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Review Article

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Development, applications, and future directions of triboelectric nanogenerators

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ABSTRACT

Since the invention of the triboelectric nanogenerator (TENG) in 2012, it has become one of the most vital innovations in energy harvesting technologies. The TENG has seen enormous progress to date, particularly in applications for energy harvesting and self-powered sensing. It starts with the simple working principles of the triboelectric effect and electrostatic induction, but can scavenge almost any kind of ambient mechanical energy in our daily life into electricity. Extraordinary output performance optimization of the TENG has been achieved, with high area power density and energy conversion efficiency. Moreover, TENGs can also be utilized as self-powered active sensors to monitor many environmental parameters. This review describes the recent progress in mainstream energy harvesting and self-powered sensing research based on TENG technology. The birth and development of the TENG are introduced, following which structural designs and performance optimizations for output performance enhancement of the TENG are discussed. The major applications of the TENG as a sustainable power source or a self-powered sensor are presented. The TENG, with rationally designed structures, can convert irregular and mostly low-frequency mechanical energies from the environment, such as human motion, mechanical vibration, moving automobiles, wind, raindrops, and ocean waves. In addition, the development of self-powered active sensors for a variety of environmental simulations based on the TENG is presented. The TENG plays a great role in promoting the development of emerging Internet of Things, which can make everyday objects connect more smartly and energy-efficiently in the coming years. Finally, the future directions and perspectives of the TENG are outlined. The TENG is not only a sustainable micro-power source for small devices, but also serves as a potential macro-scale generator of power from water waves in the future.

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1 Introduction

1.1 Development of triboelectric nanogenerators

The harvesting and conversion of mechanical energy is one of the main ways in which mankind obtains electricity. As shown in Fig. 1, the electromagnetic generator invented by Faraday has been the dominant mechanical energy harvesting technology from 1831 until now [1]. In 1861, Maxwell first proposed Maxwell's equations to unify electromagnetism and displacement current [1, 2]. In 2006, the piezoelectric nanogenerator (NG) was invented by Wang, and provided a novel mechanical energy harvesting technology [3–10]. The second term in Maxwell's displacement current is directly related to the output of the NG [2]. Subsequently, the pyroelectric NG for thermal energy harvesting was also invented [11]. The triboelectric nanogenerator (TENG) was first invented in 2012 [12]. Both the piezoelectric and triboelectric nanogenerators can convert mechanical energy into electricity. Compared with other kinds of NGs, the TENG has many advantages, including large power density, high efficiency, and low-cost. Therefore, the TENG has become one of the most important innovation in energy harvesting technologies.

The TENG can convert various types of mechanical energy from the ambient environment into electricity, which works based on the coupling of triboelectric and electrostatic induction [13–15]. To date, four fundamental modes have been developed for the TENG: vertical contact-separation mode, in-plane sliding mode, single-electrode mode, and free-standing triboelectric-layer mode [14, 15]. Each mode of the TENG has distinct structural features and superiorities. As the first-invented mode, the vertical contact-separation mode TENG is suitable for harvesting cyclic motion, intermittent impact and vibration [12, 16–22]. The power generation principle is based on a periodic switching between the contact and separation of two contact surfaces. It offers various advantages, such as simple structure, excellent robustness, and high instantaneous power density. The in-plane sliding mode has several advantages over the vertical contact-separation mode [23–29]. The triboelectric effect of sliding between two materials is stronger than the contact effect, and the sliding mode is easier to optimize for obtaining a high-performance TENG. The in-plane sliding mode TENG is suitable to harvest energy from planar motions and rotation. The single-electrode-mode TENG has only one working electrode and another contact layer that can move freely without restriction, and thus can harvest energy from any freely moving object [30–36]. The free-standing triboelectric-layer mode can conveniently harvest energy from the sliding or contact-separation motion without constraints in the freestanding triboelectric layer [37–43]. With a unique structure, this mode can be widely applied in various conditions.

Since the birth of the TENG in 2012, extensive research has been carried out for its development. In order to widen the actual application range of the TENG, new methodologies for enhancing output performance are always a goal. These efforts mainly focus on two major directions: One is output performance enhancement of the TENG, while the other is system integration.

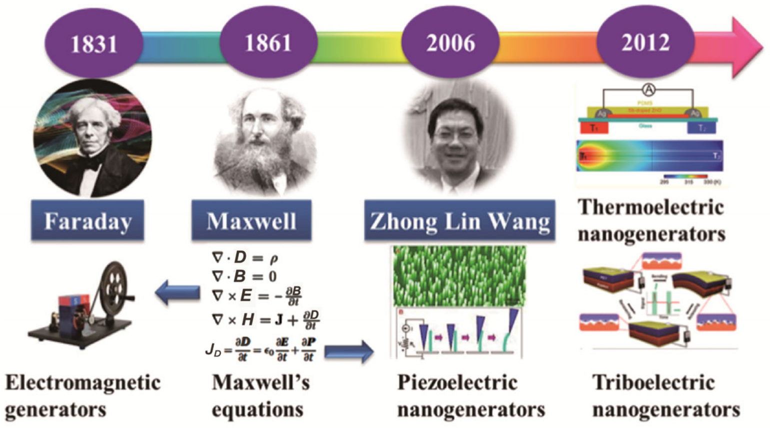

Figure 1 The birth of the TENG and related major historical events. Reproduced with permission from Ref. [3], © Science 2013; Ref. [11], © American Chemical Society 2012; Ref [12], © Elsevier 2012.

1.2 Output performance enhancement of the TENG

Continuous efforts have been made to improve the performance of the TENG, which is the key factor in determining its applications. There are numerous ways to enhance the performance of the TENG from the materials point of view. The first way is through the selection of the right materials [13–15, 44–46]. Almost all materials we know, from metal to polymer, silk, and wood, can be candidates for fabricating a TENG. The ability of any one material to gain or lose electrons depends on its polarity. The difference in polarity between two kinds of materials is beneficial for increasing the output of a TENG. Suitably paired materials can offer maximum output performance. Therefore, the material selection principle for a TENG is that the greater the distance between two materials in the triboelectric series, the greater the charge transferred [47]. The second way to achieve high output is through surface structure design and modification [13–15, 48–50]. The surface morphologies of the TENG can be modified by physical and chemical techniques to create different nano- or microstructures, such as strips, cubes, and pyramids. The surface nano- or microstructures are effective for enhancing the contact area for triboelectrification. In addition, surface charge density is essentially correlated with the output performance of the TENG. The surface charge density of materials could be increased by surface modification, such as ionized air injection or surface functionalization with an organic solvent [51, 52]. The third way to enhance output performance of the TENG is by optimizing the device structure design [53, 54]. The contact and separation speeds are closely related to the output power, which could be modulated by different device structures. The output power density of the TENG has been enhanced largely through advanced structure design. For instance, four modes of the TENG with different structures, including multilayered electrodes, rolling and radial arrays, have different output properties. The output power density may increase significantly with the change in device structure. Therefore, device structure design plays a very important role in the improvement of TENG output performance.

Since the first report on the TENG, its output performance has seen rapid improvements. A power density of 500 $W \cdot m^{-2}$ and total energy conversion efficiency of 85% have been demonstrated [55, 56]. TENGs with different output power can provide energy for a variety of applications with different power requirements, such as portable electronics and Internet of Things.

1.3 System integration of the TENG

In order to adapt to different operating environments, a hybrid energy system was developed by integrating the TENG with other power generators for harvesting energy from various sources. For instance, a TENG can be hybridized with thermoelectric generators, solar cells, electromagnetic generators, etc. [57–62]. In addition, the output signals of a TENG are usually pulses with irregular magnitudes. However, most commercial electronics need constant direct current (DC) voltage. Hence, a TENG should be integrated with energy storage units like supercapacitors and lithium ion batteries, to meet these needs [63–67].

The ultimate goal of the TENG is practical application. Depending on the application field, the TENG may have one of two major applications: harvesting energy from the environment, or serving as self-powered active sensors. Generally, the TENG can aggregate a variety of mechanical energies from the environment, including from water, wind, vibration, and biomechanical energies. TENG-based self-powered active sensors can be divided into four main types: pressure sensors, vibration sensors, motion sensors, and chemical sensors.

2 TENG for harvesting energy from the environment

Energy harvesting now attracts intensive attention due to the worldwide energy crisis. Because advanced technologies have managed to reduce the power consumption and increase the efficiency of electronics, it is feasible to exploit the harvested mechanical energy from the ambient environment to power electronic devices.

2.1 Harvesting water energy

Harvesting clean energy from the ambient environment is a desirable solution to on-site energy demands for organic electronic and optoelectronic devices. Water-related energy is an inexhaustible, green energy resource in our environment, available in the form of ocean waves, river water, raindrops, and so forth. This type of resource holds an enormous amount of energy, which is not governed by time of day and sunlight conditions. However, it is challenging to realize this energy harvesting due to the lack of suitable techniques. Most water energy harvesters depend on normal electromagnetic generators, which have low conversion efficiency in a low frequency range, and suffer the drawbacks of bulkiness, heaviness, and high cost. Since the emergence of the TENG, many attempts have been made to effectively yield water-related energy. To date, there have been several unique prototypes proposed with excellent output performance, good flexibility, and high stability and robustness [68–71]. Lin et al. first proposed the idea of water-solid contact electrification for harvesting water energy in 2013 [72]. The device structure is one dielectric layer of a typical contact-mode TENG replaced by water. Cyclic contact between the polydimethylsiloxane (PDMS) layer and the water surface would generate periodic charge flows in the external load. The water-TENG was able to produce a voltage and current density of 82 V and 1.05 mA·m^{-2}, respectively, driven by a linear motor at a frequency of 2 Hz. The optimized power density reached up to 50 mW·m^{-2} at 5 Hz. By measuring the output of real-time performance, the water-TENG could serve as a self-powered temperature and ethanol sensor. The transparent characteristic plays a key role in practical applications of devices designed for harvesting water-related energy. The Zhang group reported a glass-based, highly transparent TENG (T-TENG) operated under the single-electrode mode, as shown in Fig. 2(a) [30]. The T-TENG was developed to harvest electrostatic energy from flowing water. With a polytetrafluoroethylene (PTFE) film acting as an antireflection coating, the maximum transmittance of the fabricated T-TENG is 87.4%, which is larger than that of the glass substrate

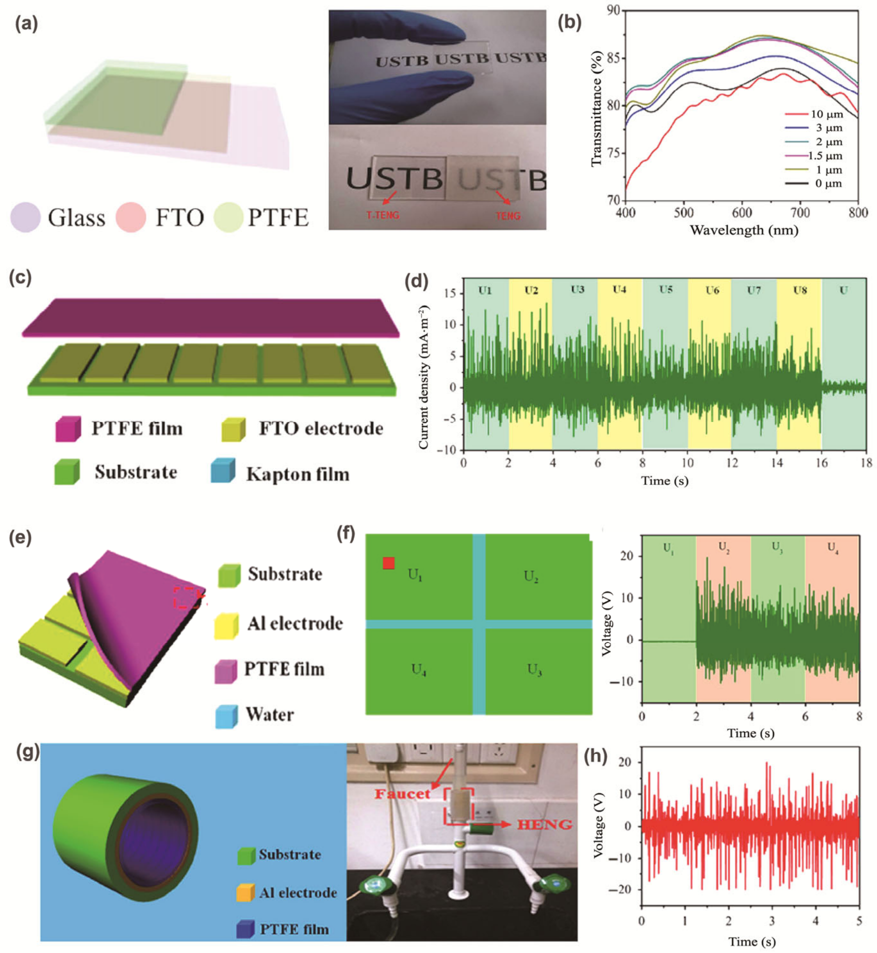

Figure 2 TENG for harvesting water energy. (a) T-TENG. (b) Ultraviolet–visible (UV–vis) spectra of the TENG with different thicknesses of the PTFE film. (c) Integrated multi-unit transparent TENG. (d) Output current densities of MT-TENG and individual T-TENG. (e) Multi-unit hydroelectric TENG. (f) Rational design of the multi-unit TENG beneficial for the future service behavior. (g) Tubular multi-unit TENG integrated with a household faucet. (h) Typical output voltage signals of the multi-unit TENG. Reproduced with permission from Ref. [30]. © Nature Publishing Group 2015; Ref. [73], © Elsevier 2015; Ref. [74], © Elsevier 2016.

alone. The instantaneous output power density of the T-TENG is 11.56 mW·m^{-2} when connected to a load resistor of 0.5 MΩ. Furthermore, the Zhang group developed a multi-unit transparent TENG (MT-TENG) to integrate the advantages of T-TENG and the multi-unit TENG, as depicted in Fig. 2(c) [73]. The instantaneous output power density of the MT-TENG reaches 27.86 mW·m^{-2}, which is 11.6 times greater than that generated by the individual T-TENG. The improvement in efficiency of the MT-TENG results from the facilitation of charge transfer. In addition, the logical design of the MT-TENG is capable of overcoming the degradation and failure problem experienced by the water-based T-TENG. The dependence of the temperature and pH value of water on the electric outputs is also systematically studied with consideration for different application environments. The Zhang group further reported a flexible and tubular multi-unit TENG, shown in Fig. 2(e), for harvesting water-related energy in the living environment [74]. With the flow rate of tap water at 35 mL·s^{-2}, the instantaneous output power density of the multi-unit TENG array is 0.07 W·m^{-2}. The influences of the flow and falling height of water, and the tilt angle of the TENG were systematically studied. Regulation methods for the output of the TENG were explored. Through integration with the multi-unit TENG, the household faucet can be a source of continuous clean energy.

In addition to the planar structure prototype, other prototypes were also proposed for high-efficiency water energy harvesting. Cheng et al. designed a water wheel-hybridized TENG for simultaneously harvesting two types of energies from the tapwater flowing from a household faucet, composed of a water-TENG part and a disk-TENG part [75]. The current of the water-TENG and the disk-TENG reached 12.9 and 3.8 μA at a water flow rate of 54 mL·s^{-1}. At a flow rate of 54 mL·s^{-1}, the instantaneous maximum power density of the water-TENG and disk-TENG is around 0.03 W·m^{-2}. The hybridized TENG was also demonstrated to harvest energy from the wind. Chen et al. proposed the innovative idea of using TENG networks for large-scale blue energy harvesting [76]. The network, made of millions of TENGs, would flow in the vicinity of the water surface. An averaged power density of 1.15 MW·km^{-2} is predicted. The network introduces a green alternative to traditional methods, which has potential for large-scale blue energy harvesting.

In view of the complexity of potential application environments, it is essential to explore the service behavior of the TENG. However, few reports focus on the service behavior of the water-TENG working in harsh environments and its resistance to mechanical damage, which may include being cut, pierced, or torn. It is highly desirable to investigate these issues, and to develop reliable TENG-based energy systems. The Zhang group provided an in-depth investigation of the service behavior of textile-based, customizable TENG, as depicted in Fig. 3 [64]. As a water energy harvester, the customizable TENG is capable of yielding mechanical energy from water efficiently, even if it is partly damaged. This work is an inspiration to the future development of reliable energy systems, flexible and wearable electronics, and water energy harvesters.

2.2 Harvesting wind energy

Wind energy as an alternative to fossil fuels is plentiful, renewable, clean, and widely distributed. In recent years, wind-turbine-based wind energy generators have been actively utilized to generate electricity. Although efficient, this power generation method has many drawbacks, including structural complexity, large volume, loud noise, and high cost of manufacturing and installation. Thus, a miniature, modularized, and efficient power-generation solution is highly desired. Investigations of TENGs as wind energy harvesters uncover great potential to overcome the limits of existing technologies, due to the low cost, simple fabrication, and good scalability of TENGs. Several prototypes have been fabricated for harvesting wind energy, including flutter, buffeting, galloping, and vortex shedding TENGs [77–79].

In this respect, Wang et al. reported an aero-elastic flutter-driven TENG for yielding wind energy. This TENG consisted of a Kapton® film with two Cu electrodes at each side, fixed at both ends in an acrylic fluid channel [80]. With a fluid channel size of 125 mm × 10 mm × 1.6 mm, the device delivers a maximum output power density of approximately 9 kW·m^{-3}. Connecting 10 TENG in parallel gives an output power of 25 mW, which can directly power a globe light. Quan et al. presented a double-side-fixed TENG, which can harvest bidirectional wind energy with wind incident angles of 0° and 180° [81]. The maximum output power of the TENG was 3.4 mW at a matched load of 4 MΩ at a wind velocity of 15.9 m·s^{-1}. A liquid crystal display can be driven by the TENG at a wind velocity of 1.5 m·s^{-1}, which illustrates the wind-fluttered TENG powering an external load. The Zhang group proposed a hybrid nanogenerator composed of a gas-flow-driven TENG and a thermoelectric generator (TEG) for gas energy recycling and purification, which is

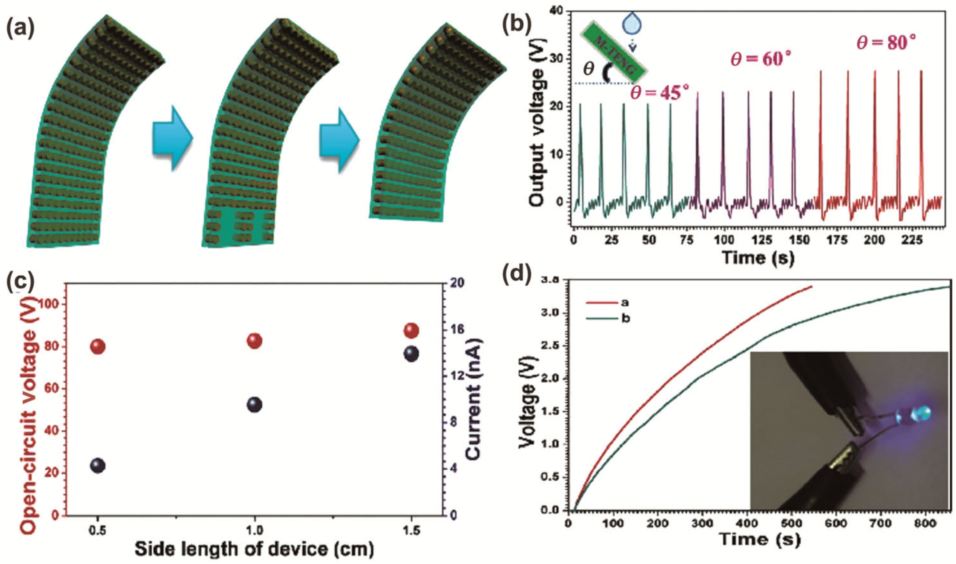

Figure 3 (a) Service behavior mechanism of the textile-based customizable TENG. (b) TENG for harvesting mechanical energy from water drops. (c) Open-circuit voltage of the TENG before and after being reduced by one-third and two-thirds of the original size. (d) Voltage of the supercapacitor charged by the TENG before (curve a) and after (curve b) being cut. Reproduced with permission from Ref. [64], © Wiley-VCH 2017.

demonstrated in Fig. 4 [58]. Both the mechanical and heat energy of the exhaust gas can be recycled by combining the merits of TENG and TEG, which achieves complementary advantages. This combination delivers a regulated power of 147.6 W·m^{-3}, which is capable of powering electronic devices or being stored. Moreover, exhaust gas purification is implemented through reclaiming exhaust gas energy with no external power. This achieves a high removal efficiency of 92.1% for a purification level of PM2.5, and realizes real-time gas quality monitoring.

Except for the oscillatory TENG based on the coupling of aerodynamic forces with elastic deformation, Xie et al. developed a rotary TENG assisted by the wind-driven rotation of a wind cup [82]. The continuous rotation of the shaft drives cyclic contact, and the sliding between the nanostructured PTFE film and the Al foils. At a wind speed of 15 m·s^{-1}, the output voltage and current reach 250 V and 0.25 mA, corresponding to a maximum power density of 39 W·m^{-2}. In addition, the rotary TENG was demonstrated to serve as a self-powered wind speed sensor. This work creates a novel operation mechanism for wind harvesters.

2.3 Harvesting biomechanical energy

In our daily life there is a large amount of biomechanical energy produced that is always wasted, such as that produced through bodily motion, hand pressing, walking, breathing, beating of the heart. The TENG has been given intensive attention owing to the fast development of wearable electronics. In this regard, several types of flexible, stretchable, and wearable TENG have been developed to harness biomechanical energy and power portable electronics [83–86]. Song et al. presented a rotating TENG to harvest biomechanical energy to power drug-delivery applications. An electrochemical microfluidic pump powered by a TENG was developed [87]. The system derives its functional power from the motion of human hands through the TENG for drug delivery. Trans-scleral drug delivery is performed in porcine eyes *ex vivo*. Under different rotating speeds of a TENG, pumping flow rates from 5.3 to 40 μL·min^{-1} were realized. The rapid growth of deformable and stretchable electronics calls for a deformable and stretchable power source. Wang et al. reported a tube-shape stretchable TENG designed to harvest biomechanical energy from everyday human locomotion [88]. The TENG was fabricated from elastomeric materials and a helix inner electrode attached to a tube with a dielectric layer and an outer electrode. It had a high surface charge density of 250 μC·m^{-2}. Wearable electronics such as an electronic watch or fitness tracker could be continuously powered by a TENG through energy extracted from walking or jogging. The Zhang group developed a highly stretchable, shape-adaptive TENG for harvesting

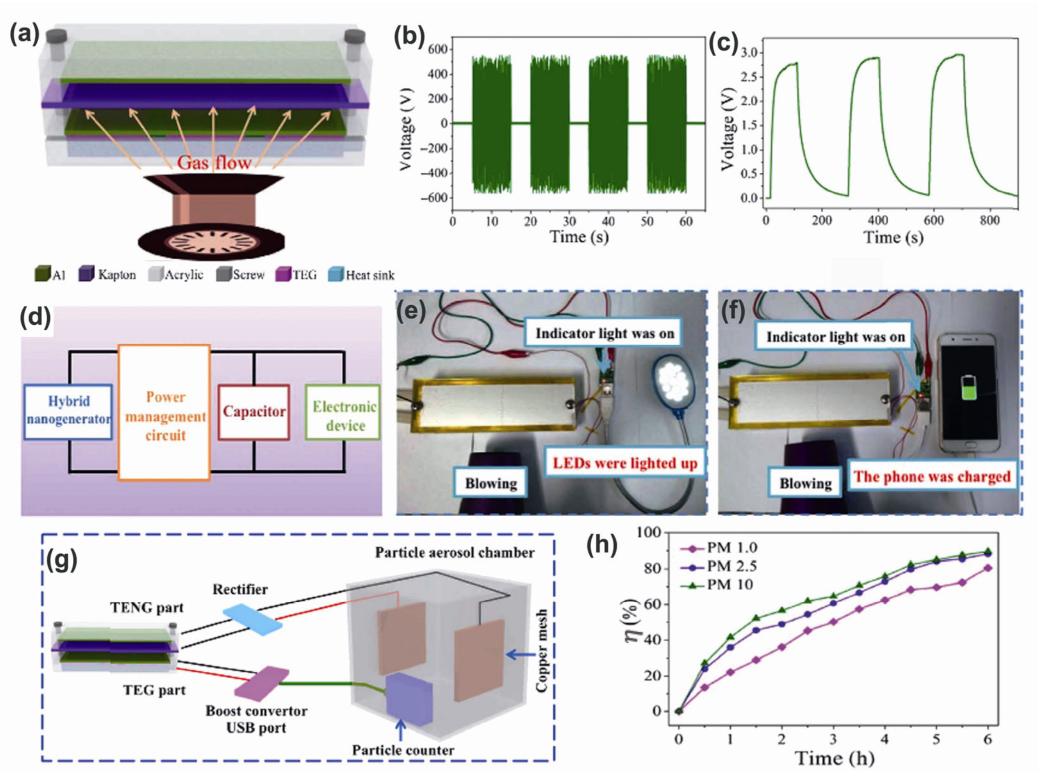

Figure 4 TENG-based hybrid nanogenerator for harvesting wind energy. (a) Schematic illustrations of the hybrid nanogenerator. ((b) and (c)) Output performance of the TENG and TEG. (d) Schematic diagram of the power supply circuit. (e) Photographs of the LEDs directly powered by the hybrid nanogenerator. (f) Photographs of the mobile phone charged by the hybrid nanogenerator. (g) Demonstration of the gas energy recycling and purification system. (h) The removal efficiency change with increasing precipitation time. Reproduced with permission from Ref. [58], © Elsevier 2017.

biomechanical energy in various working modes [31]. As shown in Fig. 5, the TENG was fabricated by conductive liquid electrodes, and maintained high performance under a tensile strain of 300%. This TENG can conform to any three-dimensional or curvilinear surface because of its high flexibility. Applications have demonstrated this TENG as a wearable power source. Moreover, this TENG can be applied for large area energy harvesting from a water cushion and rubber pipe using flowing water as the electrode. This work will be useful in the large area energy harvesting applications that use flowing liquid for powering wearable electronics and implantable devices.

The ultimate goal of the TENG through collecting ambient biomechanical energies is to power various multifunctional electronic devices. The TENG can transform low-frequency, random, and irregular biomechanical motion into electricity. However, commercial electronics require regulated and continuous power to ensure steady operation; therefore, the alternating pulse signals from a TENG cannot be utilized to drive electronics directly. A power management system is needed in which the harvested electricity can be stored by capacitors or batteries for later use. The Zhang group combined a stretchable TENG with a stretchable supercapacitor to form a self-charging power system, which is shown in Fig. 6(a) [63]. The power system can harvest energy from almost any kind of large-degree deformation because of its pliable structure. Moreover, the power system is washable and waterproof owing to its fully-sealed enclosure and the hydrophobic property of its exterior surface. The power system can be worn on the human body to effectively harvest energy from various kinds of human motion, including patting the hands, rotating the wrists, and bending the arms and legs. The wearable power source has been demonstrated to be capable of driving an electronic watch. Niu et al. fabricated a high-efficiency self-charging power system for exploiting biomechanical energy exclusively from humans [89]. It consists of a TENG, a power management circuit, and an energy

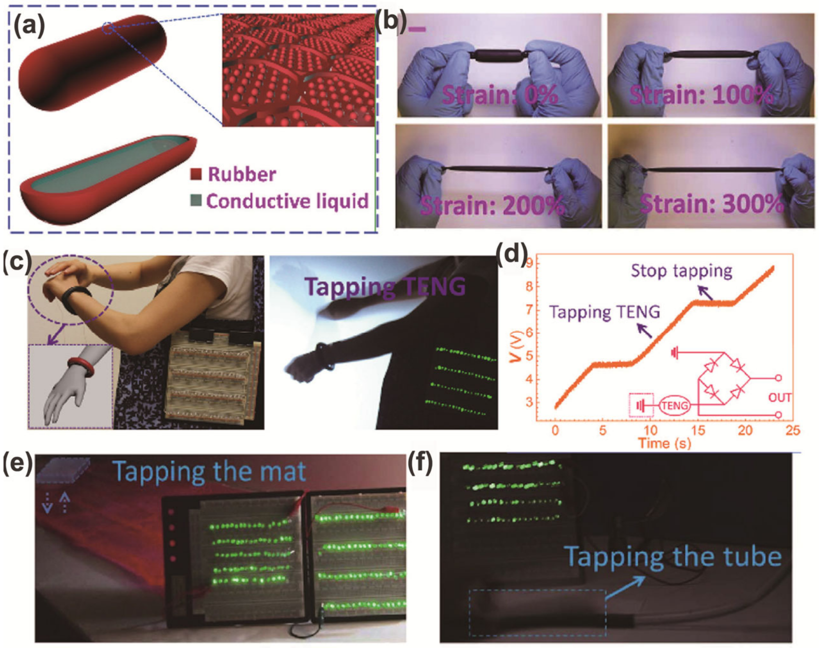

Figure 5 TENG for harvesting biomechanical energy. (a) Schematic diagram of the shape-adaptive TENG. (b) Photographs showing the TENG under different tensile strains. (c) TENG looped around the arm of a subject to harvest energy from tapping motion. (d) Charging a capacitor by a TENG harvesting tapping motion. (e) and (f) Photograph showing that many LEDs were lighted up by tapping the water cushion and the rubber pipe with flowing water as the electrode. Reproduced with permission from Ref. [31], © Science 2016.

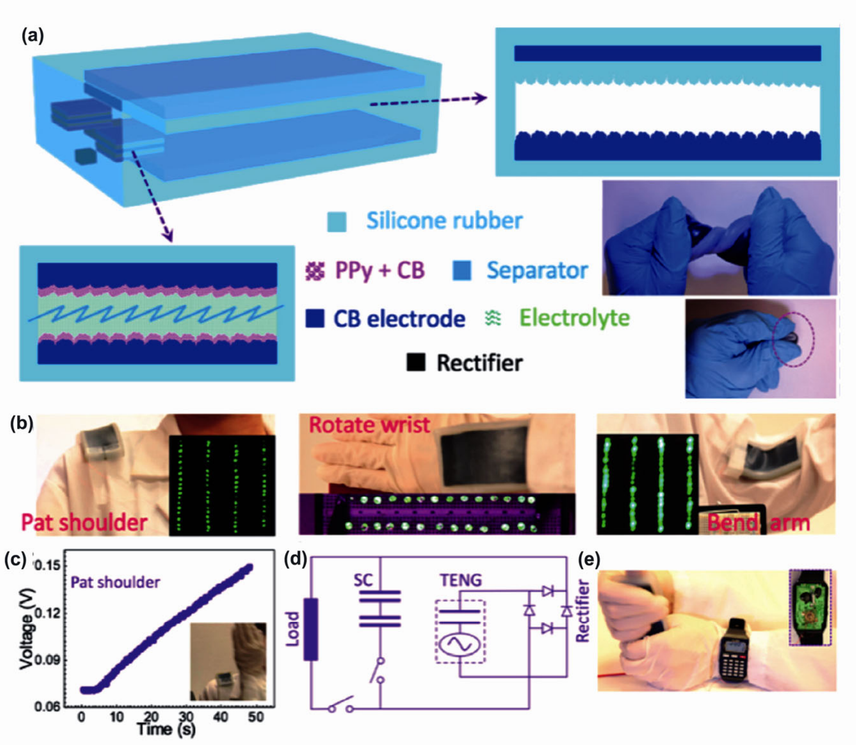

Figure 6 TENG-based self-charging power system for harvesting biomechanical energy. (a) Schematic diagram of the power system. (b) Demonstration of the TENG part harvesting energy from patting the shoulder, rotating the wrist, and bending the arm. (c) The charging curve by patting the shoulder. (d) Circuit diagram of the power system. (e) Photograph showing an electric watch driven by the self-charging power system. Reproduced with permission from Ref. [63], ©American Chemical Society 2016.

storage device. The power system provides continuous DC power of 1.044 mW with palm tapping as the only energy source. It can be used for continuously driving conventional electronics, including thermometers, wearable watches, scientific calculators and wireless radio-frequency communication systems.

For devices that operate in settings without access to a traditional power source, such as inside human body, of building even space, sustainable energy supply is essential to their long-term operation. However, the maintenance, replacement, and recycling of these power units, which are mostly batteries, remain a challenging or even impossible task due to the high cost and potential risk. The Zhang group provides a solution for these challenging issues. As demonstrated in Fig. 7(a), they designed and fabricated a fast soluble and recyclable TENG that is capable of efficiently harvesting mechanical energy from the environment to supply continuous power on the basis of triboelectrification and electrostatic effects [90]. After it exceeds its service life period, the TENG can be completely dissolved and removed within minutes with water. Additionally, after being dissolved, the TENG can be reproduced with the generated dissolution, realizing green electronics with zero environmental waste. The developed recyclable TENG provides a power solution for biomedical implants, environmental monitoring, and secure electronics.

Electromagnetic radiation generated from electronics is considered a heavy pollution that threatens human health. It is highly desirable and meaningful to incorporate electromagnetic shielding properties into micro and nano energy systems. The Zhang group developed an electromagnetic shielding hybrid nanogenerator composed of a TENG, a pyroelectric nanogenerator, and a piezoelectric nanogenerator, as shown in Fig. 7(d) [57]. It exhibits excellent electromagnetic shielding properties, which can shield more than 99.9978% of the electromagnetic radiation. The hybrid nanogenerator is capable of harvesting mechanical and thermal energy from the ambient environment.

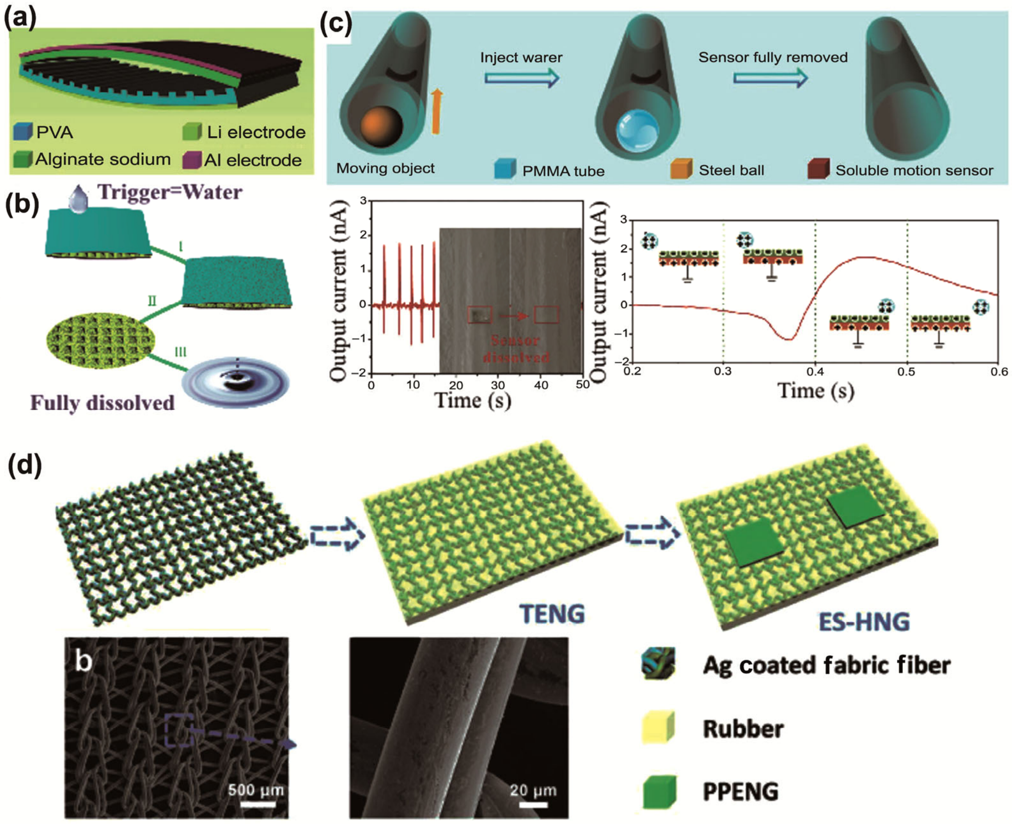

Figure 7 (a) Recyclable, green TENG. (b) Dissolution processes during the dissolution of each component. (c) Recyclable TENG to detect object motion inside a tube. (d) TENG-based electromagnetic shielding hybrid nanogenerator for harvesting biomechanical energy. Reproduced with permission from Ref. [90], © Wiley-VCH 2017; Ref. [57], © Wiley-VCH 2017.

3 TENG for self-powered active sensors

The TENG can transform mechanical motion into output electrical signals, and in turn, by analyzing the obtained signals, dynamic mechanical actions can be interpreted. In particular, no external power supply is required, which is a considerable advantage over other sensing techniques, as the sensing signals come from the output signals of the TENG. By correlating the mechanical input with the corresponding parameters, TENGs have been used in a wide range of sensing applications, including pressure sensors, vibration sensors, motion sensors, and chemical monitors. Self-powered active sensors based on TENG will strongly promote the construction of the Internet of Things.

3.1 Self-powered pressure sensors

A TENG generates output electrical signals when it is triggered by external mechanical stimuli. The magnitude and frequency of the mechanical stimuli can affect the output performance of the TENG. Thus, the external stimuli can be quantified by analyzing the corresponding output signals of the TENG. A TENG would be applied as self-powered pressure sensor based on this sensing principle [91, 92]. Fan et al. invented a transparent, flexible TENG as a self-powered pressure sensor, which is the first proof-of-concept prototype [93]. Through sensing relative deformation of the two polymer layers, the sensor was able to detect gentle pressure, such as a falling feather with a contact pressure of only 0.4 Pa. The sensor exhibited a high sensitivity of up to 0.31 kPa, a low detection limit of 2 Pa, and an excellent stability of over 30,000 cycles. Yang et al. proposed a similar design by integrating single-electrode TENG arrays for realizing pressure mapping. By using the power output from each TENG unit to light up the corresponding LEDs, a pressure distribution could be visualized [94]. High spatial resolution is a key factor of a pressure sensor to enable the perception of a pressure distribution. The Zhang group reported a TENG for high-resolution, self-powered pressure sensing by using conductive micron fibers as electrodes, which is demonstrated in Fig. 8(a) [23]. The resolution of the micron fibers is over 10 times higher than the mechanoreceptors in skin.

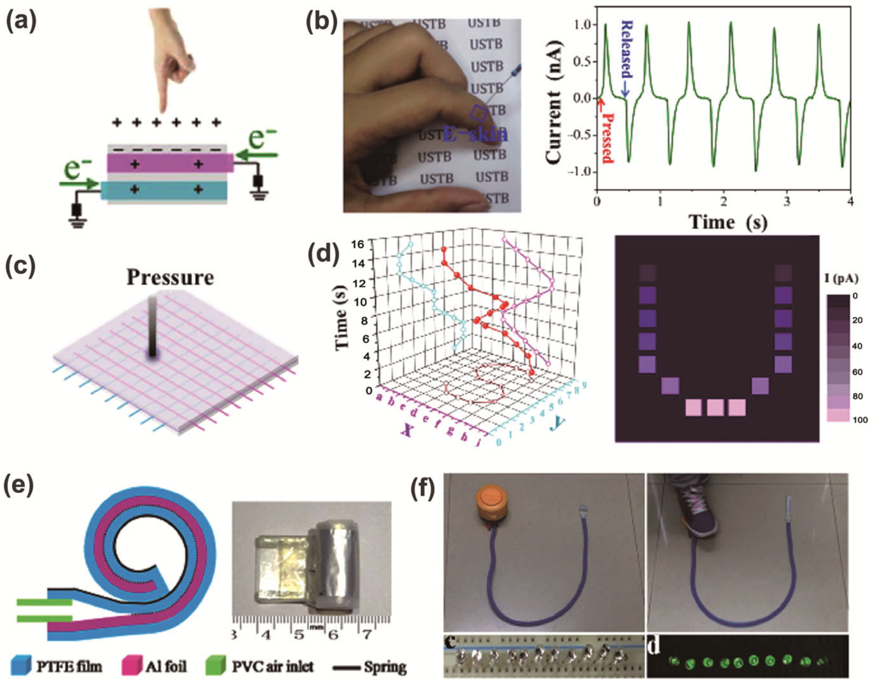

Figure 8 TENGs as self-powered pressure sensors. (a) Pressure sensing mechanisms of the high-resolution sensor. (b) Device on a human finger detects pressure through the steel tip. (c) TENG arrays detect the applied pressure information. (d) The measured tactile trajectory curve of the tip. (e) Schematic diagram of the self-recovering TENG. (f) A TENG used for pressure detection when an air pump is stepped on. Reproduced with permission from Ref [23], © Elsevier 2017; Ref [32], © Wiley-VCH 2015.

Due to its excellent flexibility, the device can be attached to most curved surfaces, including a human finger, or a beetle for tactile sensing purposes. The unique construction of the sensor brings about a significant reduction in the number of test channels from $N \times N$ to $2 \times N$, which greatly decreases the costs of measurement and monitoring.

To demonstrate the practical applicability of self-powered pressure sensors, Zhu et al. developed a wireless sensing system by integrating the TENG with a signal processing circuit [95]. The output power from the TENG was used to trigger a wireless transmitter for remote control of a siren alarm. Once a human hand touched the door handle, the sensing system immediately began operation. The sensing system can be adopted for a wide range of applications by using other functional electronics for the wireless transmitter. In addition, the Zhang group reported a novel self-recovering TENG to serve as an active multifunctional sensor, as indicated in Fig. 8(e) [32]. This TENG is self-recovering, and is able to roll because it is built with a spring. The output performance is approximately 251 V and 56 μA, corresponding to an output power of 3.1 mW. It can be utilized to detect multiple signals, including humidity level, airflow rate, and motion with fast response time (18 ms) and recovery time (80 ms). A wireless motion monitoring system was designed as a security system by integrating a self-recovering TENG with an air pump and LEDs. When the air pump is pressed with a foot, warning LEDs immediately light up.

3.2 Self-powered vibration sensors

Vibration, which is generated as a result of mechanical disturbance with the sources of wind, sound, engine and so on, is one of the most common phenomena existing in our daily life. Vibration detection is a useful sensing technology for monitoring machine operations, predicting disasters, and warning of security breaches. Building self-powered systems is an effective and practical method to maintain sustainable operations of sensor networks and mobile electronics without an external power supply. A few prototypes of TENG-based, self-powered vibration sensors have been developed. As shown in Fig. 9(a), the Zhang group reported on a self-powered vibration sensor based on a contact mode TENG [96]. The vibration sensor was able to detect under both contact mode and non-contact mode, which would protect the device and the detected objects from mechanical and chemical damage. The vibration sensor delivers a detection range of 0–500 Hz, high accuracy (relative error below 0.42%), and long-term stability (10,000 cycles). A lightweight, cost-effective integrated vibration sensor system was then fabricated for vibration monitoring with multiplexed operation by the contact electrification between the sensor and detected objects [97]. The as-fabricated sensor system shown in Fig. 9(d) is capable of monitoring and mapping the vibration state of a large number of units. The monitoring content includes on-off states, vibrational frequency, and the vibration amplitude of each unit. The active sensor system has great potential for remote operation, automatic control, surveillance, and security systems.

Acoustic waves are a special form of vibration existing in the ambient environment. The detection of acoustic waves is extremely important for information technology and environment monitoring. The TENG has provided an effective method for achieving self-powered acoustic sensing. Yang et al. were the first to develop a single-electrode-mode TENG as a self-powered acoustic sensor, which was composed of a Helmholtz cavity with a size-tunable narrow neck on its back [98]. The cavity structure would cause oscillation of the PTFE film in response to an external sound wave. This acoustic sensor has high sensitivity of 51 $\text{mV}\cdot\text{Pa}^{-1}$, a lower pressure detection limit of 2.5 Pa, a fast response time of less than 6 ms, and a frequency range from 0.1 to 3.2 kHz. The sensor can pick up and recover human vocalizations even in an extremely noisy environment. This work has a substantial range of applications in fields that include intruder detection, military surveillance, sniper localization, and underwater acoustics. Moreover, Fan et al. developed an ultrathin, rollable paper-based TENG for self-powered sound recording [99]. Under a sound pressure of 117 dB, the TENG could produce a maximum power density of 121 $\text{mW}\cdot\text{m}^{-2}$. Its novel structure enabled it to harvest acoustic energy to power portable electronics and to charge a capacitor at a rate of 0.144 $\text{V}\cdot\text{s}^{-1}$. The TENG was demonstrated to serve as a microphone for sound recording.

3.3 Self-powered motion sensors

Motion detection is of cardinal significance in various applications like automatic control, robotics, and surveillance. Recently, efforts have also been devoted to using the

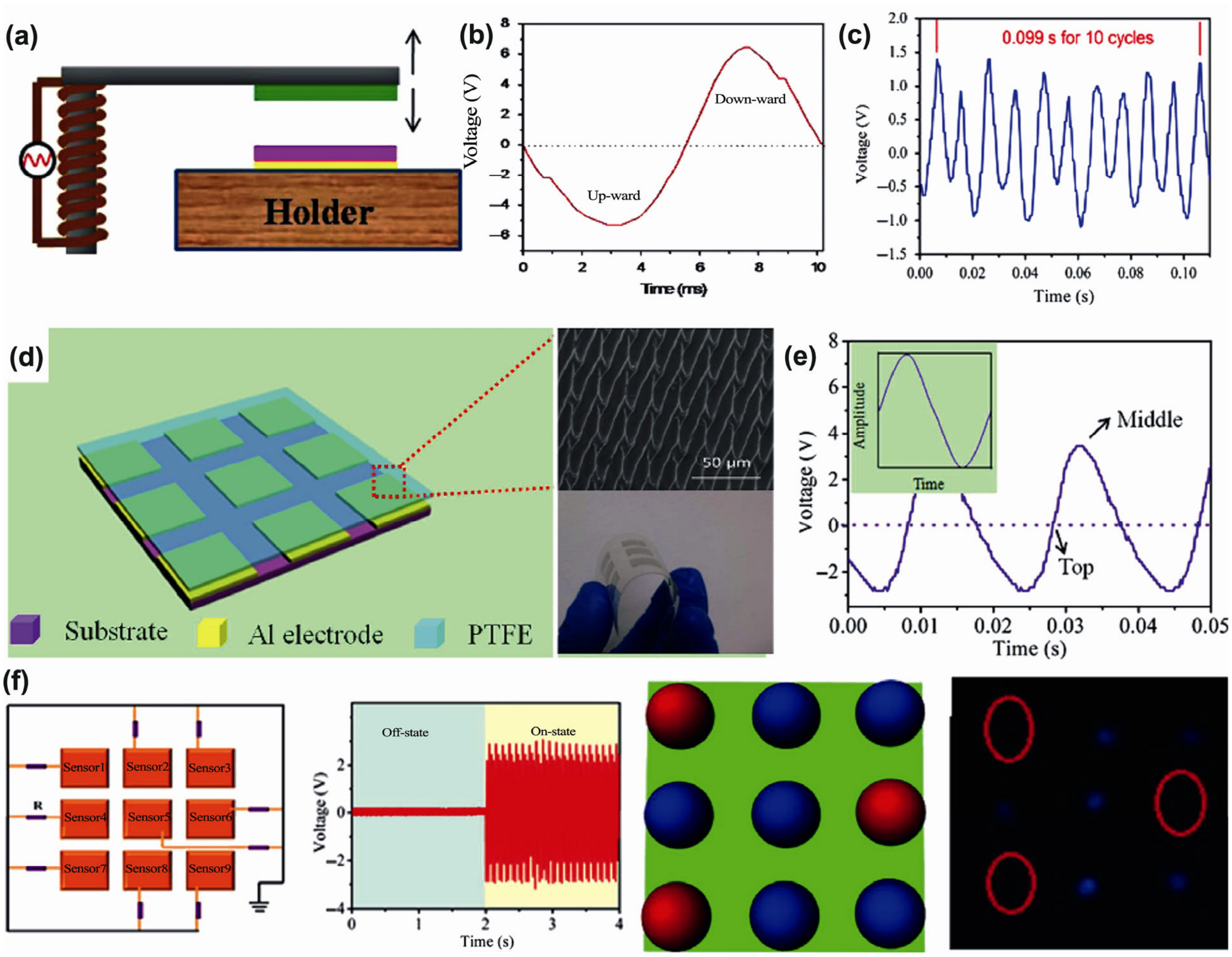

Figure 9 TENGs as vibration sensors. (a) A TENG as vibration sensor with contact and non-contact modes. (b) Output voltage of the TEG during one cycle. (c) Output voltage of the TENG for detecting vibrations of an ultrasonic cleaner. (d) Integrated vibration sensor system. (e) Output voltage for different loading processes. (f) On-off state monitoring and working amplitude monitoring of nine vibrating units. Reproduced with permission from Ref. [96], © Elsevier 2015; Ref. [97], © Nature Publishing Group 2015.

TENG as a self-powered motion sensor to instantaneously monitor parameters of motion and trajectory. Su et al. fabricated a series of single-electrode tube structure TENG for one-dimensional motion sensing. The TENG consists of a tube-shaped PTFE thin film and copper electrode arrays for tracking the real-time speed and location of a steel ball moving inside the tube [100]. The Zhang group reported on a multifunctional two-dimensional (2D) motion sensor by using single-electrode-mode TENG arrays [101]. As depicted in Fig. 10(a), the movement of an object on the top surface of a PTFE layer induces changes in the electrical potential of the patterned aluminum electrodes underneath. The 2D motion sensors can detect the trajectory, velocity, and acceleration of moving objects in two dimensions. Moreover, the TENG can detect the motion of more than one object moving at the same time. Visualization of the movement of a sliding object and the steps of a person can be realized by integrating the self-powered sensor with LEDs. This work opens up new perspectives for visualized motion motoring. A high-resolution motion sensor was fabricated by Han et al. for velocity, acceleration, and trajectory tracking by visual observation [102]. According to a simple electrode weaving method, a high-resolution sensor with 41 × 41 pixels at a size of 1 cm × 1 cm was obtained, which could detect a tiny displacement of 250 μm.

In order to better adapt to the detection of human behavior, the Zhang group developed a self-powered flexible and wearable body motion sensor by using a new type of stretchable rubber-based TENG [19]. It consisted of a layer of elastic rubber and a layer of aluminum film that acted as the electrode, as shown in Fig. 10(c). By stretching

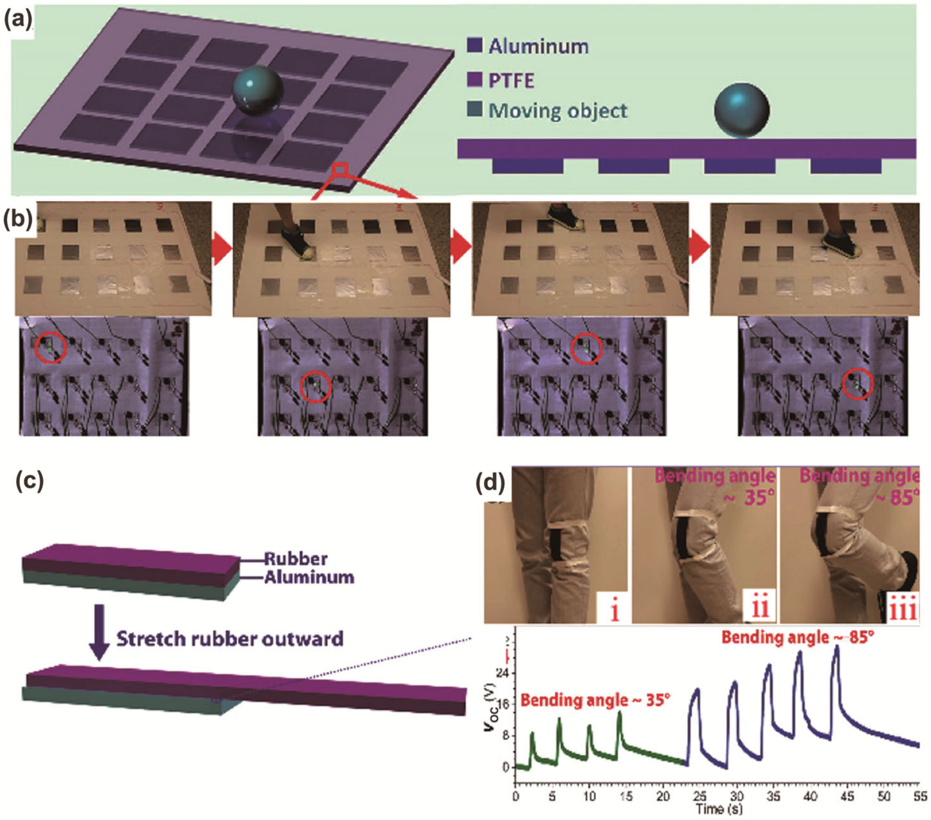

Figure 10 TENGs as self-powered motion sensors. (a) A single-electrode-based TENG to detect the movement of a moving object. (b) Demonstration of the TENG for monitoring human feet while walking. (c) Stretchable-rubber-based TENG as self-powered body motion sensors. (d) Applications of the TENG to detect joint motion. Reproduced with permission from Ref. [101], © Wiley-VCH 2014; Ref [19], © Wiley-VCH 2015.

and releasing the rubber, the changes in triboelectric charge distribution and density on the rubber surface induce alterations in the electrical potential of the aluminum electrode, leading to an alternating charge flow in the external load. It is capable of detecting movements in different directions by integrating the devices into a sensor system. The sensor can be attached to a human body to detect diaphragm breathing and joint motion. Wearable motion sensors that can detect direction, breathing, and joint motion are very important for the diagnosis of disease and medical treatment.

3.4 Self-powered chemical sensors

Triboelectric charge density on the material surface can determine the output performance of a TENG. Chemical species absorbed on the materials' surface or changes in environmental factors will affect the triboelectric charge density, which changes the output performance of the TENG. Hence, the TENG can serve as a self-powered chemical sensor for detecting ion concentration, UV illumination, and so forth. Lin et al. designed an Au nanoparticle (NP)-based TENG as a self-powered Hg^{2+} ion sensor [103]. As shown in Fig. 11(a), through modification of the 3-mercaptopropionic acid molecule on assembled Au NPs, the TENG can become a highly selective Hg^{2+} ion detector due to the different triboelectric polarities of Au NPs and Hg^{2+} ions. The TENG has a detection limit of 30 nM and linear range from 100 nM to 5 μM. A self-powered chemical sensor was demonstrated by Lin et al. [104] for phenol detection, as schematically depicted in Fig. 11(c). A contact-mode TENG structure is selected, which consists of PTFE thin film coated with a copper electrode and Ti foil with TiO_2 nanowires on the surface. Then β-cyclodextrin (β-CD) was assembled onto the TiO_2 nanowires to act as a surface chemical modifier, which can effectively detect phenol molecules in aqueous solution. The output voltage decreased linearly with increasing phenol concentration in the range of 10–100 μM.

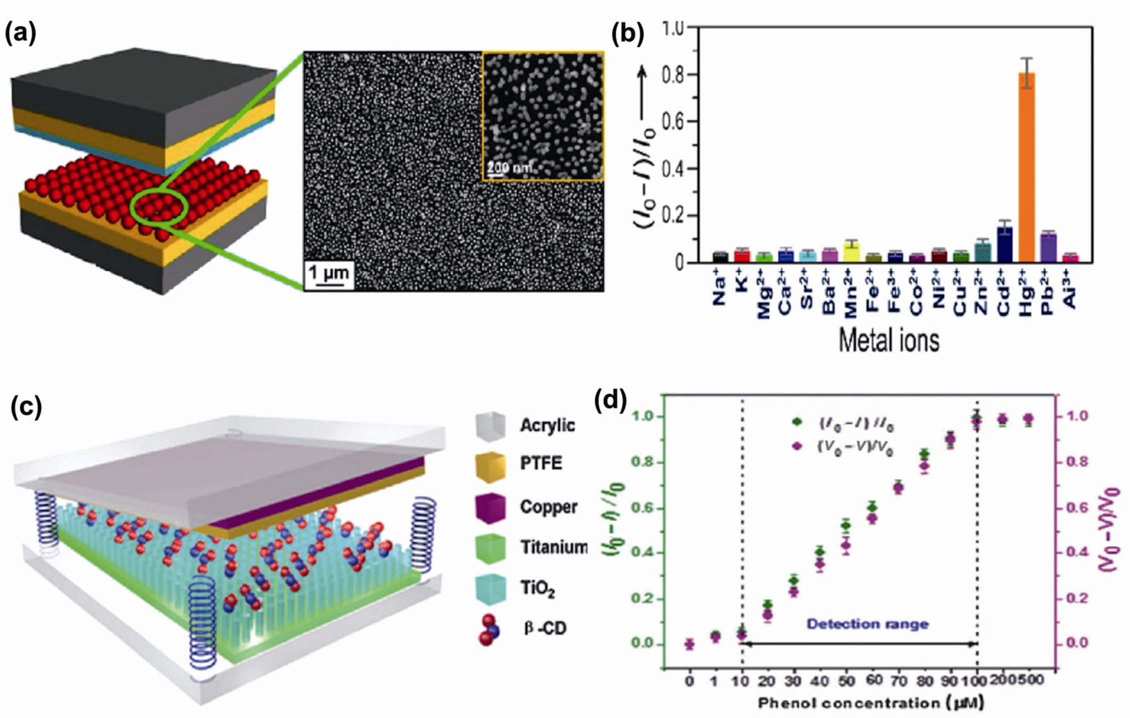

Figure 11 TENGs as self-powered chemical sensors. (a) A TENG as a self-powered chemical sensor for detecting Hg^{2+} ions. (b) Sensitivity and selectivity of the TENG for Hg^{2+} ions detection. (c) β-CD improved TENG for self-powered phenol detection and electrochemical degradation. (d) The sensitivity and detection range of the TENG for phenol detection. Reproduced with permission from Ref. [103], © Wiley-VCH 2013; Ref. [104], © Royal Society of Chemistry 2015.

The TENG was also used for self-powered electrochemical phenol degradation due to its high output performance. This work can be extensively applied in various areas, such as wastewater treatment, environmental degradation, ecological sanitation, and assessment.

4 Summary and perspectives of TENG

Since its first invention in 2012, the TENG has experienced a very rapid development both in fundamental understanding and technological improvements. Research areas that have been developed in depth include fundamental theory, efficiency enhancement, hybridization, multifunctionality, system integration, and service behavior. Through this research, the TENG has made great progress on many fronts. In particular, the understanding of the fundamental theory of TENG has gradually deepened, and the output performance of the TENG was enhanced significantly. Areas of TENG applications have expanded day by day and are moving to the commercialization.

The invention of the TENG is a major milestone in the field of energy harvesting. After rapid development, the TENG as a new energy harvesting technology is gradually moving towards practical application. In the future, the TENG may serve not only as a sustainable micro-scale power source for small electronic devices to achieve self-powering, but may also harvest water energy, advancing the frontier of blue energy. Furthermore, the TENG can be a self-powered active sensor focused on areas of the human-machine interface, intelligent sensing, and security systems, etc. Thus the TENG will make great breakthroughs in key technologies for the Internet of Things, which is an unavoidable tool connecting everyday objects and facilitating human life progress. In order to promote the development and application of the TENG, more work must be done to ensure its commercialization in the future.

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