TENGs which used a Kapton film (a thickness of 125 μm) as the substrate and is shaped into a zigzag structure. A surface modified thin aluminum foil and fluorinated ethylene propylene (FEP) layer are

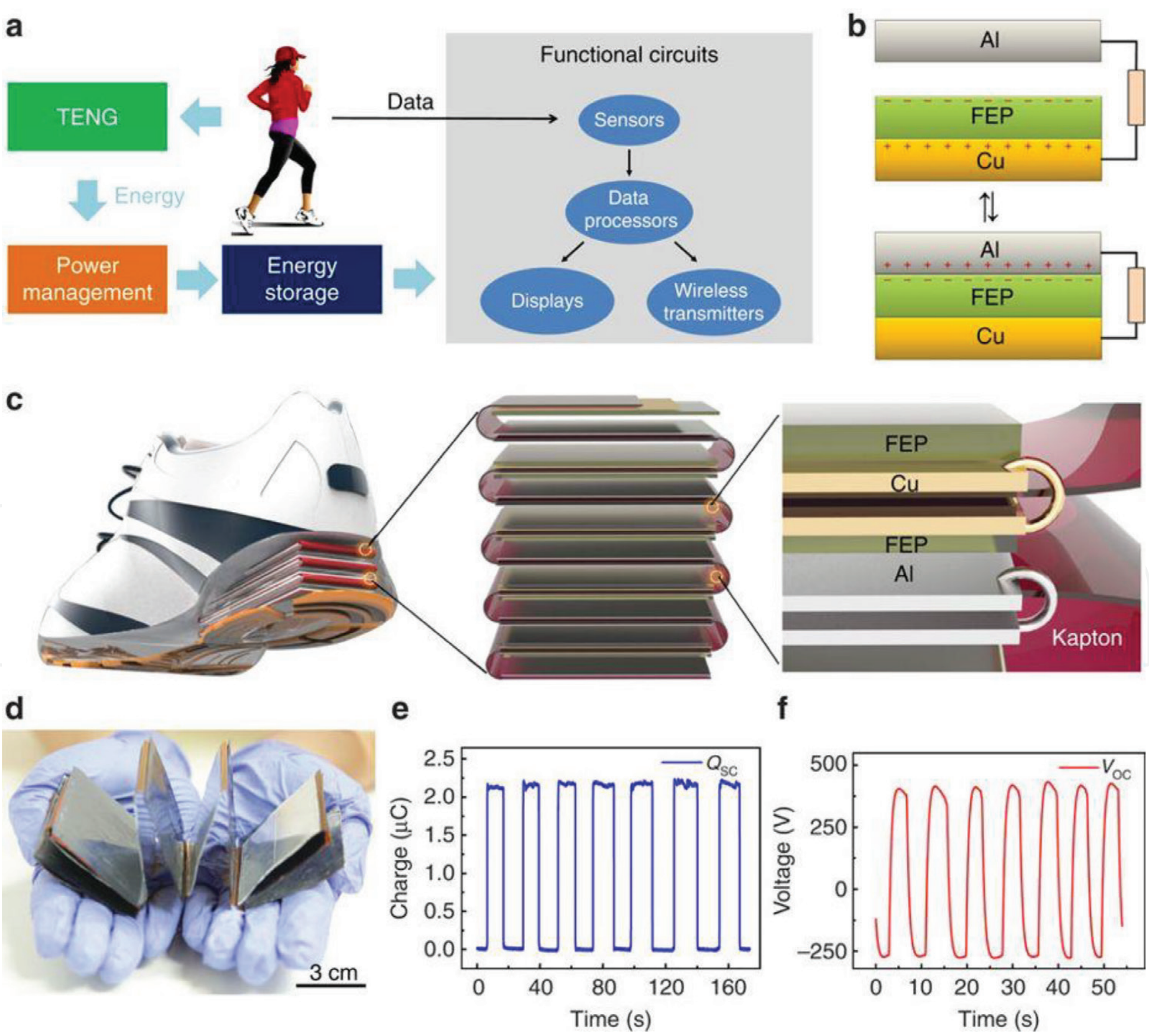

Figure 2.
(a) System diagram of a TENG-based self-powered system, (b) working mechanism of an attached-electrode contact-mode TENG, (c) structure of the designed multilayer TENG, (d) photo of an as-fabricated TENG, (e) triboelectric charge output, and (f) Voc output of the as-fabricated TENG [14].

utilized as the triboelectric materials. **Figure 1d** displays the small volume and lightweight of as-fabricated TENG (5.7 × 5.2 × 1.6 cm/29.9 g for a 10-layer TENG and 5.7 × 5.2 × 2.4 cm/43.6 g for a 15-layer TENG). As shown in **Figure 2e,f**, a human walking can drive this TENG to generate about 2.2 μC short-circuit transferred charge and about 700 V voltage output when embedded the TENG in the shoe insoles.

Shen et al. proposed a humidity resisting triboelectric nanogenerator to harvest energy from human biomechanical movements and activities for wearable electronics [30]. The obtained HR-TENG is fabricated by a nanofibrous membrane via electrospinning method. Under a relative humidity of 55%, the current and voltage output of the self-powered unit can still reach as high as 28 μA and 345 V, corresponding to a power density of 1.3 W/m^2 with hand tapping. With the relative humidity raising from 30 to 90%, its electrical output still kept a relatively high level. A wide-range of electronics such as an electronic watch, a commercial calculator, a thermal meter, and a total of 400 LEDs has demonstrated to be successfully powered from human biomechanical movements under different ambient humidities.

Textile-based device is highly desirable for wearable electronics due to its low-mass, durable, flexible, and conformable [31]. As the most efficient power sources, textile substrate-based TENGs are fabricated for the features of simple structure, wide material choices, and low cost [32–37]. Series efforts have been made to develop fabric TENGs for harvesting mechanical energy induced from body motions to sustainably drive wearable electronics [34, 38]. Lee et al. reported an electrical response of a textile substrate-based TENG including nanostructured surface provided by Al nanoparticles and polydimethylsiloxane (PDMS) [32]. The obtained TENG can power wearable electronics using low-frequency mechanical movements driven by human arm activity. Under the simple folding-releasing stage of an arm near 90°, the output voltage and current of 139 V and 39 μA are achieved, respectively.

To enhance the output performance, a highly stretchable 2D fabric was developed as a wearable TENG for harvesting footstep energy during walking to driven wearable electronic devices [39]. The fabric-structured TENG composes by Al wires and PDMS tubes with a high-aspect-ratio nanotextured surface with vertically aligned nanowires. It shows a stable high-output voltage and current of 40 V and 210 μA, corresponding to an instantaneous power output of 4 mW. The TENG also exhibits high robustness behavior even after 25% stretching, enough for use in smart clothing applications and other wearable electronics. Seung et al. reported a fully flexible, foldable nanopatterned wearable TENG with high power-generating performance and mechanical robustness [40]. Both a silver (Ag)-coated textile and PDMS nanopatterns based on ZnO nanorod arrays on a Ag-coated textile template are used as active triboelectric materials. A high voltage and current output with an average value of 170 V and 120 μA, respectively, are obtained from a four-layer-stacked wearable TNG under the compressive force of 10 kgf. Notably, there are no significant differences in the output voltages measured from the multilayer-stacked WTNG over 12,000 cycles, confirming the excellent mechanical durability of WTNGs. Without external power sources, the fabricated wearable TENG can drive the LEDs, LCD, and the keyless vehicle entry system, exihibting the potential applications in self-powered smart clothes, health care monitoring and self-powered wearable devices, and even personal electronics. Tian et al. demonstrated a high-performance double-layer-stacked triboelectric textile (DTET) for harvesting human motion energy [41]. Both the Ni-coated polyester conductive textile and the silicone rubber are adopted as effective triboelectric materials. A high output Voc of 540 V and an Isc of 140 μA can be obtained from the DTET with the size of

5 × 5 cm^2, corresponding to a high peak surface power density of 0.892 mW/cm^2 at a load resistance of 10 MΩ. The output peak signal of the DTET can be used as a trigger signal of a movement sensor to design movement monitoring equipment. With only the energy harvested from walking, running, or flapping, the DTET can directly light up 100 LEDs connected serially and drive portable electronics, such as competition timer, digital clock, and electronic calculator.

Owing to the high power density, stable cycle life, good safety, and potentials in integration into flexible wear, introducing supercapacitors as energy-storing devices into a fabric TENG show promising prospects. Pu et al. introduced a self-charging power textile for harvesting human motion energy. The self-charging power textile was fabricated by weaving the yarn supercapacitors together with a fabric TENG into an individual fabric [42]. Based on the integrated system, the motion-charging process is carried out by charging the yarn supercapacitors by the contact-separation motions between the TENG cloth and a common cotton cloth. The yarn supercapacitors and the fabric TENG endowed the excellent flexibility and weaveability of the self-charging power textile. Chen et al. developed a self-charging power textile, consisting of a fabric triboelectric nanogenerator and a woven supercapacitor, which can simultaneously harvest and store body motion energy to sustainably drive wearable electronics [43]. Utilizing traditional weaving craft, contact-separation mode and free-standing mode FTENG are designed and fabricated on a piece of textile by weaving the cotton, carbon, and PTFE wires. Combined with the energy-storing component, utilizing RuO_2-coated carbon fiber and cotton threads, the obtained self-charging power textile can harvest energy from common daily activities such as running and walking to drive the wearable electronics, such as an electric watch.

For developing low-cost TENG, paper served as a supporting component for preparing TENG for the first time [44]. Paper-based TENGs represent an low-cost, light-weight, and environmentally friendly energy harvesting methodology. Nowadays, different types of paper-based TNEG have been designed and prepared for harvesting energy from human biomechanical movements [45]. Xia et al. proposed a X-shaped paper TENG formed from a ballpoint ink layer coated by painting with a commercial brush pen for harvesting mechanical energy from human walking [46]. In this design, paper served as both a component of the triboelectric pairs and a supporting component. When a brush pen is painted on the paper, the maximum values of current and voltage output can be achieved at 326 V, 45 μA, corresponding to a power density of 542.22 $\mu W/cm^2$. The staked X-shaped paper TENG is proposed to increase the output performance and harvest the mechanical energy generated by motion of the human body, which can directly light up 101 blue high-power LEDs with a working voltage of 3.4 V.

Additionally, various efforts have been made to promote the development of TENGs for harvesting biomechanical energy based on external devices attached to the human body. In them, human skin-based TENGs are developed for converting biomechanical energy induced from human body itself into electronic energy. According to these series TENGs, human skin is used as one of the triboelectric materials with the single-electrode-mode. With the contact/separation between an area of human skin and a PDMS film, a Voc up to −1000 V, a short-circuit current density of 8 mA/m^2, and the corresponding power density of 500 mW/m^2 on a load of 100 MΩ were obtained from the skin-based TENG delivers, which could be used to directly drive tens of green light-emitting diodes [47]. Due to its fantastic features, skin-based TENGs are developed to transform physical parameters such as pressure, sliding, and other physiological variables into electronic signals, which exploit potential application. For realizing visual-image recognition, a self-powered brain-linked vision electronic-skin (e-skin) for mimicking retina is achieved from polypyrrole/

polydimethysiloxane (ppy/PDMS) triboelectric-photodetecting pixel-addressable matrix [48]. The e-skin can directly transmit photodetecting signal into brain for participating in the vision perception and behavioral intervention. Besides visual-image recognitio, more functional sensors including sliding sensor [49], touch screen [50], pressing sensor [51], and motion sensors [52] are also deeply explored.

In order to satisfy the requirement of self-powered, highly stretchability, and transparency of triboelectric skins, different materials including silicone rubber [53], metal nanowire [54, 55], and conductive polymer [56] are widely studied. To introduce the characteristic of instilling self-healing and further enhance the performance of energy generation, stretch ability, transparency, and slime-based ionic conductors were first used as transparent current-collecting layers of TENG for harvesting mechanical [57]. The ionic-skin TENG consists of a silicone rubber layer with a thickness of 100 ± 10 μm, utilized as the triboelectrically negative material, a slime layer (a crosslinked poly(vinyl alcohol) gel) with a thickness of 1 mm that works as the ionic current collector, and a VHB tape with a thickness of 1 mm as the substrate (**Figure 3a**). **Figure 3b** shows the photograph of the real highly transparent ionic-skin TENG. As depicted in **Figure 3c**, the resulting ionic-skin TENG displays a transparency of 92% transmittance for visible light. The mechanism of the ionic-skin TENG is based on the single-electrode mode, wherein human skin and silicone rubber serve as frictional layer, respectively (**Figure 3d**). **Figure 3e** shows the digital photographs of the fabricated ionic-skin TENG suffering various mechanical deformations including uniaxial stretching up to 700% strain as well as folding and rolling. The produced slime exhibits high ionic conductivity due to the presence of positive (Na^+) and negative ions ($B(OH)^{4-}$), which is measured using electrochemical impedance spectroscopy (**Figure 3f**). Thanks for the series of design, the energy-harvesting performance of ionic-skin TENG is 12-fold higher than that of the silver-based electronic current collectors. Besides, fabricated ionic-skin TENG can recover its property even suffering 300 times of complete bifurcation, exhibiting an autonomously self-healing capacity.

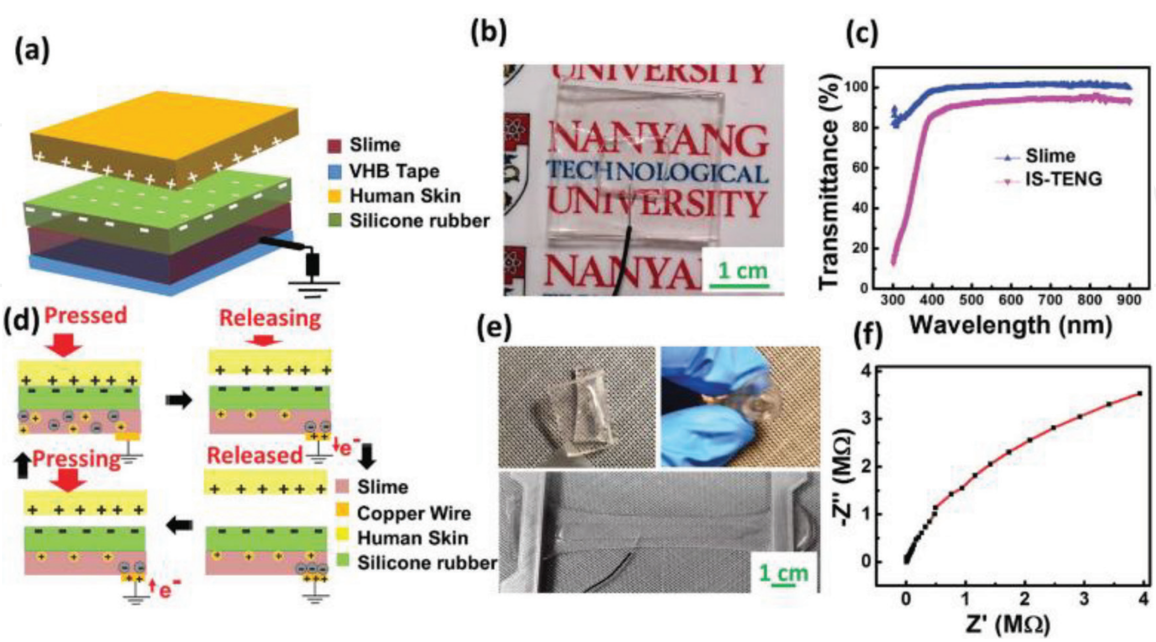

Figure 3.
(a) Schematic diagram of the IS-TENG. (b) Digital photo of the highly transparent IS-TENG. (c) Transmittance spectra of the slime (ionic conductor) and the IS-TENG with respect to a glass slide. (d) Schematic illustration of the working mechanism of the IS-TENG. (e) Digital photos of the IS-TENG under various mechanically deformed states such as axial strain up to 700%, rolled, and folded. (f) EIS measurement of the slime (ionic conductor) [57].

For versatile scavenging mechanical energy induced from arbitrary mechanical moving objects such as humans, a new mode of triboelectric nanogenerator is first demonstrated based on the sliding of a freestanding triboelectric-layer between two stationary electrodes on the same plane [58]. With two electrodes alternatively approached by the tribo-charges on the sliding layer, electricity is effectively generated due to electrostatic induction. To reduce the direct friction between triboelectric layers for energy loss, a linear grating-structured freestanding triboelectric-layer nanogenerator (GF-TENG), consisting of a freestanding triboelectric layer with grating segments and two interdigitated metal electrodes, was developed for high-efficiency harvesting vibration energy from human walking [59]. As shown in **Figure 4a**, 60 commercial LEDs (Nichia NSPG500DS) can be lighted up instantaneously with the motion of hand sliding under a slow speed and a small displacement. The GF-TENG can also havest energy from the monement of car for powering electronic components on the vehicle (**Figure 4b**). Four identical extension springs are used to suspend and anchore the triboelectric layer, as displayed in **Figure 4c**. Owing to the structure, the obtained GF-TENG can scavenge

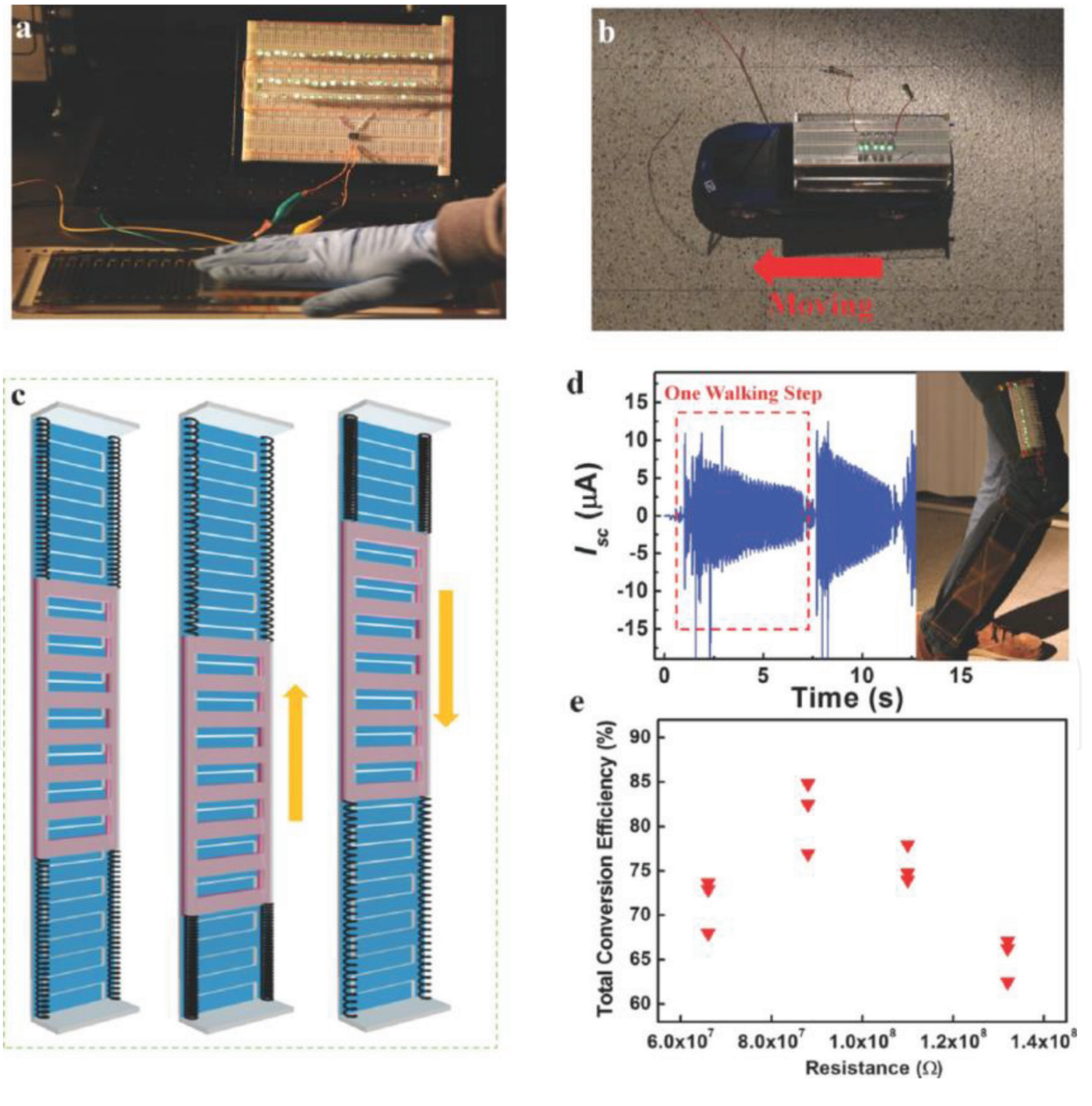

Figure 4.
Applications of GF-TENG for harvesting a wide range of mechanical energy. (a) Harvesting energy from sliding of a human hand. (b) Harvesting energy from acceleration or deceleration of a remote control car. (c) Device structure for noncontact GF-TENG. (d) Harvesting energy from people walking by noncontact GF-TENG and the real-time measurement of Isc. (e) Total conversion efficiency of noncontact GF-TENG for harvesting slight vibration under different load resistances [59].

the mechanical energy from people's walking motion when it is bonded to human legs (**Figure 4d**). An excellent stability and maxmiun energy conversion efficiency of 85% are realized at a matched load resistance of 88 MU under the noncontact mode (**Figure 4e**).

3.2 TENGs harvesting energy from vibration

Vibration, as a type of common mechanical phenomena, ubiquitously exists in ambient environment in a variety of forms and wide range of scales. Therefore, vibration can be regarded as a sustainable source of power for driving small electronics if it can be effectively collected. Contributing to the distinctive working mechanism, TENG has been proposed recently and proved a promising approach for scavenging mechanical energy from vibration, especially in the low-frequency range. To date, a variety of device and machine-based TENGs have been applied to convert mechanical energy induced from vibration into electric energy.

Chen et al. presented a harmonic-resonator-based TENG as a sustainable power source and an active vibration sensor [60]. The harmonic-resonator-based TENG, held a multilayer structure consisting of aluminum with nanoporous surface as contact electrode and nanowire-modified PTFE as frictional layer, is the first TENG that can harness random and tiny ambient vibration. It can effectively respond to vibration frequencies ranging from 2 to 200 Hz with a considerably wide working bandwidth of 13.4 Hz.

The above-mentioned harmonic resonator-based TENG with a simple structure design can only scavenge vibration energy from a single direction. In practice, vibrations in living environments generally display multiple motion directions. With this in mind, a three-dimensional TENG (3D-TENG) was designed for harvesting random vibration energy from multiple directions [61]. The 3D-TENG has a multilayer structure with circular acrylic as supporting substrates, as shown schematically in **Figure 5a**. The cylindroid core of the 3D-TENG lies at the center of the acrylic substrate with a bottom diameter of 3 cm. On the top of the core, an iron mass is mobile and suspended by three identical springs with an included angle of 120° between each other. The designed structural symmetry ensures that the whole system has a constant resonant frequency in arbitrary in-plane directions. A layer of PTFE film as one contact surface is adhered onto the bottom side of

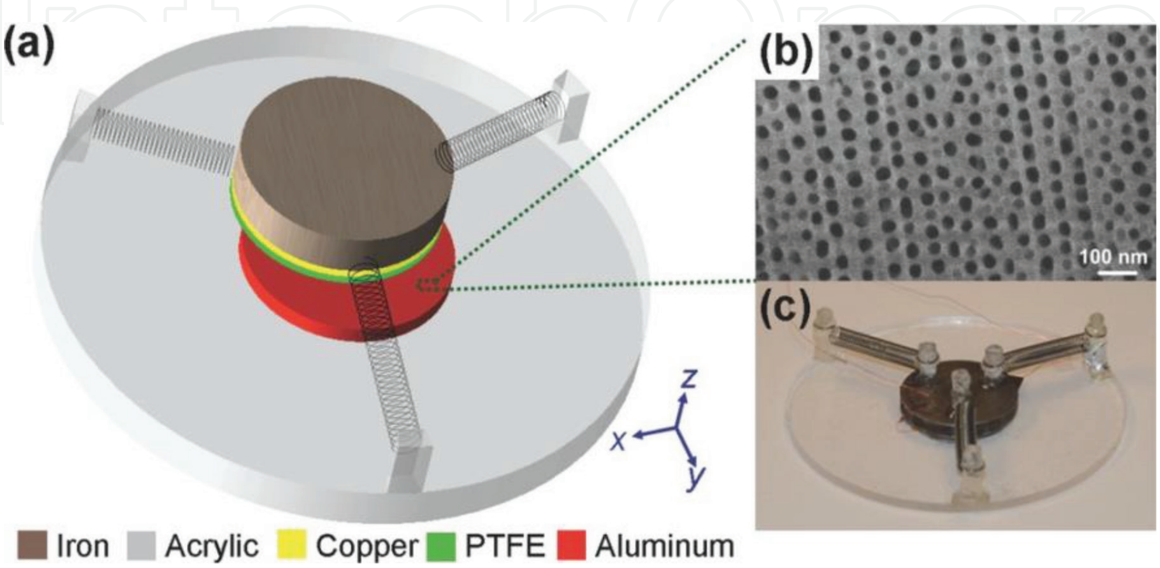

Figure 5.
3D triboelectric nanogenerator: (a) schematic of a 3D-TENG, (b) SEM image of nanopores on an aluminum electrode, and (c) a photograph of the fabricated 3D-TENG [61].

circular iron mass with a deposited copper thin film as the back electrode. Attached to the bottom acrylic substrate, an aluminum thin film with nanopore modification plays dual roles as a contact electrode and the other contact surface. The scanning electron microscopy (SEM) images of aluminum nanopores can be observed in **Figure 5b**. A photograph of the real 3D-TENG device is shown in **Figure 5c**. Owing to the conical-shaped spring structure, the 3D-TENG can operate in a hybridization mode combining with the vertical contact-separation mode and the in-plane sliding mode, which is beneficial to harvest random vibrational energy in multiple directions over a wide bandwidth.

For better sensitivity response to external disturbance, a suspended 3D spiral structure was integrated with a TENG for energy harvesting and sensor applications [62]. Operating in the vertical contact-separation mode, the desired TENG with unstable mechanical structure can balance itself when be oscillated, which makes it a superior choice for vibration energy harvesting and vibration detection. The newly designed TENG has a wide working bandwidth of 30 Hz in low-frequency range with a maximum output power density of 2.76 W/m^2 on a load of 6 MΩ.

Beyond that, a spherical three-dimensional TENG (3D-TENG) with a single electrode, consisting of an outer transparent shell and an inner polyfluoroalkoxy (PFA) ball, was designed for scavenging ambient vibration energy in full space [63]. By working at a hybridization of both the contact-separation mode and the sliding mode, the 3D-TENG can deliver a maximal output voltage of 57 V, a maximal output current of 2.3 μA, and a corresponding output power of 128 μW on a load of 100 MΩ, which can be used to directly drive tens of green light-emitting diodes. Moreover, the TENG is utilized to design the self-powered acceleration sensor with a detection sensitivity of 15.56 V/g.

Besides multiple motion directions, ambient vibrations generally exhibit a wide spectrum of frequency distribution. To solve this problem, a TENG with a wavy-structured Cu-Kapton-Cu sandwiched between two flat nanostructured PTFE films was designed for broadband vibration energy harvesting [64]. The core of the wavy structure is composed of a set of metal rods (with a diameter of 1/4 in.), as shown in **Figure 6a**. PTFE films are processed with inductively coupled plasma (ICP) etching to produce the nanostructures shown in **Figure 6b**, which would largely enhance contact electrification. The device structure is schematically shown in **Figure 6c**, accompanied by a magnified schematic in **Figure 6d** and a picture of a real device in **Figure 6e**. This structure design allows the TENG to be self-restorable after impact without the use of extra springs and converts direct impact into lateral sliding. Based on the wavy structure, the TENG can harvest vibrational energy from 5 to 500 Hz, and the generator's resonance frequency was determined to be ~100 Hz at a broad full width at half-maximum of over 100 Hz, producing a Voc of up to 72 V, an Isc of up to 32 μA, and a peak power density of 0.4 W/m^2.

After that, an elastic multiunit TENG was also realized to efficiently harvest low-frequency vibration energy over a wide frequency range [65]. The obtained TENG can provide a maximum instantaneous output power density of 102 W/m^3 at as low as 7 Hz and maintain its stable current outputs over a wide frequency range (from 5 to 25 Hz). Besides, it can act as an active vibration sensor to monitor the running status of equipment. Moreover, by combining the TENG with a power management unit to form a self-charging power unit, the vibration energy harvesting from ambient environment, such as an operating machine and running bicycle, can sustain power electronics such as thermometers, humidity sensors, speedometers, and a micro-meteorological instrument.

For improving the lower output current, a multi-layered stacked TENG was reported as a cost-effective, simple, and robust approach for harvesting ambient vibration energy [66]. The 3D-TENG has a multilayered structure with acrylic as

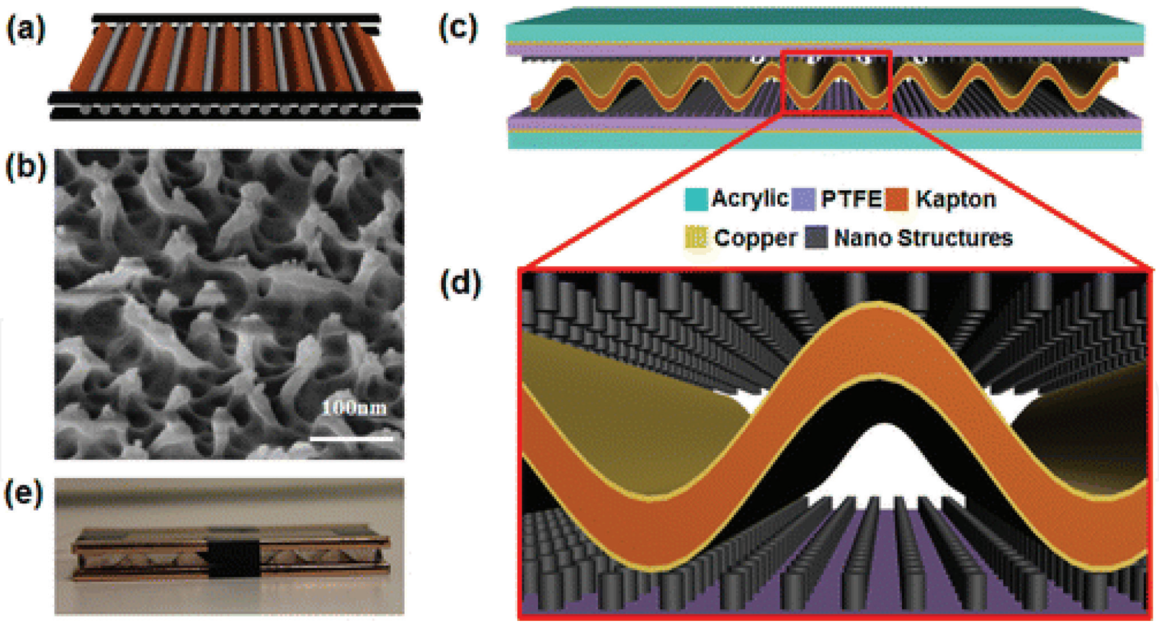

Figure 6.
(a) Schematic of the method to fabricate wavy Kapton films. (b) SEM image of the ICP-processed PTFE film surface. (c) Schematic of the device structure. (d) Magnified schematic of the device, showing that the wavy core is in periodical contact with the nanostructures on the PTFE films. (e) Photograph of an as-fabricated TENG device before packaging [64].

supporting substrates, as schematically shown in **Figure 7a**. A photograph of an as-fabricated TENG and SEM image of the PTFE nanowires is shown in **Figure 7b**-**c**. With superior synchronization, the 3D-TENG produces a short-circuit current as high as 1.14 mA and an Voc up to 303 V with a remarkable peak power density of 104.6 W/m^2. As a direct power source, it is capable of simultaneously lighting up 20 spot lights as well as a white G16 globe light.

To reduce the direct friction between triboelectric layers, a liquid-metal-based TENG (LM-TENG) was developed for high-efficiency vibration energy harvesting [67]. Owing to an intimate contact between the liquid metal and the polymer dielectric layer, the direct friction between triboelectric layers for energy loss is effectively reduced, resulting in high effective contact, shape adaptability, and low friction coefficient with solid. Therefore, the LM-TENG exhibits an output charge density of 430 μC/m^2, which is four to five times higher than that in the case if the electrode is solid film.

On the other hand, soft electrode can effectively increase the contact intimacy between the triboelectric layers [68]. Xu et al. reported a novel soft and robust TENG made of a silicone rubber-spring helical structure with nanocomposite-based elastomeric electrodes for harvesting arbitrary directional vibration energy and self-powered vibration sensing [69]. The schematic diagram and a photo of the S-TENG are shown in **Figure 8a,c**, respectively. As displayed, the TENG exhibits a helical structure based on the integration of elastomer and spring. A mixing well silicone rubber and carbon nanofiber, which can be stretched up to the strain of 133%, serves as the elastomeric electrode (**Figure 8b**). The working mechanisms of the S-TENG under vertical and horizontal vibration are shown in **Figure 8d,e**, respectively. Under external vertical vibration excitation, the distance between a helical structure's adjacent surfaces changes, forming a contact-separation mode TENG. Under horizontal vibration excitation, the S-TENG's helical structure's adjacent surfaces can contact on one side and separate on the other side, also forming a contact-separation mode TENG. Under the resonant states of the S-TENG, its peak power density is found to be 240 and 45 mW/m^2 with an external load of

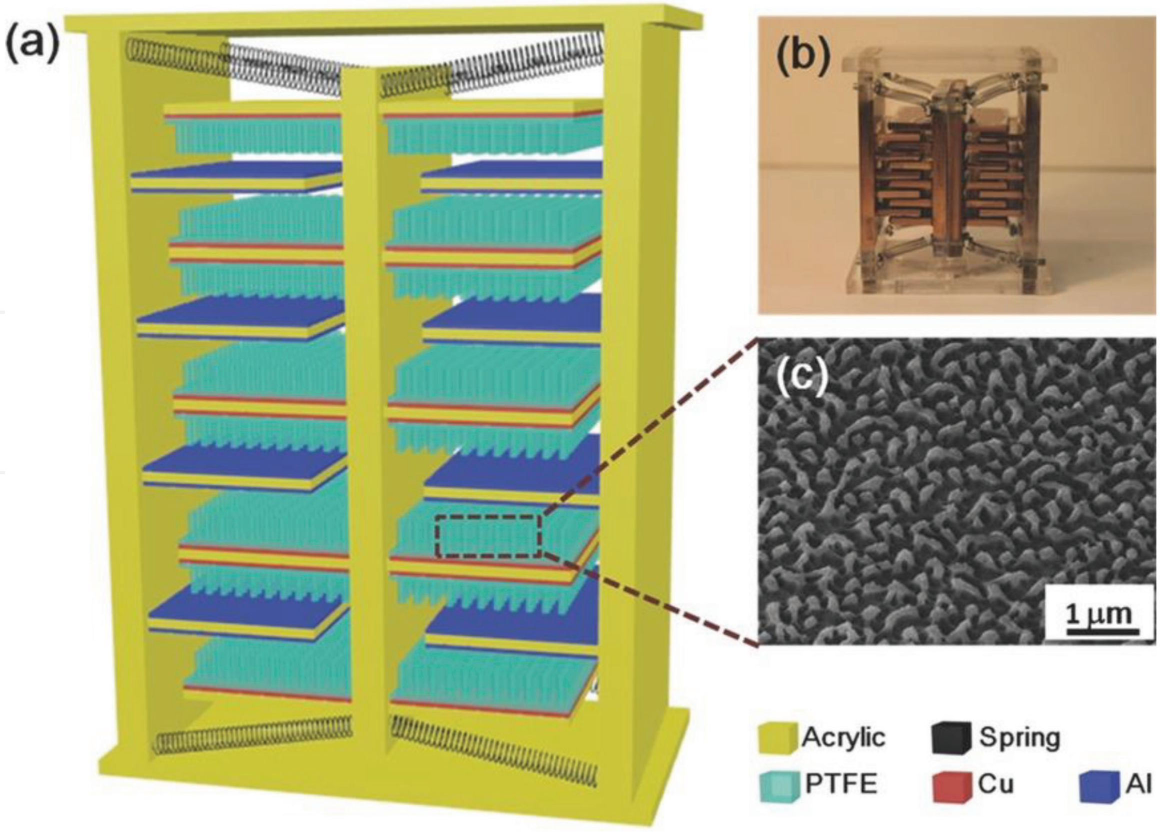

Figure 7.
Three-dimensional triboelectric nanogenerator. (a) Schematic of a 3D-TENG. (b) SEM image of nanopores on aluminum electrode. (c) A photograph of the as-fabricated 3D-TENG [66].

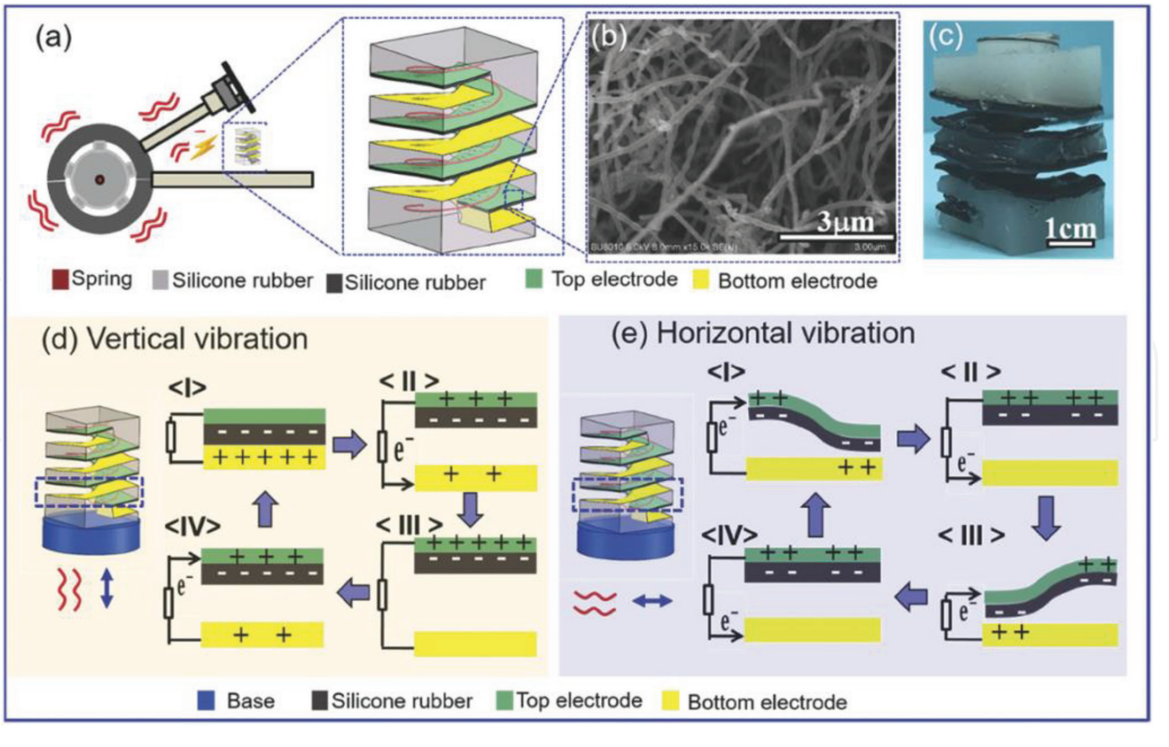

Figure 8.
(a) The device schematic of the S-TENG. Note that the gray silicone rubber layer containing a spring forms a base on which other layers can be built, and the black silicone rubber layer along with the electrode layer forms a contact-separation pair. Both top and bottom electrodes are made of carbon nanofiber-mixed silicone rubber. (b) SEM image of the carbon nanofiber for preparing the elastomeric electrode. (c) Photo of the as-prepared S-TENG. Working mechanisms of the S-TENG under (d) vertical vibration excitation and (e) horizontal vibration excitation [69].

10 MΩ and an acceleration amplitude of 23 m/s^2. Additionally, the dependence of the S-TENG's output signal on the ambient excitation can be used as a prime self-powered active vibration sensor that can be applied to monitor the acceleration and frequency of the ambient excitation.

3.3 TENGs harvesting energy from water

Water energy deriving from rainwater, ocean waves, and waterfalls has been regarded as an alternative renewable energy resource source without polluting the environment. Energy harvesting from water has been further reinforced due to the abundant reserves and little dependence on environmental conditions. Through decades of exploration, a variety of wave energy converting devices and machines based on TENG has been invented to harvesting energy from water.

Liquid-solid-mode TENGs for harvesting liquid-wave energy have drawn much attention for the features of relatively stable output and durability [70–72]. For the liquid–solid-mode TENG, contact separation is the main representative strategies applied to scavenge water energy [73, 74]. A hydrophobic surface on water-solid TENGs is beneficial for inducing separation at the interface of liquid and solid [75]. Based on this, Zhu et al. reported a liquid-solid electrification-enabled TENG based on a FEP thin film for harvesting energy from a variety of water motions [76]. Owing to the modification of aligned nanowires, the thin film with a property of hydrophobicity can increase the contact area at the liquid-solid interface, leading to enhanced surface charging density and thus electric output at an efficiency of 7.7%. Due to the creation of continuous contact separation between water and the solid surface, a cylindrical water TENG was designed by using a hydrophilic surface along with the hydrophobic surface to control the water flow inside a packaged system for enhanced electrostatic induction [77].

Generally, an effective way of integrating a number of electrodes together to make them area scalable is helpful for promoting output power density. On the other hand, the electric power is highly affected by nanostructures at the solid/liquid interface. According to this, a flexible thin-film TENG was reported for harvesting kinetic wave energy [78]. Because of the integration method that use an array of surface-mounted bridge rectifiers to connect multiple parallel electrode together, the induced current between any pair of electrodes can be constructively added up, leading to a significant enhancement in output power and realizing area-scalable integration of electrode arrays. However, the thin-film TENG is only applicable to regular water waves that interact with the TENG through a linear water level. For improving the adaptive means of harvesting water energy, a networked integrated TENG was fabricated for harvesting energy from interfacing interactions with water waves of various types [79]. Additionally, interdigital electrode-based TENGs were designed in the contact-sliding mode for the harvesting of triboelectric energy from water [80], resulting in a higher output performance than those of one- and two-electrode-based TENGs.

Beside liquid-solid-mode TENGs, other structure TENGs were designed for harvesting water energy generating by flowing water, such as multi-layered disk structure [81], floating buoy structure [82], radial-arrayed rotary structure [10], and so on. Although many water-based TENGs have been fabricated, there is a lack of effort in realizing TENG harvesting water energy directly on the fabric/textile, due to the poor water resistance of the fabrics related to their intrinsic hydrophilicity that can be ascribed to their abundant hydrophilic groups, and the strong adsorption capacity because of their large specific surface area [83]. For realizing the practical wearable device harvesting energy from water flow, Xiong et al. reported a wearable fabric-based WTEG with additional self-cleaning and antifouling performance for the first time [83]. This is realized with the preparation of hydrophobic cellulose oleoyl ester nanoparticles by a nontoxic esterification method and nanoprecipitation technology based on the microcrystalline cellulose. In this study, PET fabric-based WTEG can generate the output power density of 0.14 W/m^2 at a load resistance of 100 MΩ.

There are two parts to water wave energy including the electrostatic energy from the contact electrification between water and surrounding media and the mechanical impact energy. For simultaneously scavenging both the energy from water, some works have been well done. For example, Su et al. presented an all-in-one hybridized TENG based on the conjunction of liquid-solid interfacial electrification enabled TENG and impact-TENG for harvesting water wave energy and as a self-powered distress signal emitter [84]; Lin et al. designed a fully integrated TENG for harvesting water energy and as a self-powered ethanol nanosensor, which contained a water-TENG unit to collect the electrostatic energy of water and a contact-TENG unit to collect the mechanical/kinetic energy of water [85]; Cheng et al. developed a water wheel hybridized TENG, composed of a water-TENG part and a disk-TENG part, for simultaneously harvesting the two types of energies from the tap water flowing from a household faucet [86]. Based on a unique structure design, the hybridized TENGs are shown to be suitable for harvesting multiple types of energies from water.

During a working process, the acting surfaces of the above mentioned TENGs will be exposed to ambient atmosphere, which will limit their applications in some cases. The interface electrification was seriously affected by humidity, causing a quick decline of the surface charge density [87]. In order to improve the performance of TENGs under harsh conditions with the presence of water, fully enclosed or packaged TENGs should be developed for tolerating the environment. So far, different designs were developed based on packaged TENG such as wavy-shaped models [88], fully packaged contact-separation configurations [89–91], and rolling spherical structure [92]. Wang et al. designed a freestanding, fully enclosed TENG that encloses a rolling ball inside a rocking spherical shell for harvesting low-frequency water wave energy [93]. An image of the fabricated TENG floating on water is shown in **Figure 9a**. **Figure 9b** shows the schematic diagram of the freestanding structured design that consists of one rolling ball and two stationary electrodes. To enhance the electric output of the TENG, nanowire arrays are fabricated on the surface of the Kapton film (**Figure 9c**) that provides a large contact area to generate more triboelectric charges on the surface. Through the optimization of materials and structural parameters, a spherical TENG of 6 cm in diameter actuated by water waves can provide a peak current of 1 μA over a wide load range from a short-circuit condition to 10 GΩ, with an instantaneous output power of up to 10 mW. This rolling-structured TENG is extremely lightweight, has a simple structure, and is capable of rocking

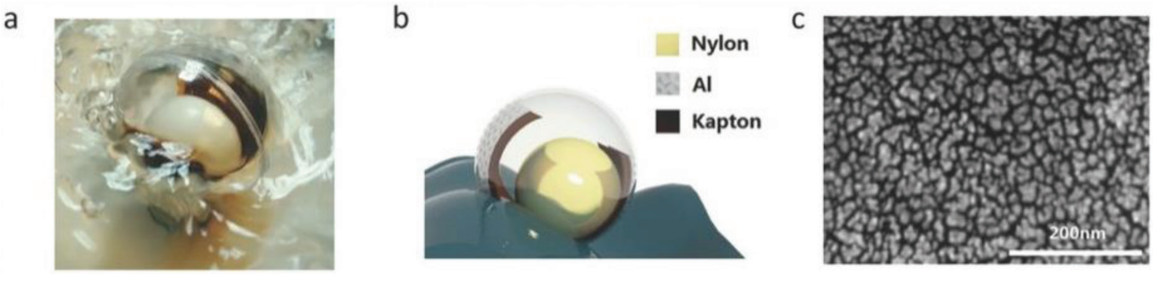

Figure 9.
Device structure, basic operations of the freestanding-triboelectric-layer-based nanogenerator (RF-TENG) with a rolling Nylon ball enclosed. (a) Photograph of a rocking nanogenerator floating on water. (b) Schematic diagrams of freestanding-structured design. (c) SEM image of nanorod structure on the Kapton surface [93].

on or in water to harvest wave energy. Additionally, rolling spherical TENGs and coupled TENG networks have been demonstrated to harness the water wave energy because of the advantages of light-weight, small-resistance under the water wave motions, and easy to be integrated [94, 95].

For enhancing the output current and enlarging the practical applications of packaged TENG, introducing a spring structure into the TENG can store the kinetic energy from water impact and later convert into electric power via residual vibrations [96]. Combining the advantages of spring structure and integrated multilayered structure, Xiao et al. demonstrated a kind of spherical TENG with spring-assisted multilayered structure for harvesting water wave energy [97]. The introduction of spring structure enhances the output performance of the spherical TENG by transforming low-frequency water wave motions into high-frequency vibrations, while the multilayered structure increases the space utilization, leading to a higher output of a spherical unit. The structure of spherical TENG designed with spring-assisted multilayered structure floating on water surface is schematically shown in **Figure 10a**. **Figure 10b** displays a photograph of as-fabricated spherical TENG device, and the inset shows the photograph of the device in the water waves. The working principle of each TENG unit is demonstrated in **Figure 10c**. The periodic movement of the mass block under the triggering of water waves, which leads to the contact and separation between two surfaces of the top aluminum foil and FEP film, produces periodic electric output signals. Owing to its unique structure, the output current of one spherical TENG unit can reach 120 μA, which is two orders of magnitude larger than that of previous rolling spherical TENG, and a maximum output power up to 7.96 mW is realized as triggered by the water waves.

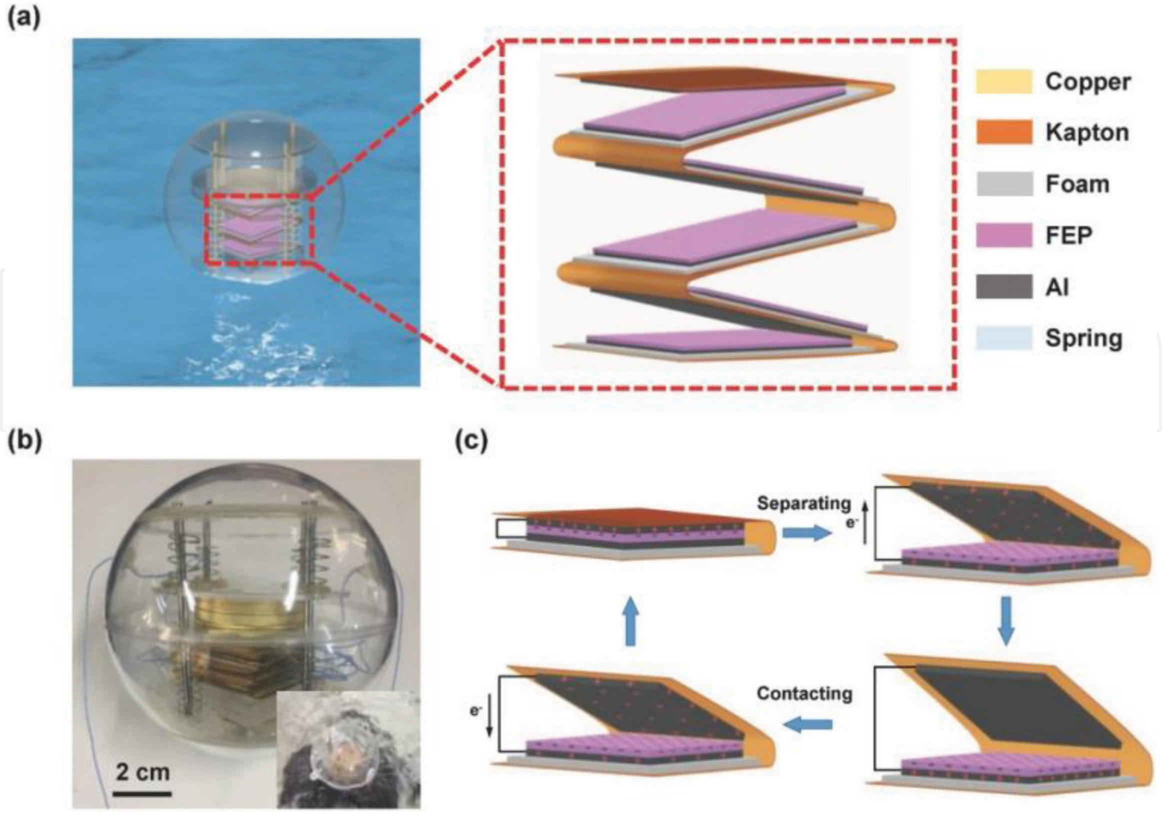

Figure 10.
(a) Schematic diagram of the spherical TENG with spring-assisted multilayered structure floating on water, and schematic representation enlarged structure for the zigzag multilayered TENG with five basic units. (b) Photographs of the as-fabricated TENG device. (c) Working principle of each TENG unit of the spherical TENG [97].

3.4 TENGs harvesting energy from wind

Wind energy can be a renewable energy sources for energy harvesting on account of widespread and absolute abundance. The practical application of traditional wind power in our daily life is largely limited by the extra-large volume, high cost of installation, noise and geographical environment. In this regard, TENG is one of the most alternative wind energy conversion strategies on accord of its small scale, low cost, simple fabrication routes, and portability [98]. In order to harvest wind energy, flutter-driven structure [99, 100] and rotational structure [101, 102] are the two main methods for preparing wind-driven TENG.

Flutter-driven structure TENG for harvesting wind energy was realized by Yang et al. for the first time [103]. As displayed in **Figure 11**, the TNEG is composed of two layers of Al foils and a FEP film laying in midair of a cuboid acrylic tube. The Al foils act as both triboelectric surfaces and electrodes, respectively. The FEP film is fixed one side, leaving the other side freestanding. The FEP film will vibrate periodically to contact the two Al foils inducing from wind, resulting in an output signal in an external circuit. Output voltage and current about 100 V and 1.6 μA are achieved, and a corresponding output power of 0.16 mW is realized under a loading resistance of 100 MΩ.

Although single-side fixed-based TENG exhibits good performance for scavenging wind energy, the stability of output performance is a challenge because of the arbitrary fluttering of the FEP film. For solving the problem, an elasto-aerodynamics-driven TENG, consisting of a Kapton film with two Cu electrodes fixed on two ends in an acrylic fluid channel, was reported for scavenging air-flow energy [104], where the flutter effect of Cu electrodes was induced to contact two triboelectric materials of the PTFE films and the Kapton film to realize the output performance of the device.

Based on flutter-driven structure, many other efforts have been made to enhance the performance of TENG through optimizing the structure or the morphologies of material surface design. A lightweight and freestanding flag-type woven TENG, consisting of conductive belts of Ni-coated polyester textiles and Kapton film-sandwiched Cu belts, was designed for scavenging high-altitude wind energy from arbitrary directions [105]. When wind fluttering is applied in each woven unit, wind energy converts into electrical energy induced by the interlaced interactions between the Kapton film and a conductive cloth under wind-introduced fluttering of the flag. Besides, a flutter-driven TENG, consisting of a flag and a counter plate arranged in parallel with interwoven microstructure, was fabricated for harvesting wind energy based on contact electrification caused by the self-sustained oscillation of flags [106]. As shown in **Figure 12**, a flexible flag and a rigid plate are arranged in face to face in order to prepare a wind-driven energy-harvesting system using fluttering behavior. Owing to the design, interaction between them can lead to a rapid

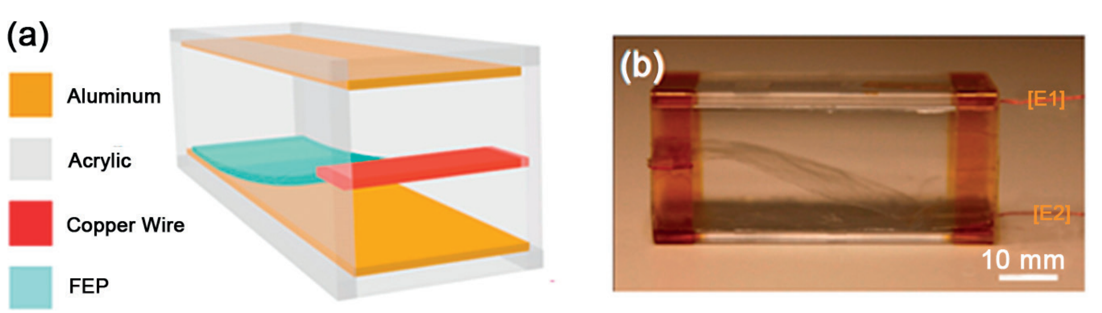

Figure 11.
(a and b) The structure and photograph of the first reported flutter-driven mode WD-TENG [103].

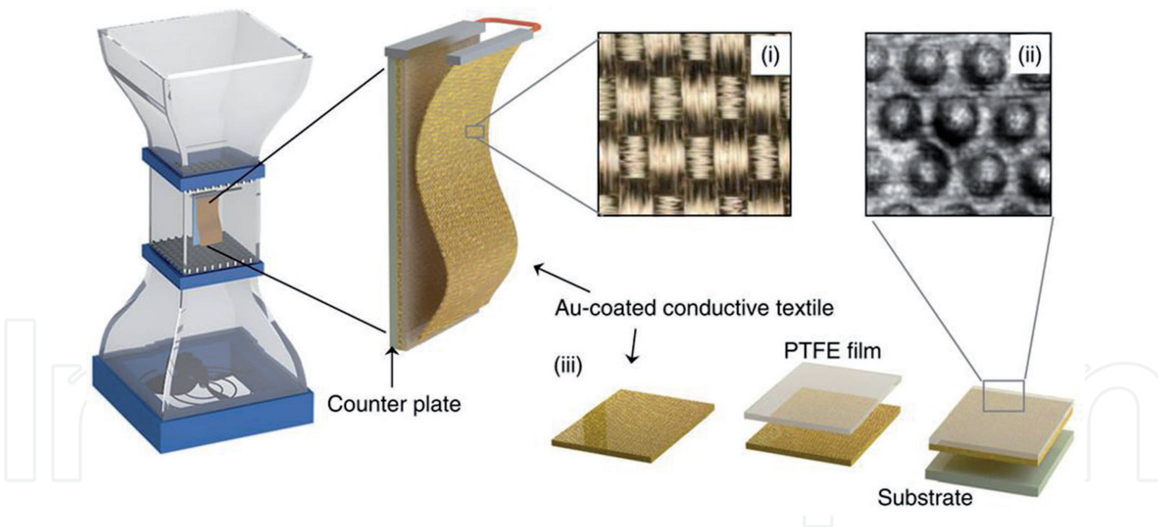

Figure 12.
Schematic diagrams of a wind tunnel and the structural design of a flutter-driven triboelectric generator including surface characteristics of (i) a highly flexible flag, (ii) a counter plate, and (iii) the fabrication of the counter plate [106].

periodic contact and separation, and that movement can be successfully employed for converting the kinetic energy of the wind into electrical energy.

For rotational structure, wind cup is a main method for scavenging wind energy. Deriving from the conventional wind cup structure, a rotary structured TENG was presented for scavenging weak wind energy in our environment [101]. As illustrated in **Figure 13**, the rotary structured TENG is composed of a framework, a shaft, a flexible rotor blade, and two stators. When wind flowing is utilized in the rotation of the shaft and the flexible rotor, a flexible and soft polyester (PET) rotor blade with a PTFE film adhered at the end will periodically sweep across the Al electrodes. In this process, a consecutive face-to-face contact and separation between PTFE film and Al electrodes are produced, regarding as the basic process for generating electricity.

Aiming to improve the robustness and lifetime of wind-driven TENG, a freestanding disk-based TENG was fabricated to harvest wind energy through automatic transition between contact and noncontact working states [102]. The major structure of the disk-based TENG includes two parts: the rotational inner acrylic barrel that connects with the freestanding rotor of the disk TENG and the stationary outer barrel that connects with the stator of the TENG. Two bearings

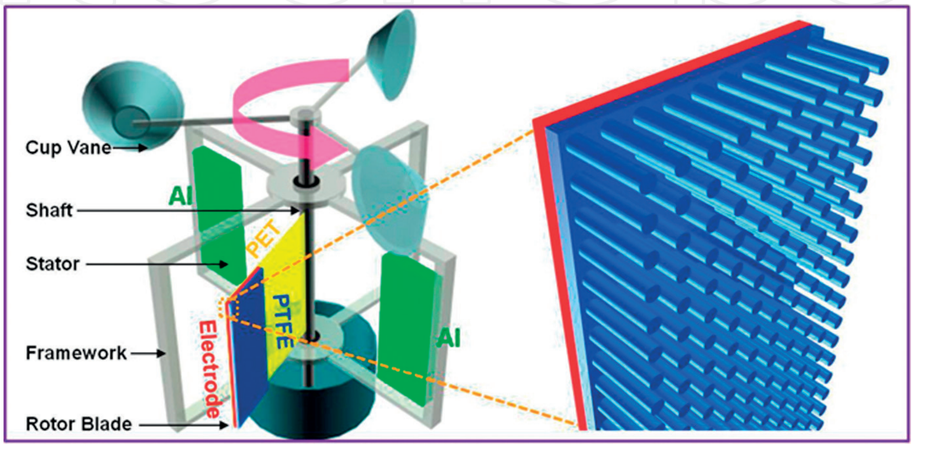

Figure 13.
The schematic diagram showing the structural design of the R-TENG, with the enlarged picture showing the nanowire-like structures on the surface of PTFE [101].

are used to link the two parts and enable the relative rotation. Benefiting from the unique structural design, the TENG can work in the noncontact state with minimum surface wear and also transit into contact state intermittently to maintain high triboelectric charge density.

Besides serving as a power source for running some electric devices, wind-driven TENG is also expected to be utilized as various self-power systems by integrating with other electric devices. Chen et al. introduced the first self-powered air cleaning system focusing on sulfur dioxide (SO_2) and dust removal as driven by the electricity generated by natural wind, with the use of rotating TENG [107]. Another common wind-driven TENG-based self-power system is the wind speed sensor. Kim et al. prepared wind-driven TENG based on rolling motion of beads for harvesting wind energy as a self-power wind speed sensor [108]. Wen et al. fabricated a blow-driven TENG, acting as an active alcohol breath analyzer, which is featured as high detection gas response of ~34 under an optimized sensor working temperature, fast response time of 11 s as well as a fast recovery of 20 s [109].

3.5 Hybrid nanogenerator

Aiming to simultaneously harvesting multitypes of energies from various sources, TENG has been hybridized with various other energy harvester strategies from the environment. It is well known that solar irradiance is another clean and renewable energy sources. To develop a practical method to simultaneously scavenge solar and mechanical energies, the concept of a hybridized energy harvester integrating TENG and solar cell was presented [110, 111]. Based on lightweight and low cost, fabric-based material is served as the ideal strategy utilized to fabricate these kinds of hybrid generator [112]. Chen et al. presented a foldable and sustainable power source by fabricating an all-solid hybrid power textile with economically viable materials and scalable fabrication technologies [34]. The wearable all-solid hybrid power textile has a single-layer interlaced structure, which is a mixture of two polymer-wire-based energy harvesters, including both a fabric TENG to convert mechanical movement into electricity and a photovoltaic textile to gather power from ambient sunlight, as schematically illustrated in **Figure 14a,b**, respectively. An enlarged view of the interlaced structure is presented for both the fabric TENG (**Figure 14c**) and photovoltaic textile (**Figure 14d**). Under ambient sunlight with mechanical excitation, like human motion, car movement, and wind blowing, the as-woven textile was capable of generating sufficient power for various practical applications, including charging a 2 mF commercial capacitor up to 2 V in 1 min, continuously driving an electronic watch, directly charging a cell phone, and driving the water splitting reactions.

Aiming to largely collect the energy from mechanical motions, an integrated TENG and an electromagnetic generator (EMG) for concurrently harvesting mechanical energy are a promising way. By integrating two kinds of mechanical energy harvesting units, the weight of the EMG can be reduced and the total output power can be increased to expand the potential applications [113–117]. In them, rotational structure is the typical strategy utilized to simultaneously convert mechanical energy into electrical energy from one rotating motion. By integrating an EMG and a TENG, a rotation-based hybrid generator is first fabricated to generate a high output that can sustainably drive a commercial globe light with an intensity of illumination up to 1700 lx [118]. As illustrated in **Figure 15a**, the main structure of the hybrid generator consists of an EMG including the top and bottom layers (1 and 5) and a TENG including the middle layers (2, 3, and 4) with the planar structures, where the rotator and the stator are composed of layers 1 and2 and layers 3–5, respectively. The corresponding photographs of each layer are displayed

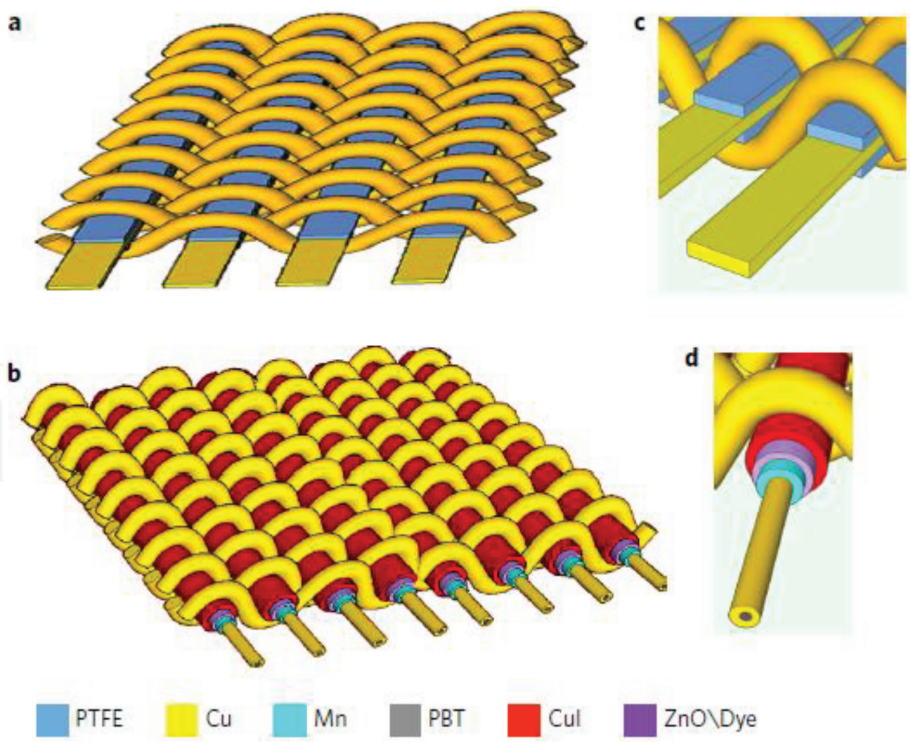

Figure 14.
Structural design of the hybrid power textile. (a and b) Schematic illustration of the hybrid power textile, which is a mixture of two textile-based all-solid energy harvesters: fabric TENG (a) and photovoltaic textile(b). Enlarged view of the interlaced structure of both the fabric TENG (c) and the photovoltaic textile (d) [112].

in **Figure 15b**. Based on the relative rotation between the rotator and the stator, the hybrid generator simultaneously collects biomechanical energy from human hand-induced rotating motions. In order to compare the two generators with each other systematically, Guo et al. fabricated a water-proof triboelectric-electromagnetic hybrid generator, including a fully enclosed packaging of TENG achieved by the interactions between pairs of magnets as the noncontact mechanical transmission forces [119]. Systematic study of the influences of the designed parameters, including the segment's number of the TENG, the rotation speed, and the arrangement of the coils, on the electrical outputs of the WPHG were performed experimentally. The result demonstrated that TENG can produce a stable voltage to power commercial electronic device even under a low rotation speed compared with EMG.

Besides the above mentioned, other strategies have been applied to intergrate with TENG for collecting other types of energies. Lee et al. presented a flexible hybrid cell to simultaneously harvest thermal and mechanical energies from skin temperature and body motion [120]. For fabricating the hybrid cell, ZnO nanowires are grown on the sputtered-coated seed layer surface of a thin Al substrate. And then, a 2-μm thick poly(methyl methacrylate) (PMMA) layer is coated on the surface of the as-grown ZnO nanowires, and a thin Al substrate is stacked on the PMMA-coated layer to be used as the top electrode. Owing to the structure design, the hybrid cell can simultaneously harvest thermal and mechanical energies so that the energy resources can be effectively and complementarily utilized for power sensor network and micro/nanosystems. Addtionally, combining the TENG with piezoelectric nanogenerator (PENG) is a alternative manner for concurrently collecting mechnical energy. Guo et al. developed an all-fiber hybrid piezoelectric-enhanced TENG that fabricated by electrospinning silk fibroin and poly(vinylidene fluoride) (PVDF) nanofibers on conductive fabrics [121]. Contributing to the large specific surface area of nanofibers and the extraordinary ability of silk fibroin to donate electrons in triboelectrification, the hybrid nanogenerator exhibited an

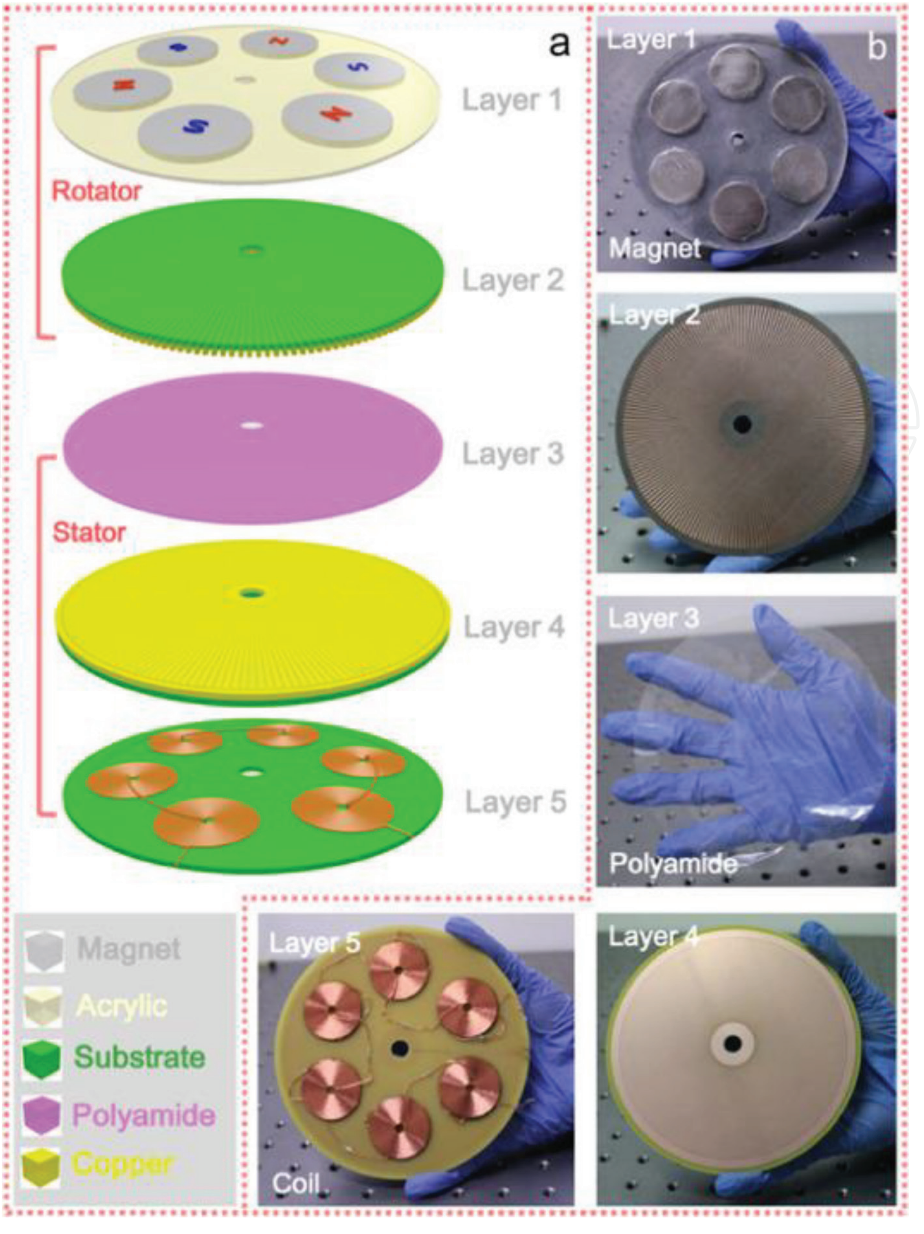

Figure 15.
(a) Schematic diagram of the designed hybridized nanogenerator. (b) Photographs of the hybridized nanogenerator [118].

outstanding electrical performance, with a power density of 310 μW/cm^2, so that it can be regarded as a self-powered wearable microsystem for falling-down detection and timely remote alarm.

4. Conclusions

In order to seek an intelligent life, trillions of electronic device for the Internet of Things are requisite with higher personal, portable, complex, multifunctional, and smart. Aiming to maintain the normal working status of these small electronic devices sustainably, an effective technology to harvest small-scale energy from renewable natural resources is highly desirable. Given the collection characteristics of simple structure, flexibility, low cost, light weight, high efficiency, high power density, and environmental friendly, the invention of TENG is served as an promising small-scale energy harvester who can convert mechanical motions into electricity, even at low frequency. Futhermore, TENGs can also be utilized to transform physical parameters such as pressure, sliding, and other physiological variables into electronic signals, which directly reflected the information of mechanical stimuli and environmental conditions without an external power source. By extensively investigating, TENG can effectively harvest mechanical energy in almost any form based on the four fundamental modes, and thus can regard as the self-powered sensors for a wide application under diffident mechanical triggerings. In the future, the continuous endeavors on TENGs will lagerly enhance their output performance. Based on deeply investigating the fundamental menchanism of triboelectrification, it is possible to realize the ultrahigh charge density of TENG via material modification, structure design, or condition optimization. Besides the output perfoermance, the durability and output stability is the other bottleneck that limited the application of TENG, especially comparing with the traditional generator. It might overcome through fabricating new materials or coupling modes of operations. Based on the above discussion and analysis, it can be anticipated that TENG will soon become an ideal small-scall energy haverter with broad application as self-powered sensors through the world wide efforts.

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Conflict of interest

There is no conflict of interest.

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