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Triboelectric nanogenerators enabled internet of things: A survey

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Abstract: As pioneering information technology, the Internet of Things (IoT) targets at building an infrastructure of embedded devices and networks of connected objects, to offer omnipresent ecosystem and interaction across billions of smart devices, sensors, and actuators. The deployment of IoT calls for decentralized power supplies, self-powered sensors, and wireless transmission technologies, which have brought both opportunities and challenges to the existing solutions, especially when the network scales up. The Triboelectric Nanogenerators (TENGs), recently developed for mechanical energy harvesting and mechanical-to-electrical signal conversion, have the natural properties of energy and information, which have demonstrated high potentials in various applications of IoT. This context provides a comprehensive review of TENG enabled IoT and discusses the most popular and significant divisions. Firstly, the basic principle of TENG is re-examined in this article. Subsequently, a comprehensive and detailed review is given to the concept of IoT, followed by the scientific development of the TENG enabled IoT. Finally, the future of this evolving area is addressed.

Key words: Triboelectric Nanogenerator (TENG); Internet of Things (IoT); energy harvesting; sensing system; smart cities

1 Introduction

The Internet of Things (IoT) has attracted tremendous attention from both academia and industry since it was firstly proposed by Kevin Ashton in 1999[1–3]. With the help of sensing, communication, and computing techniques, IoT has brought significant changes and revolutions to many traditional areas, such as healthcare[4–7], transportation[3,8], smart cities[9–11], the industrial Internet[12–14], smart grid[15–17], and so on. Achieving the ultimate goal of IoT, which connects everything from anywhere at any time, it will depend on the large-scale deployment of massive sensors. This, however, poses vital challenges to the existing sensor techniques, for example, how to provide sustainable and stable power supplies to the distributed massive sensors, how to further improve the sensor performance while lowering the costs, etc.[18,19]

To tackle the above-mentioned issues, many researchers worldwide have made great efforts and achieved fruitful results. For the power supply part, the lithium battery and supercapacitor techniques have dramatically increased the energy storage density and hence improved the working life for IoT sensing systems[20,21]. Moreover, the ambient energy harvesting techniques, including solar

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cell[22], electromagnetic generators[23,24], piezoelectric generators[25,26], electrostatic generators[27], radio-frequency energy harvesters[28,29], and so on, are utilized to work as promising alternatives or complements to the batteries. For the sensor part, the recent developments of the Micro-Electro-Mechanical System (MEMS) techniques have significantly reduced the sensor cost as well as size, enabling the dense deployment[30,31].

Nevertheless, conventional methods usually consider power supply and sensing as two separate tasks, which can be better realized in a more synergic way, especially in mechanical applications. The Triboelectric Nanogenerator (TENG), invented by Fan et al.[32] in 2012, has emerged as a promising mechanical-to-electrical conversion method by coupling the triboelectrification and electrostatic induction. As a new energy harvesting technique, the TENG has many desirable features, including low cost, structural versatility, robust electrical production[33,34], high efficiency in energy conversion[35–37], flexibility[38,39], and environmental-friendliness[40–43]. Various TENG structures have been designed to capture ambient mechanical energy from wind[44,45], water waves[46–50], vibrations[51–54], and biomechanical movements[55–59]. Also, TENGs have been adopted for realizing self-powered sensors for pressure[60–62], motion[63–65], vibration[66–69], wind[70–72], wave[73], biomedical information[74–77], and chemical substance[78–80]. Moreover, the electric energy converted and enhanced by the TENGs can also be used to boost power management circuits[37,81,82], facilitate signal processing techniques in the sensor network[83–86], and transmit power and information wirelessly[87–90] across devices. In conclusion, the TENG is very suitable for IoT applications due to the intrinsic capabilities in both energy harvesting and sensing.

After eight-year explosive development, TENGs have been adopted in many energy and sensing applications as well as demonstrated great potential in the IoT field, as shown in Fig. 1. In this context, we provide a comprehensive summary of TENG enabled IoT and discuss the most popular and significant divisions. The following sections firstly offer the fundamental theory of TENG and the basic concepts of IoT. Then, the research progress of TENG enabled IoT is outlined by category and analyzed in-depth. Finally, future research trends and potentials in this field are highlighted and discussed.

2 Fundamental

This section briefly reviews the theory, model, and four working modes of TENG as well as the definition of IoT, which serve as the theoretical basis of the entire paper.

2.1 Theory and model of TENG

Triboelectrification, while being observed and studied over centuries, was usually considered to be a negative effect which needs to be avoided via certain designs, such as in the electronics, gasoline transportation, etc. Such a traditional view has been completely turned around since the TENG was invented by Fan et al.[32] in 2012. The first TENG module adopts the contact separation design, which covers a Polyester (PET) film and Kapton film with back electrodes (Fig. 2a), contact separation design is still the mainstream alternatives[32]. After triboelectrification, the module can produce the Alternating Current (AC) output once there is a variation in the interfacial properties due to electrostatic induction effect. The widely used equivalent circuit model of TENG is the capacitance-voltage source model proposed by Niu and Wang[91], which adopts the basic circuit elements while simplifies the performance simulation with acceptable accuracy. Figure 2b demonstrates the basic model of a TENG in contact-separation-mode[92], where V is the output voltage of TENG, $C(z)$ is the capacitance that varies with the gap distance z, Q is the amount of electric charges, and $V_{\mathrm{OC}}(z)$ is the open circuit voltage term, which can be considered as an ideal voltage source, its value changes with respect to z. Recently, the fundamental basis of TENG is found to be part of the Maxwell's displacement current, and the device output is directly related to the surface polarization-induced current term denoted by $\partial \boldsymbol{P_S}/\partial t$ as illustrated in Fig. 2c[92], where $\boldsymbol{J_D}$ is the displacement current, $\boldsymbol{D}$ is the displacement field, ε is the medium permittivity, $\boldsymbol{E}$ is the electric field, and $\boldsymbol{P_s}$ is the polarization contributed by surface polarization charges. Building on these concepts, Dharmasena et al.[93–95] recently presented the Distance-Dependent Electric Field (DDEF) model, which comprehensively describes the

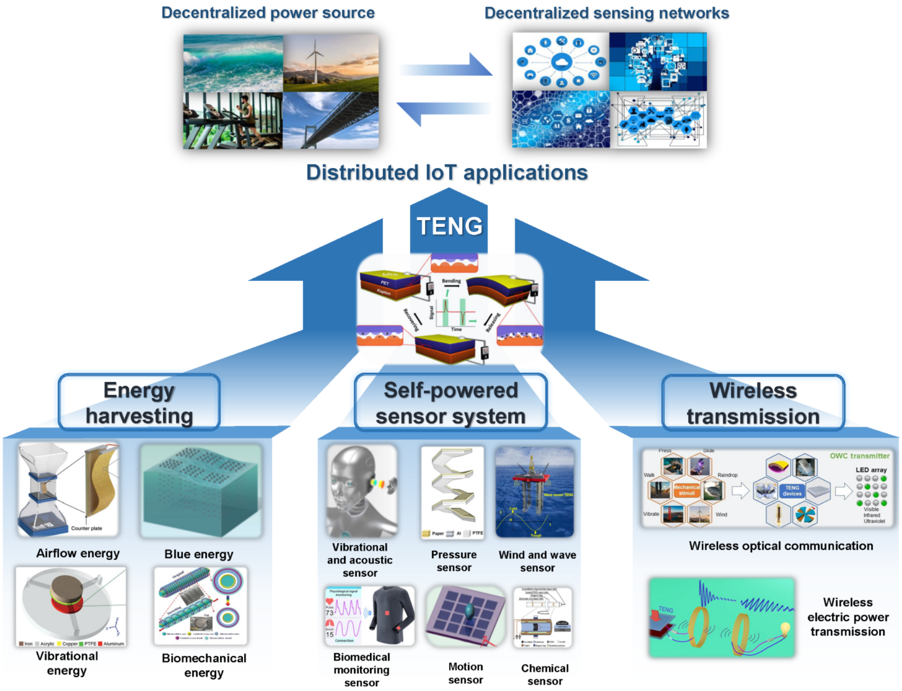

Fig. 1 Schematic diagram illustrates the ideal paradigm of distributed IoT applications with sustainable TENG systems. Three major technologies support the TENG-based decentralized power source and sensing networks for IoT applications. Reproduced with permission[45]. Copyright 2014, Springer Nature. Reproduced with permission[46]. Copyright 2017, Springer Nature. Reproduced with permission[52]. Copyright 2014, John Wiley and Sons. Reproduced with permission[55]. Copyright 2018, John Wiley and Sons. Reproduced with permission[68]. Copyright 2018, The American Association for the Advancement of Science. Reproduced with permission[60]. Copyright 2015, American Chemical Society. Reproduced with permission[73]. Copyright 2019, Elsevier. Reproduced with permission[74]. Copyright 2020, American Chemical Society. Reproduced with permission[63]. Copyright 2014, John Wiley and Sons. Reproduced with permission[78]. Copyright 2020, Elsevier. Reproduced with permission[87]. Copyright 2018, Elsevier. Reproduced with permission[90]. Copyright 2020, Springer Nature.

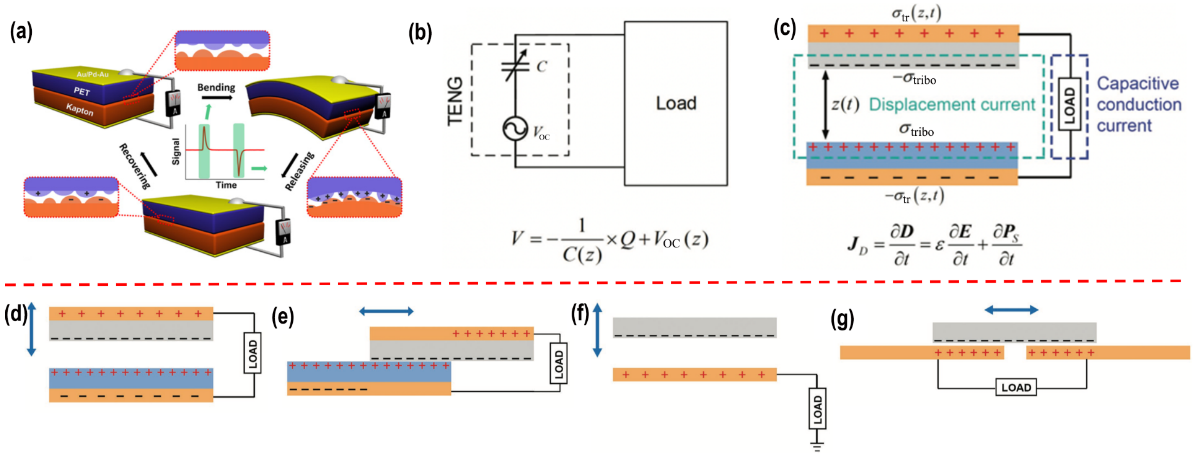

Fig. 2 (a)–(c) Fundamental models of TENG. (a) Structural design and working loop of the first TENG. Reproduced with permission[32]. Copyright 2012, Elsevier. (b) Corresponding electrical circuit design of TENG[92]. Copyright 2019, John Wiley and Sons. (c) Displacement current model of TENG with a vertical CS mode[92]. Copyright 2019, John Wiley and Sons. (d)–(g) Fundamental operating modes of TENG: (d) Vertical CS mode, (e) LS mode, (f) SE mode, and (g) FT mode. Reproduced with permission[92]. Copyright 2019, John Wiley and Sons.

electric field behavior, polarization, and output induction of the triboelectric nanogenerators, corresponding to the relative movements of triboelectric surfaces.

As an efficient mechanical-to-electrical conversion mechanism, TENG has seen tremendous advancement and various practical applications, such as power sources and self-powered sensing devices. Besides, with the fast development in this field, a systematic framework comprising fundamental working modes, system design, structures, resistance materials, the figure of merit, and so on, has been established[37, 38, 82, 94, 96–111].

2.2 Four working modes of TENG

TENG has four basic working modes, including the vertical Contact-Separation (CS) mode, Lateral Sliding (LS) mode, Single-Electrode (SE) mode, and Freestanding Triboelectric-layer (FT) mode, as illustrated in Fig. 2. The vertical CS mode could harvest the mechanical stimuli which are vertical to the device surface, and the space gap between device surfaces determines the potential difference between the electrodes, hence, the extrinsic current flows[112, 113]. The LS mode, which can be implemented by a rotation-induced sliding into a compact container, requires the lateral movement alongside the surface[114, 115]. The SE mode, which uses the ground as the reference electrode, is therefore efficient in collecting energy from a moving device without the need for an electric conductor, such as vehicle movement, walking, and finger-typing[116]. The FT mode has been established upon the single-electrode system. Still, it requires a pair of symmetric electrodes, and the electric production from the asymmetric charge distribution is caused by the movement of the freestanding triboelectric-layer[117, 118]. More recently, a new type of Direct Current TENG (DC-TENG) based on air breakdown effect has been reported and fast developed[119–121]. The air breakdown DC-TENG demonstrates intrinsic rectification-free and switching features, which tremendously simplify the power management requirements, and thus improving the system power efficiency.

The fundamental theory and conceptual structures of all four modes were thoroughly investigated in preceding papers, and hence, are not discussed in-depth here due to the space limit[91]. Additionally, it should be noted that in practice, TENGs, instead of operating at merely a single mode, are more reliant upon merging or hybridizing multiple modes for better adaptability and efficiency. For this reason, the implementation of TENG enabled IoT will be addressed in the next section based on application circumstances, rather than according to the operation modes.

2.3 Definition of IoT

IoT is commonly delineated as an interlinked and global network architecture with standardized and interoperable communication protocols to achieve self-configuring functionality. Different from the traditional networks, there are both physical and virtual objects with personalities and properties in IoT, enabling it to utilize smart interfaces and built as an information network[122–124]. Specifically, IoT involves numerous technologies ranging from hardware to software, including energy harvesting, sensing, computing, communications, networking, data collecting, storage, processing and analyzing, and many others[125, 126]. With the help of such techniques, IoT has been widely adopted and brought breakthroughs to many traditional fields, for example, healthcare[4–7], transportation[3, 8], smart cities[9–11], industrial Internet[12–14], smart grid[15–17], and so on. Consequently, potential challenges and future research perspectives have arisen accordingly.

In this paper, we provide a comprehensive review of the TENG enabled IoT applications from three perspectives. Firstly, the energy harvesting part will review the recent research progress on the TENG-based wind, wave, vibrational, and biomechanical energy harvesters as well as the corresponding power management techniques, which reveal the possibility of TENG to work as the alternatives to the IoT power supplies. Secondly, the sensing part will discuss the TENG-based self-powered sensors, including the pressure, motion, vibrational and acoustic sensors, wind and wave sensors, biomedical monitoring sensors, and chemical sensors as well as the functional and integrated sensing system in human-machine interfacing with advanced signal processing technology, which indicates the potential of TENG in the IoT sensing areas. Thirdly, wireless power transfer and information transmission research based on TENG is briefly reviewed as a new technological trend.

3 Application of TENG in IoT

3.1 TENG-based mechanical energy harvesting

(1) Wind energy

The wind is one of the greenest and ubiquitous energy sources in the world[127–129]. It is found by researchers that 1700 TW of wind power is available at 100 m above earth surface and that 80 TW could be harvested in a cost-effective and practical manner[130, 131]. The conventional windmills based on the electromagnetic generator are usually equipped with large wind blades and require a relatively high wind speed to start, which have limitations for small-scale and portable applications.

In 2014, Bae et al.[45] proposed a flutter-driven TENG utilizing the electrification of touch triggered by self-supporting flag oscillation, as demonstrated in Fig. 3a. Through analyzing the relationship between a fluttering extendable flag and a solid plate, three different contact types were identified: chaotic, double, and single. The proposed devices, minimized the scales to 7.5 cm × 5 cm and working with a low wind speed of 15 m/s, reported high power outputs: instant peak voltages of 200 V as well as a 60 mA current at a frequency of 158 Hz, which produced a power density of around 0.86 mW on average. Following this work, a circular-shaped TENG system was constructed with five TENGs packed to take in NO_x instantaneously and reduce its primary nitrate and nitrate enrichment into the aqueous solution, which is shown in Fig. 3b[44]. The device also had intrinsic phase variations and constant direct current energy outputs after rectification. Furthermore, Han et al.[44] verified that NO_x produced by a chemical process was effectively reduced by the TENG mechanism, powered by artificial wind flow at a velocity of 6 m/s. Zhang et al.[132] also developed a single electrode cylindrical TENG for rotational energy harvesting. A self-powered meteorological monitoring device was developed through integration with a wind sensor, as shown in Fig. 3c. This research pioneered a new method to turn wind energy into electric power, which could be converted into a meteorological forecasting network in remote regions without using inefficient external power supplies or batteries.

(2) Wave energy

Since 71% of the earth's surface is covered with water, water wave energy is another abundant energy source and could solve the sustainable power supply problem of the Internet of Underwater Things (IoUT)[133–135]. Similar to the wind energy case, the traditional water turbines are of large sizes and high costs and have to be built over the seabed, making it difficult to be distributed to small-scale deployment. As an advanced energy harvesting system, the TENG has appealing features, especially when converting low-frequency mechanical energy into electricity, creating new possibilities for capturing water

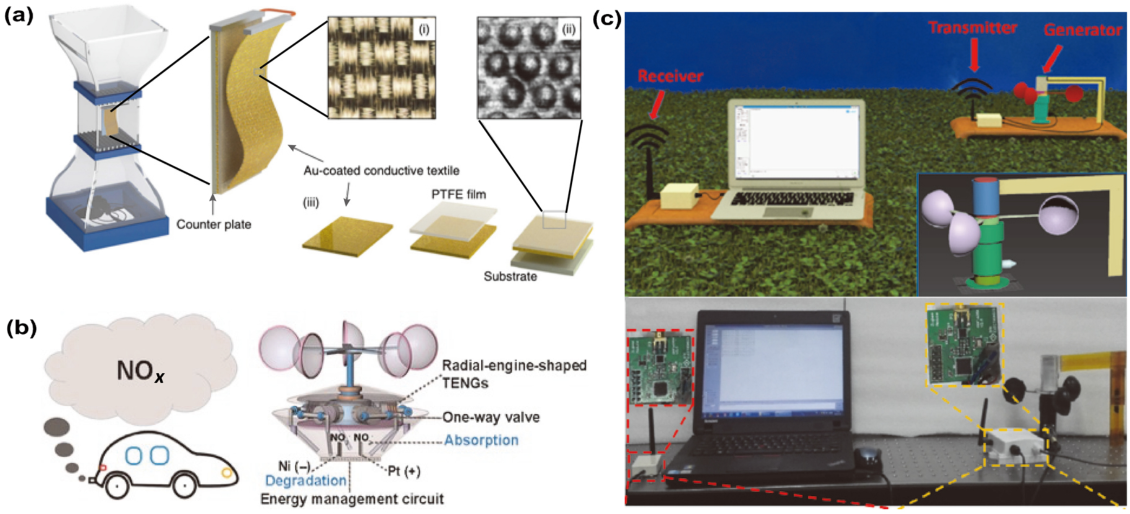

Fig. 3 TENG as the wind energy harvester for IoT applications. (a) Structural design of a wind tunnel and the system architecture of a flutter-driven triboelectric generator with surface characteristics of (i) an extremely flexible flag, (ii) a counter plate, and (iii) counter plate fabrication. Reproduced with permission[45]. Copyright 2014, Springer Nature. (b) Structure design of the self-powered radial-engine-shaped TENG system driven by wind power. Reproduced with permission[44]. Copyright 2020, American Chemical Society. (c) Schematic diagram and a real photo of the TENG-based self-powered system. Inset: the illustration of the TENG manufactured with a commercial wind sensor. Reproduced with permission[132]. Copyright 2016, American Chemical Society.

wave energy effectively on a small scale[136].

As Fig. 4a demonstrates, a fundamental module of the TENG network has been researched and designed by Jiang et al.[50] in 2015 for the architectural optimization of wavy configured TENG. Through integrating theoretical model computation and laboratory experiments, they discovered optimal ball volume or weight to achieve maximum energy efficiency and electrical output. Furthermore, in 2017, Xu et al.[47] demonstrated an optimized TENG system, based on air-driven membrane architectures, as shown in Fig. 4b. The paper introduced the innovative models of a spring-lift oscillator design and a framework utilizing air pressure for the transmission and delivery of gathered water wave power. Besides, in 2019, Wu et al.[48] presented the hybridized Water Wave Energy Harvester (WWEH) centered on an electromagnetic sphere, which is illustrated in Fig. 4c. The water flow was detected by a flexible rotating electromagnetic sphere to force the traction subject, moving back and forth on a firm TENG surface. With the WWEH set on a test buoy in Lake Lanier, the supercapacitor could be powered to 1.84 V over 162 s, with the electrical power capacity at around 1.64 mJ. Following the elegant design of the above work, in 2020, Feng et al.[49] developed an internal swinging system for efficient wave accumulation of power for cylindrical TENG, as seen in Fig. 4d. The rotational dielectric films can be suspended over stator electrodes centered on the supportive impact of the bearing components rather than in direct contact with

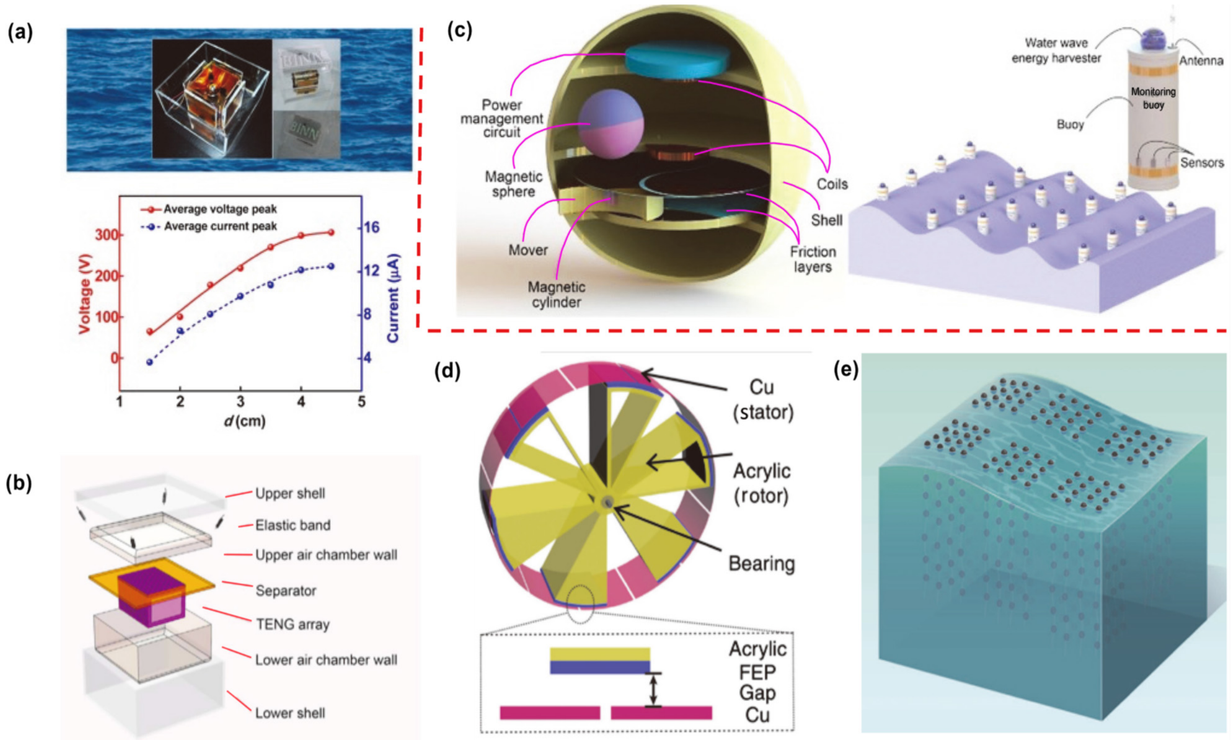

Fig. 4 TENG as the wave energy harvester for IoT applications. (a) The upper side is an image of an as-made TENG system for water wave power retrieval and the unit floating on water and digital pictures of 70 wave-driven Light-Emitting Diodes (LEDs). At the bottom is the relation between the average maximum and the present maximum voltage with ball volume. Reproduced with permission[50]. Copyright 2015, American Chemical Society. (b) An exploded structure picture of the TENG device array. Reproduced with permission[47]. Copyright 2017, Elsevier. (c) Structural design and diagram of the Water Wave Energy Harvester (WWEH). The left side is the schematic illustration of the WWEH. The right side is the structure design of the WWEH-based buoy system for environmental and ecological monitoring. Reproduced with permission[48]. Copyright 2019, American Chemical Society. (d) Schematic TENG diagrams composed of two key components, an FEP-film rotor and a Cu-electrode acrylic shield. The zoom-in image reveals a distance between the FEP film and Cu electrodes. Reproduced with permission[49]. Copyright 2020, American Institute of Physics. (e) A blue energy network implemented by TENG. Reproduced with permission[46]. Copyright 2017, Springer Nature.

them.

In principle, a light bulb can be powered by 1000 devices distributed at an interval of 10 cm in a cubic meter. Wang[46] approximated that today's global energy power demand can be achieved by filling a marine region of the US state of Georgia with a 3D nanogenerator array system distributed 10 cm apart and 10 m deep below the surface. The vital power generated by TENG underwater will undoubtedly act as a significant power supply for IoT.

(3) Vibrational energy

Vibrational energy harvesting and sensing happen to be a conventional but rising area of research where diverse structures and technologies for enhancing performance have been created. TENG has been used to revitalize the field of vibration energy harvesting, in particular for vibrations with low frequency, such as humanoid movements[137], vehicles[138], machinery[139], and bridge vibrations[140]. The instantaneous power conversion efficiency of 70% and overall efficiency of up to 85% have differentiated TENG from conventional vibration energy harvesters.

In 2014, Yang et al.[52] proposed a 3D-TENG hybridization mechanism, in which the vertical CS mode and in-plane sliding mode are integrated, as illustrated in Fig. 5a. The revolutionary architecture allows the spontaneous accumulation of vibrational power across a broad spectrum in different directions. Through outboard and in-plane excitation, average energy densities of 135 and 145 mW/m^2 were obtained, respectively. As shown in Fig. 5b, where m_0 indicates mass of brass, acrylic, and aluminum block; m_1 indicates mass of brass block; and m_2 indicates mass of aluminum block. Wu et al.[54] invented a TENG incorporating a hydraulic spring-based enhancer, which amplified the vibration rate and amplification to boost its low-frequency output by up to 10 times.

Inspired by the previous work, a system was

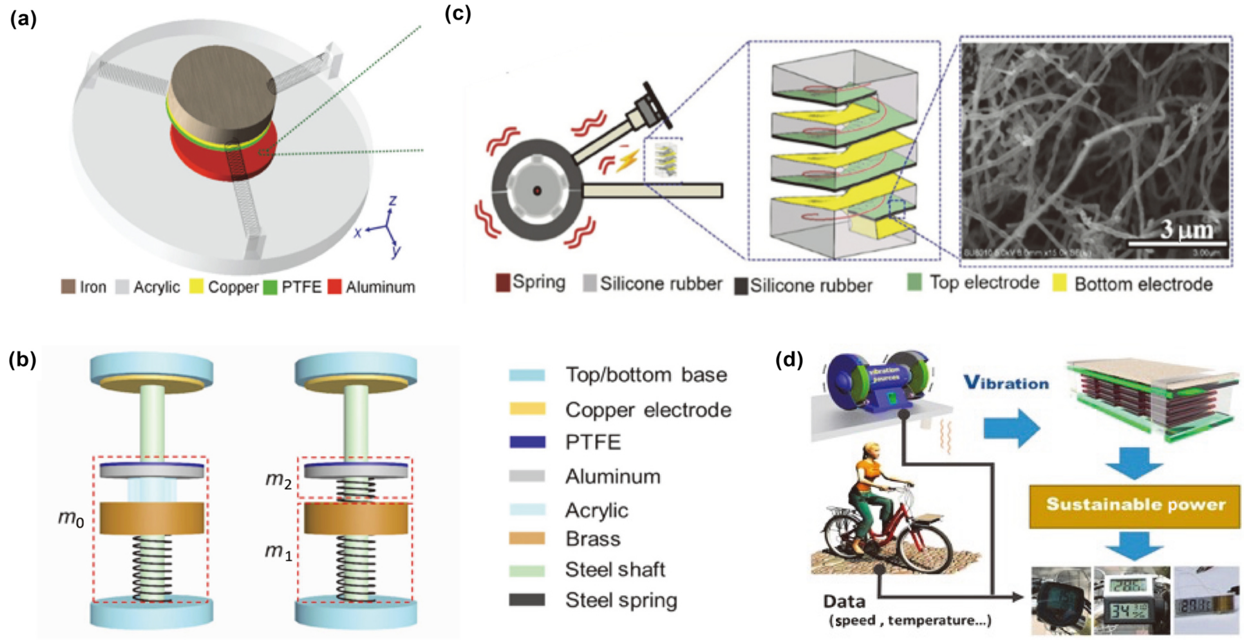

Fig. 5 TENG as the vibrational energy harvester for IoT applications. (a) Schematic diagram of a 3D TENG. Reproduced with permission[52]. Copyright 2014, John Wiley and Sons. (b) Single-spring Resonator (SR)-TENG and Mechanical Amplifier-assisted (MA)-TENG system architecture. The left side is the basic configuration of the TENG with the single-spring resonator. The TENG with the mechanical amplification on the right is composed of two springs. Reproduced with permission[54]. Copyright 2017, Elsevier. (c) Schematic illustration of the S-TENG. The right side is a Scanning Electronic Microscopy (SEM) image of the carbon nanofiber for preparing the elastomeric electrode. Reproduced with permission[53]. Copyright 2018, John Wiley and Sons. (d) Structural design of the fabricated multiunit TENG at the top right corner. The left side is a schematic of a vibration-energy storage device based on the power from a working grinder and cycling. Feasible applications display in the right-hand corner for speedometer, moisture, and digital temperature monitor. Reproduced with permission[51]. Copyright 2017, American Chemical Society.

demonstrated by Xu et al.[53], which relied on Spring TENG (S-TENG) that works in contact separation state during vibration, as shown in Fig. 5c. Under the S-TENG's resonant conditions, the optimum energy density was 240 mW/m^2 as well as 45 mW/m^2 with an external load of 10 MΩ and an acceleration of 23 m/s^2. Furthermore, a rationally engineered elastic TENG multiunit was built, as Fig. 5d illustrates, which had an instant peak energy density of 102 mW/m^3 at a minimum capacity of 7 Hz and sustained a constant output current of 5–25 Hz[51]. A Self-Changing Power Unit (SCPU) integrated with a 10 mF supercapacitor, generates a consistent Direct Current (DC) power of 1.14 mW with an output efficiency of 45.6% at 20 Hz. With such a specially constructed energy management system, the SCPU's output can be further increased, with a consistent DC power of 2 mW and a power management efficiency of 60% at 7 Hz. The vibration energy obtained from a riding bicycle or machine can sustainably power electronics including speedometer, hygrometer, thermometer, and more[51]. Therefore, the aforementioned method has practical applications in self-powered systems for transportation, machine safety, and environmental monitoring for IoT.

(4) Biomechanical energy

Biomechanical energy harvesting can be a significant change in the power supply of current wearable devices with batteries that require frequent recharge and replacement in IoT applications[39, 141–144].

In 2016, Wang et al.[56] designed a TENG made of elastomeric compounds and an inside electrode helix, which sticks to a dielectric substrate and an external electrode on a wire, as Fig. 6a illustrates. The TENG characteristics included flexibility, isotropy, extendibility, a 250 μC/m^2 high surface charging density, and water resistance. Furthermore, as shown in Fig. 6b, Dong et

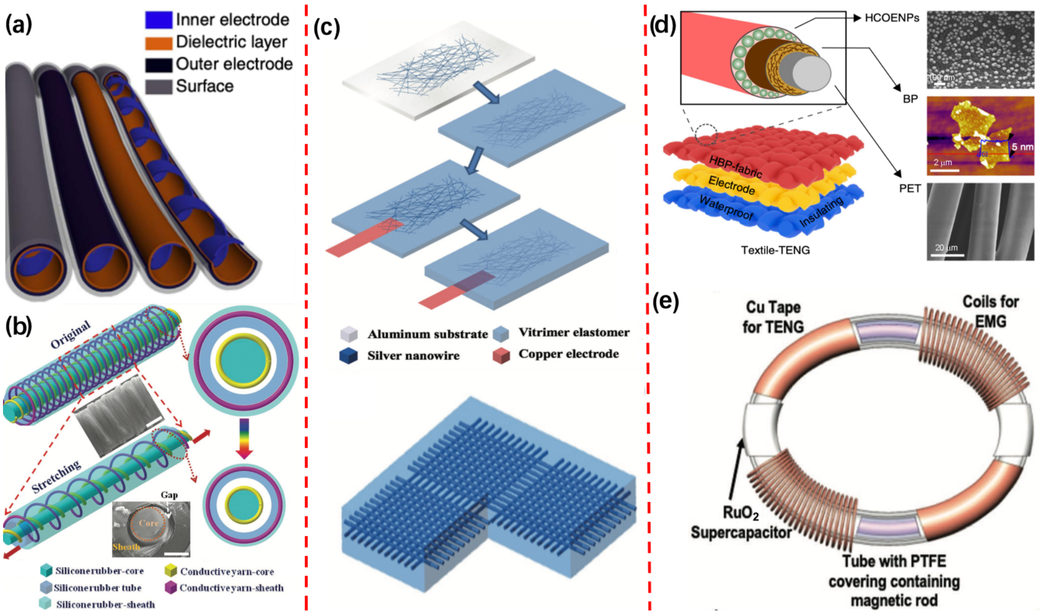

Fig. 6 TENG as the biomechanical energy harvester for IoT applications. (a) Enlarged image of the TENG tube structure. Reproduced with permission[56]. Copyright 2016, Springer Nature. (b) Scheme illustrations of pre and post extending for yarn-based TENG. The embedded SEM images are the exterior characteristics of the functional inner center with spring-like circular twisting (middle) and the boundary-section of the TENG (bottom right). Reproduced with permission[55]. Copyright 2018, John Wiley and Sons. (c) Schematic description of the manufacturing process of VTENG. A picture of the SEM metal nano-wire system (up). Structural illustration of the square ruler-like VTENG (down). Reproduced with permission[59]. Copyright 2018, John Wiley and Sons. (d) Schematic diagram of the textile-TENG, whose development cycle depends on fabrics of Polyethylene Terephthalate (PET). HCOENP indicates Hydrophobic Cellulose Oleoyl Ester Nanoparticle, BP indicates Black Phosphorus, and HBP indicates HCOENP/BP/PET. Reproduced with permission[58]. Copyright 2018, Springer Nature. (e) Schematic diagram of the hybrid energy harvesting bracelet combining with the magnetic mover element. EMG indicates Electromagnetic Generator. Reproduced with permission[141]. Copyright 2019, John Wiley and Sons.

al.[55] developed a heavily expandable yarn-based TENG with integrated, spring-like winding architectures as well as coaxial central sheath based on a silicone rubber elastomer and a silver-coated nylon yarn in 2018. The system can be adopted in the real-time golf scoring devices and the self-powered glove with the gesture recognition function. When being twined into a large-scale energy production thread, they can illuminate LEDs, power a capacitor, and charge a smartwatch.

Besides, Deng et al.[59] introduced a Vitrimer-based TENG (VTENG) that was constructed by the incorporation of the silver nano-wires into the bonded vitrimer elastomer built on the flexible substrate, which is demonstrated in Fig. 6c. The structural stability and conductance of VTENG are recovered through fast heat stress in case of a breakup or exterior damage. This self-healing and form-adaptive VTENG is utilized for enhancing the lifetime and structure versatility of the TENG-based energy harvesters. In 2018, Xiong et al.[58] introduced a fabric fiber-based TENG for the accumulation of mechanical power from both intentional and unintentional physical movements, as depicted in Fig. 6d. Significantly high performance (output voltage: ~250–880 V, output current: ~0.48–1.1 μA/cm^2) can be achieved easily by hand with a minor force (~5 N) and a low frequency (~4 Hz). A hybrid energy harvesting bracelet, combining a dual triboelectric and electromagnetic nanogenerator, was reported by Zhang et al.[141] in 2019, as shown in Fig. 6e. A single shake from the human wrist was used to charge the RuO_2-based microsupercapacitor to 2 V, which allowed the supercapacitor to power many electronics, such as a calculator and temperature and humidity sensors over minutes.

(5) Power management circuit

TENG, exploiting omnipresent environmental mechanical power, is a compelling energy source to satisfy the dispersed need for electricity on consumer electronics, IoT, and so on[145, 146]. An effective power management strategy can further boost the performance of TENG in terms of various characteristics and applications.

In 2015, Niu et al.[81] reported a highly efficient self-charging device that comprises of a high-performance TENG, a power management device for transforming the arbitrary AC power to DC power with 60% energy conversion efficiency, and a power storage unit, as Fig. 7a shows. Utilizing hand tapping as the only power source, the energy system generated a regulated and controlled constant DC electricity with the power of

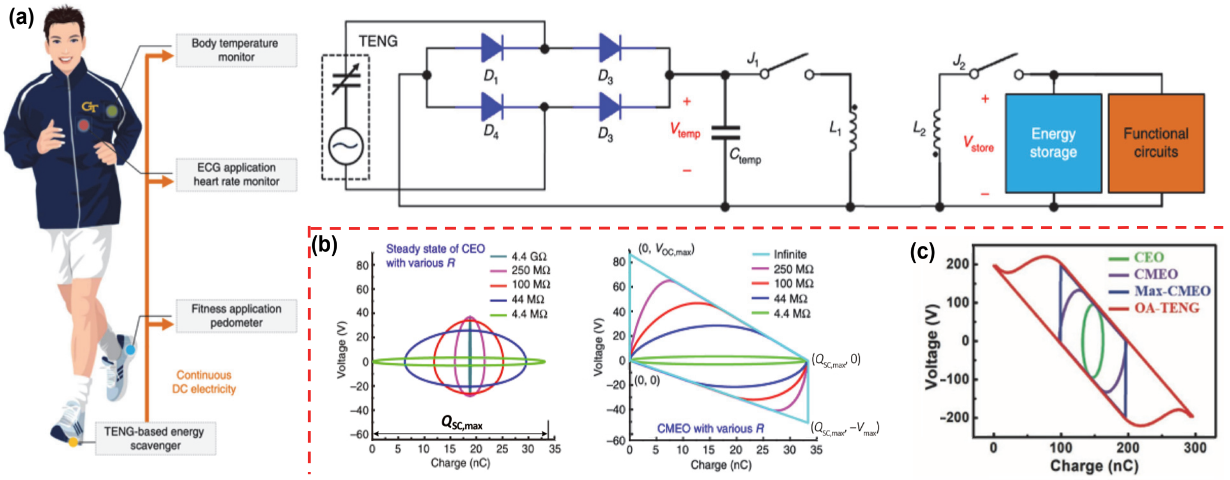

Fig. 7 TENG-enabled power management circuit for IoT applications. (a) Structural design of self-powered sensors for human activity with the power management circuit. The left side is the circuit schematic illustration. ECG indicates Electrocardiogram. Reproduced with permission[81]. Copyright 2015, Springer Nature. (b) Operation cycles and schematic diagram of TENG. The left-hand side is the Cycles for Energy Output (CEO)'s stable state with different loading resistances. The right side is the Cycles for Maximum Energy Output (CMEO) with different loading resistances. There are labeled vertices of the CMEO with infinite loading resistances. Reproduced with permission[82]. Copyright 2015, Springer Nature. (c) Voltage-charge plot compares the Oscillation Assisting TENG (OA-TENG), CMEO, maximized CMEOs, and CEO. Reproduced with permission[37]. Copyright 2019, John Wiley and Sons.

1044 mW (7.34 W/m^3). In the same year, as illustrated in Fig. 7b, Zi et al.[82] invented the standard Figure-Of-Merits (FOM) to quantify the efficiency of a TENG, which consisted of a system FOM relative to the structural design and a material FOM which is the square density of the interface load. The optimum resistance of a TENG, defined as the external load corresponding to its maximum power output, is typically high (MΩ to GΩ range), which could limit the applicability of direct powering electronics by TENGs. Dharmasena et al.[94] introduced TENG power transfer theory and TENG impedance plots to minimize internal impedance and manage output power internally through device design and structural optimization.

As demonstrated in Fig. 7c, Xu et al.[37] also suggested a successful power storage technique in 2019 that could swap the free charges of the conductive surface over a regulated LC oscillatory circuit device consisting of the switch, diode, internal capacitor, and inductor. The relative load density was thus higher than the distorted polarized load density. The simulation and experimentation revealed that the power supply limit might be surpassed with arbitrary load resistance, in particular with respect to low impedance traditional electronics. This generic, low-cost, and greatly efficient approach was considered to be a modern performance assessment model for TENG and further to extend its applications within areas, such as IoT.

3.2 TENG-based sensors and sensing systems

Highly sensitive and small-size self-powered sensing systems have broad applications in fields including portable devices, environmental monitoring, wireless sensor networks, and medical instruments.

(1) Pressure sensor

Pressure sensors of high performance play a vital role in the production of artificial sensing technology. So far, pressure sensors have been studied based on multiple detection methods. A common disadvantage of this form of sensors is that a power supply is needed for their operation[147, 148]. Currently, the TENG has been utilized for a self-powered pressure sensing system as well as a promising power source, such as Tire Condition Monitoring Systems (TCMS), comparing to piezoelectric and electromagnetic devices[149].

In 2015, as Fig. 8a shows, Yang et al.[60] designed lightweight origami TENGs with excellent versatility, reusability, and low costs. The proposed doodlebug-shaped and slinky TENG could be effectively manufactured by correctly flipping printer papers, which can be used as self-powered force sensors. In addition, Luo et al.[61] reported a self-powered force sensor device consisting of a passive resistive force sensor and a TENG, as demonstrated in Fig. 8b, where UVO indicates Ultraviolet/Ozone, ITO indicates Indium Tin Oxide, CNT indicates Carbon Nanotube, and NWs indicate Nanowires. The entire unit is mainly made of lightweight Polydimethylsiloxane (PDMS) and with a sandwich-like structure. Such design has achieved the highest sensitivity (204.4 kPa^{-1}), which surpasses all flexible force sensors in the record. The device revealed an incredibly low identification threshold, fast response period, and long-term reliability. They also developed a mobile graphical platform for real-time semi-quantitative pressure monitoring and evaluation. Following the previous study, in 2017, by utilizing the advanced micro and nanofabrication methods, Wang et al.[62] implemented a large-scale (100 × 100) Pressure Sensor Matrix (PSM) for the modeling of pressure distribution with both high resolution and sensitivity, as illustrated in Fig. 8c, where TESM indicates Triboelectric Sensor Matrix and PMMA indicates Poly-Methyl Methacrylate. When there exists applied force, the PSM can generate electricity as well as optical signals for detection without the need for the external power supply.

(2) Motion sensor

Motion detection in the numerous IoT fields like human-machine interfaces, robotic sensing and control, equipment automation, entertainment, sports, and even security, is of paramount significance. Besides, the precise measurements of micro and nano-scale movements and velocities have huge application demands in the industrial IoT area, including nano-manipulation and additive manufacturing[150–152].

Zhou et al.[64] presented a one-dimensional movement and velocity sensing system based on a TENG with micro-grid architectures, as shown in Fig. 9a. In 2014,

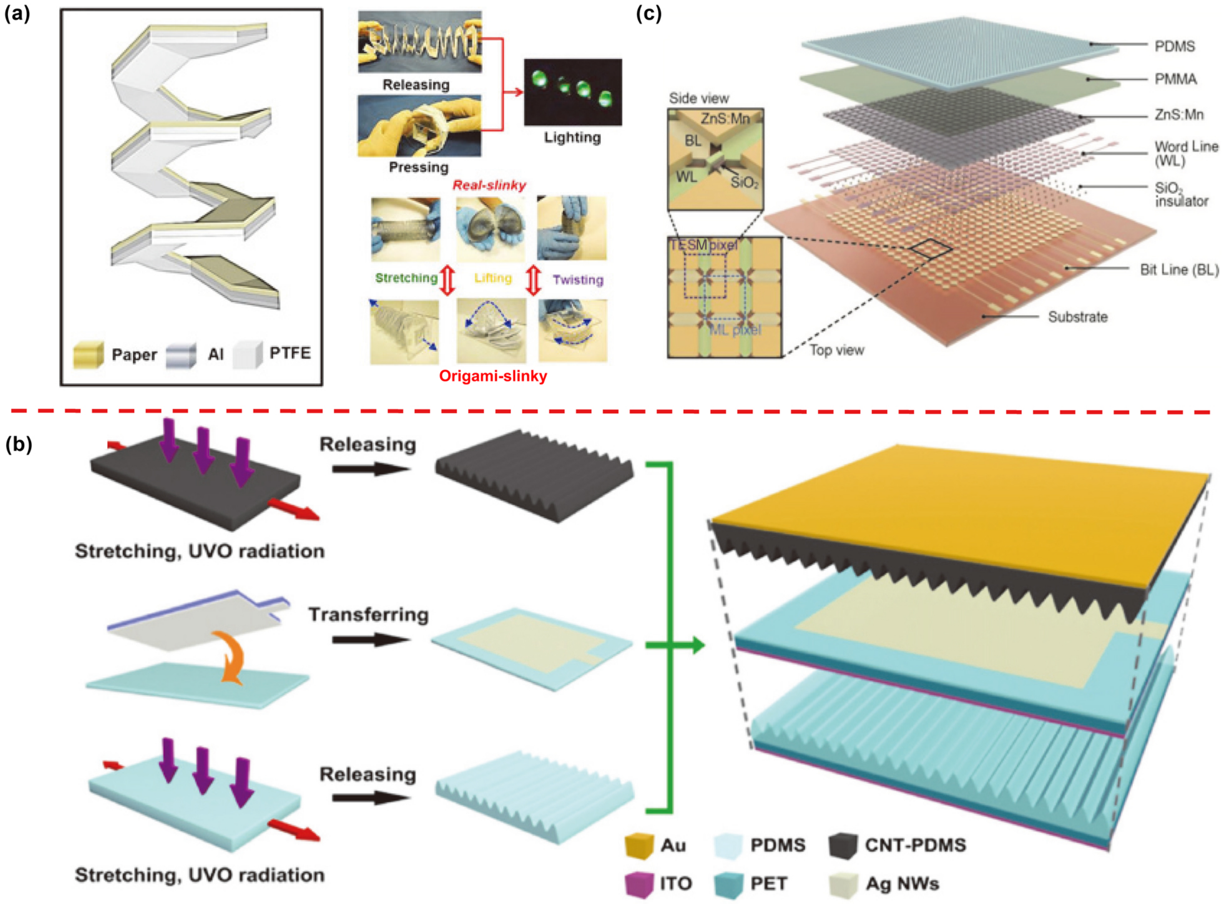

Fig. 8 TENG as the pressure sensor for IoT applications. (a) Device schematic of a slinky TENG (left). A real photo of the slinky TENG's four commercial green LEDs (top right). Four commercial green LEDs are driven by the slinky TENG (top right). The experiment of slinky movements by slinky TENG (bottom right). Reproduced with permission[60]. Copyright 2015, American Chemical Society. (b) Structural design of the manufacture of the sensor device. Reproduced with permission[61]. Copyright 2015, Elsevier. (c) Device's framework architecture. Inserts: a side view and top view separately of the extended functional model. Reproduced with permission[62]. Copyright 2017, John Wiley and Sons.

Yi et al.[63] effectively measured the orientation of a human body/moving subject in two dimensions by a self-powered, single-electrode Triboelectric Sensor (TES), as illustrated in Fig. 9b. The displacement of an object on the upper interface of a Polytetrafluoroethylene (PTFE) substrate, produced shifts in the potential difference of the shaped aluminum electrodes below it. The body movement data, such as position, direction, speed, and acceleration, were obtained in accordance with predetermined parameters from output measurements (short-circuit current and open-circuit voltage). Moreover, the TES could identify the movements of multiple subjects moving simultaneously. In the same year, Yang et al.[65] introduced TENG-based dry biopotential electrode arrays as motion sensors to track humanoid joints and muscle movements, as depicted in Fig. 9c. The Fast Fourier Transform (FFT) was utilized to evaluate the frequency range of the received electric signals to assess the speed of the circular movement. Furthermore, the motion sensing systems provided a voltage of 42.6 V with an impressive Signal-to-Noise Ratio (SNR) higher than 60 dB.

(3) Acoustic sensor

Acoustic sensing devices that transform the sound wave to the electrical signal are the most basic but essential components for human-machine interfaces, making it possible for many advanced applications, such as voice recognition, communications, biometrics identifications, and controls. In recent years, to enhance the acoustic sensing performance, many techniques

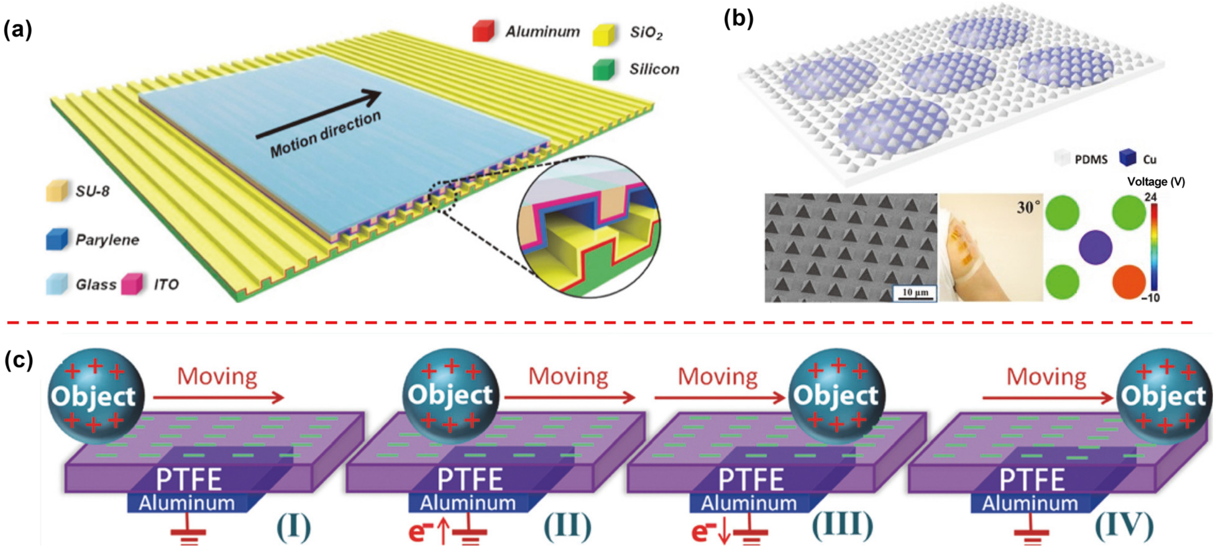

Fig. 9 TENG as the motion sensor for IoT applications. (a) Framework of a triboelectric motion sensor. Schematic illustration of a series of micro gratings and extensive surface details shown in the inset. Reproduced with permission[64]. Copyright 2014, John Wiley and Sons. (b) Device schematic of a TENG-based motion sensor. A picture (up) and SEM image (down left) of the shaped PDMS substrates with pyramids characteristics. Electrical evaluation output of the motion sensing system. Reproduced with permission[63]. Copyright 2014, John Wiley and Sons. (c) Working mechanism of the self-powered, single-electrode-based TES. Reproduced with permission[65]. Copyright 2014, American Chemical Society.

of both hardware and software have been constantly proposed. This section will mainly focus on TENG-based acoustic sensors. Such sensors will provide different possibilities to the interaction solutions between human beings and IoT[153, 154].

In 2014, Yang et al.[155] reported the first TENG-based acoustic sensor, capable of capturing mechanical energy from sound waves. Later on, this idea was further improved by introducing the paper-based approach. In this way, the devices are of super-thinness and rollability[66], with practical applications, such as external hearing aid devices[68], self-powered microphone, and human identity recognition[69].

Following the first study in 2014, Fan et al.[66] introduced an ultrathin, foldable, and paper-based TENG sensor for acoustic energy harvesting and self-powered audio recording, as demonstrated in Fig. 10a. It has a multilayered design consisting of flat, horizontally laminated film components. The polymer nano-wires array was intentionally fabricated onto a PTFE membrane to facilitate the triboelectrification, as shown in the SEM picture at the upper-left corner of Fig. 10a. This design introduced a well-customized microhole ingeniously for optimizing vibration response to the acoustic stimuli. With a 125 μm thickness, the fabricated TENG offers a peak energy density of up to 121 mW/m^2 (volume energy density reaching 968 mW/m^3) at an audio pressure around 117 dB in sound pressure level. The as-prepared paper-based TENG, with a series of convincing attributes like a wide bandwidth, structural rolling capability, and directional flexibility, will serve as a brilliant self-powered sensor to capture voice for recognition.

Based on the above device, a dual-function thin patch microphone for portable electronics is proposed by Li et al.[67], as illustrated in Fig. 10b. The transducers are composed of solid material with a Polypropylene (PP) layer comprising little external silicates (0.1–10 μm). The PP is a plastic material with a high malleability, low density, and strong fatigue resistance. In addition, the remarkably extendable assembled system contains a layered metal-insulator-metal thin-film structure without relocating components, micro-manufacturing characteristics or suspending frameworks, which makes the process scalable into large-scale manufacturing. The simulated holes in the Foam-structured TENG (F-TENG) form various gigantic dipoles with the approach of microplasma

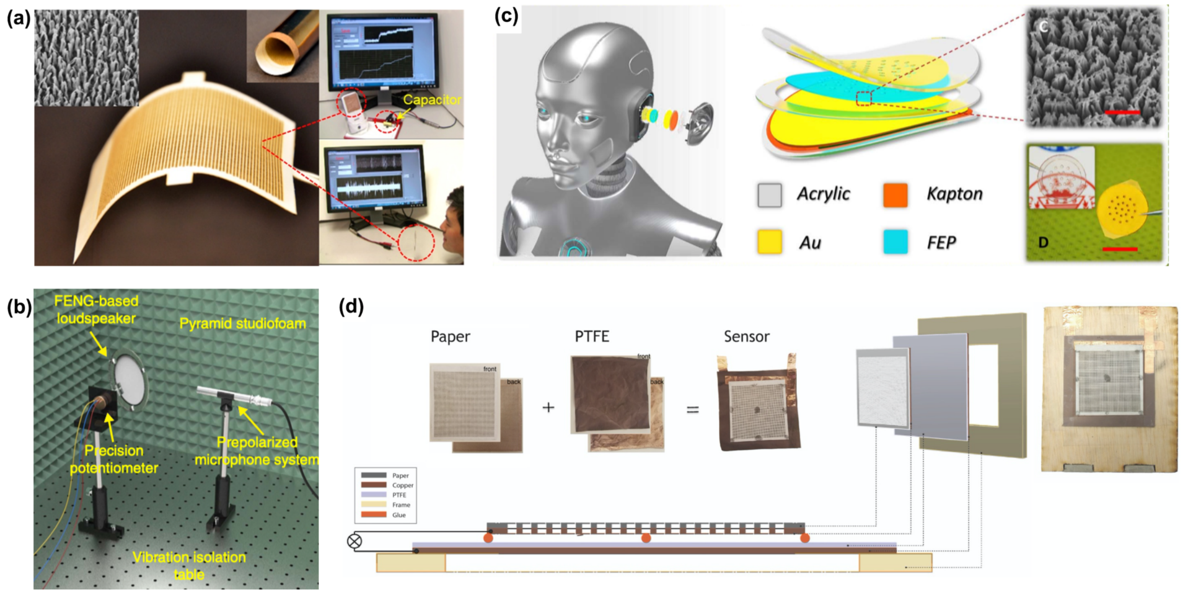

Fig. 10 TENG as the acoustic sensor for IoT applications. (a) Schematic illustration of the paper-based TENG. The left side is an actual photo of the system. Inset is the SEM graphic of the PTFE polymer nanowires. The right side is the image of a paper-thin TENG as a self-powered sound recording microphone. Reproduced with permission[66]. Copyright 2015, American Chemical Society. (b) Experimental configuration for freestanding FENG (Ferroelectret Nanogenerator)-based voice speakers. Reproduced with permission[67]. Copyright 2017, Springer Nature. (c) Mechanism and structural design of the self-powered TAS. The left side is the illustration of the triboelectric auditory system for a robot. The right side is the fundamental schematic diagram of the TAS. Reproduced with permission[68]. Copyright 2018, The American Association for the Advancement of Science. (d) Schematic illustration of SATURN Microphone composed of paper coated with copper and PTFE. Reproduced with permission[69]. Copyright 2018, Association for Computing Machinery.

discharge. Such design allows the F-TENG to achieve an excellent forward and inverse electromechanical conversion performance. Furthermore, the proposed F-TENG-based loudspeaker has a wide frequency response from 10 to 20 000 Hz. The practical applications involve both record high-fidelity symphony and the personal identity authentication.

Guo et al.[68] recently developed the self-powered Triboelectric Auditory Sensor (TAS) for the implementation of a digital acoustic device and an exterior auditory assistance interface in smart robot devices, as shown in Fig. 10c. A TAS with a bandwidth response of 100 to 5000 Hz was produced by systemically optimizing the circular or sectoral internal borderline framework with ultra-high sensitivity up to 110 mV/dB. When combined with smart robotic technologies, TAS provides high-quality music recording and accurate voice recognition for realizing human-robot interaction for intelligent IoT. Furthermore, as Fig. 10d depicts, Arora et al.[69] built up a Self-powered Audio Triboelectric Ultra-thin Rollable Nanogenerator (SATURN) microphone. By mathematical modeling and experimental analysis, they fundamentally investigated and evaluated a series of influential factors that control sound quality, such as directivity, acoustic sensitivity, and frequency response. The SATURN mic can be easily produced by conveniently implementing real-life objects and functional conditions to audio loudspeakers, with the potential applications as part of an intelligent IoT integrated network.

(4) Wind and wave sensor

A wind vector sensor network usually works for monitoring wind direction and velocity, playing a vital role in the area of weather forecasting[156, 157]. Moreover, wave monitoring is necessary for early warning of marine disasters, maritime safety, and the utilization of ocean resources[158]. Both wind and wave sensors have significant roles in IoT.

In 2013, by utilizing Fluorinated Ethylene-Propylene

(FEP) film and wind-induced resonance movement of two aluminum foils, Yang et al.[71] designed the embedded TENG, with the size of 2.5 cm × 2.5 cm × 22 cm, which is able to sense the orientation of wind and velocity with a sensitivity of 0.09 μA/(m·s^{-1}), as demonstrated in Fig. 11a. Following the previous work, a spinning EMG and TENG of the freestanding mode were combined together by Wang et al.[70] in 2018, which is shown in Fig. 11b. The result demonstrated that the sensor could be utilized for the measurement of wind velocity as small as 3.5 m/s. Furthermore, a highly responsive wave sensor built on the liquid-solid TENG framework was developed by Xu et al.[73], as shown in Fig. 11c. It was manufactured from a copper electrode filled by a PTFE film with microstructural coating. The sensor was capable of sensing the wave height in the range of millimeters. Besides, as illustrated in Fig. 11d, Wang et al.[72] in 2018 proposed a disk-like TENG coupled with the wind vane, which could track the wind speed (ranges from 2.7 to 8.0 m/s) and direction (eight directions) simultaneously and in a real-time manner. The proposed wind sensor device demonstrated the potentials for wireless environmental monitoring.

(5) Biomedical monitoring sensor

Wearable devices reflect an exciting potential in health monitoring and precision medicine because of their innovative applications. They can regularly track the health status of a patient in a non-invasive approach and in real time[159–161].

In 2016, Song et al.[77] proposed a versatile TENG built on a trapped cantilever leaf and a patterned aluminum plastic substrate, which was designed for self-powered sleep-bodies motion monitoring, as illustrated in Fig. 12a. Regarding previous research, Lin et al.[75] developed a self-powered heart-rate monitoring system in 2017, as Fig. 12b demonstrates. The heart rate pulse obtained by the sensor was analyzed in the signal processing system, transmitted through the wireless interface to an exterior computer, and viewed on a personal smartphone in real time. In Fig. 12c, the textile-sensor array has achieved low energy cost ($<6\,\mu$W), rapid reaction (224 ms), low sensor threshold (2 Pa),

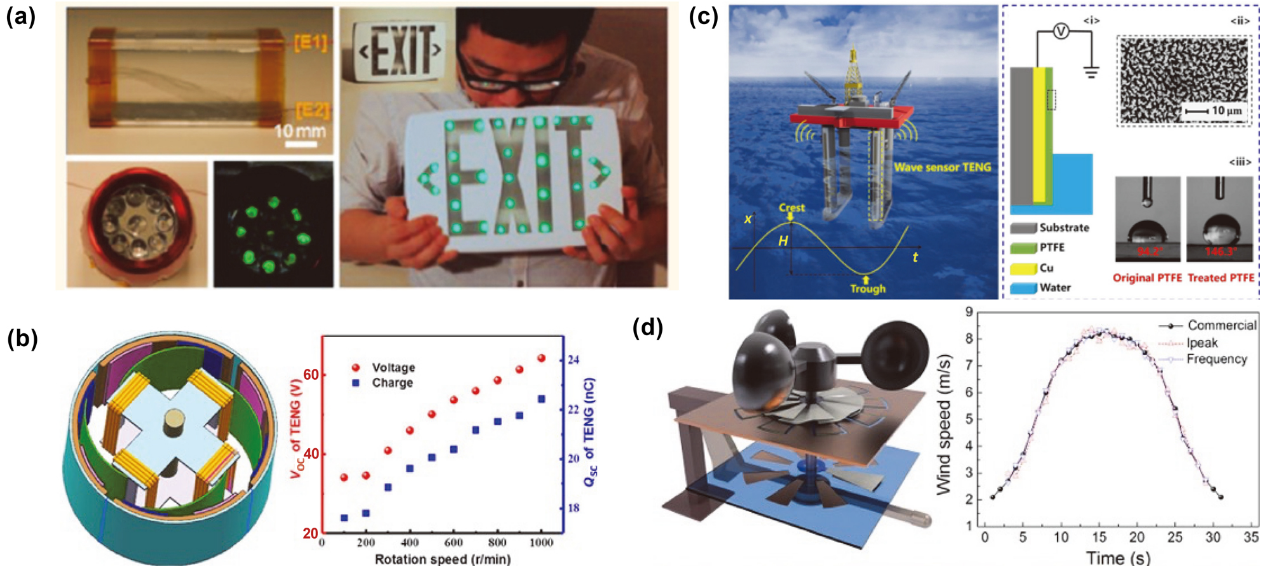

Fig. 11 TENG as wind and wave sensor for IoT applications. (a) Device schematic of the TENG system. (Up left) A photo of the TENG. (Down left) A photo of a 9-LEDs before and during the operation of the TENG. (Right) A picture reveals that TENG was used for collecting human mouth blowing to trigger exit signs. Reproduced with permission[71]. Copyright 2013, American Chemical Society. (b) Structural design of the TENG (left) and its performance characteristics (right) indicating V_{oc} as well as Q_{sc} against rotational speed. Reproduced with permission[70]. Copyright 2018, American Chemical Society. (c) Left side is Wave Sensor (WS)-TENG's structural design used to measure waves around a marine unit. The schematic illustration of the model WS-TENG is on the right side. The inset is an SEM image of a surface-treated PTFE. Reproduced with permission[73]. Copyright 2019, Elsevier. (d) Structural design of the wind sensing system based on TENG. The right-hand side is the wind velocity graph measured in real time by a wind speed sensor device and a built-in wind measurement network. Reproduced with permission[72]. Copyright 2018, American Chemical Society.

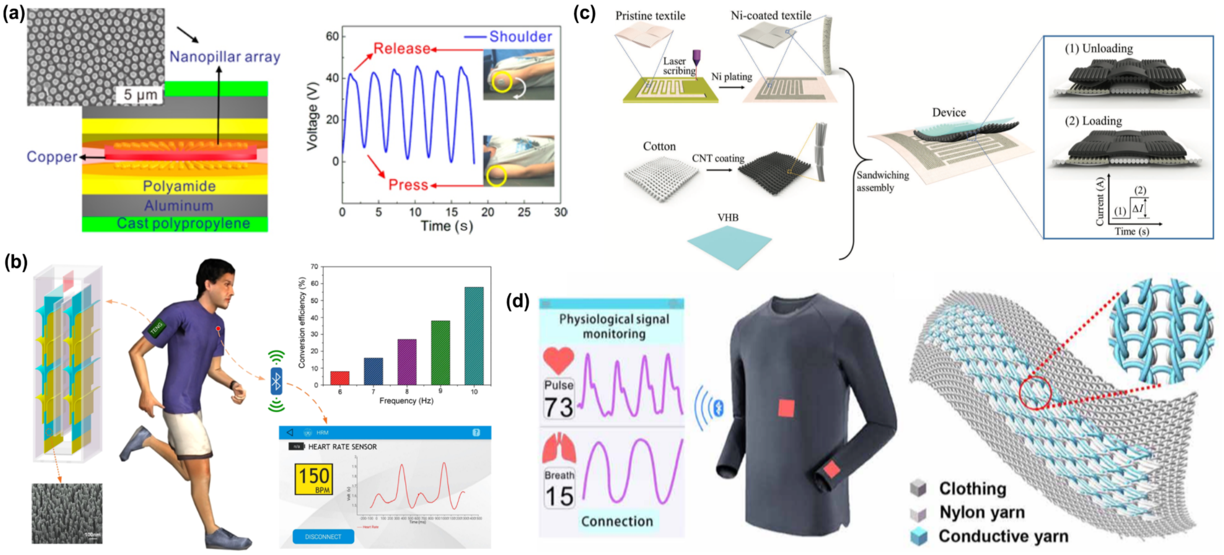

Fig. 12 TENG as the biomedical monitoring sensor for IoT applications. (a) Structure design of the TES (left). Changes in voltage over time obtained from TES trapped on various sections of a human body during shoulder sleep tracking (right). Reproduced with permission[77]. Copyright 2016, American Chemical Society. (b) On the left-hand side is a schematic illustration of the downy-structured TENG. Upright is the energy conversion efficiency performance of the devices. Downright is the broader view to display the entire device system with heart rate impulses obtained in real time. Reproduced with permission[75]. Copyright 2017, American Chemical Society. (c) Structural design of the manufacturing process of fabric pressure sensors. Reproduced with permission[76]. Copyright 2017, John Wiley and Sons. (d) Schematic illustration and manufacturing process of all-textile pressure sensors. Reproduced with permission[74]. Copyright 2020, American Chemical Society.

high sensitivity (14.4 kPa^{-1}), and structural reliability in rough compression, which was suggested by Liu et al.[76] during the same year. The system was shown to detect finger gestures and movements in real time. In 2020, as illustrated in Fig. 12d, Fan et al.[74] published a comfort and high-pressure sensitivity sensing system with an all-textile design. It has quick reaction speed (20 ms), pressure sensitivity (7.84 mV/Pa), broad bandwidth (up to 20 Hz), reliability (>100 000 cycles), and washability (>40 washes). The manufactured Triboelectric All-Textile Sensor Array (TATSA) was spliced onto various sections of the wraps to track respiratory patterns and arterial pulse signals continuously.

(6) Chemical sensor

IoT related chemical sensors, which are capable of tracking chemical pollution in manufacturing facilities, create synergy between areas of analytical techniques, devices, and machinery, sensing systems as well as information technology and network systems[162, 163].

In Fig. 13a, the Water-fluid-driven Rotating TENG (WR-TENG) was incorporated in a self-powered electrostatic rust protection and scale-preventing device, which Wang et al.[79] presented as evidence in 2019. The elements of the entire network comprised an electric water heating container, a Voltage-Doubling Rectifier Circuit (VDRC), and a WR-TENG. In the same year, Bai et al.[80] presented a tandem TENG device for water quality measurement, as illustrated in Fig. 13b. A radial grating system that can be effectively activated by slow water waves is accomplished by substrate adjustment and efficient architecture, which enhances wave power extraction devices' maximum and mean capacity separately to 45.0 and 7.5 mW. The intense power capacity allows for a series of self-powered full dissolved solid test devices, which can be extended into networks across a broad region for real-time water quality monitoring. In 2020, Wang et al.[78] published a new non-contact TENG built by the flow of ferrofluid through a packed pipe within an exterior magnetic field, as shown in Fig. 13c. In addition, a lubricant oil substrate was added to shape a fluid-liquid triboelectric layer between a ferrofluid and a substratum to allow the slipping actions of ferrofluid. The future implementation was illustrated as a self-powered sensor of fluid level

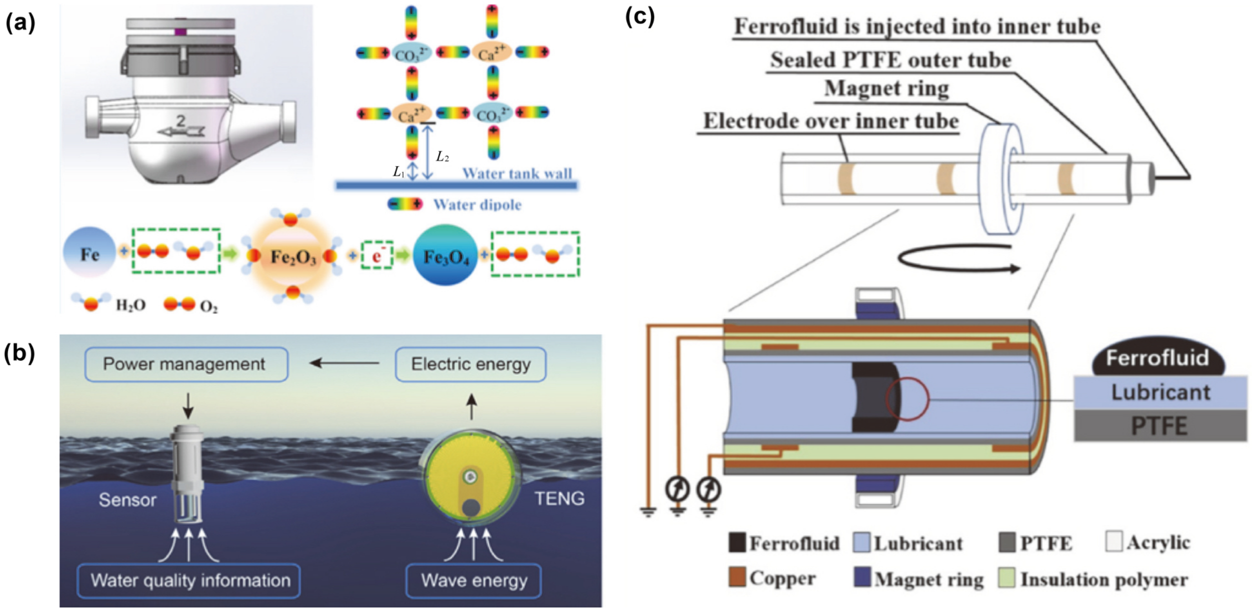

Fig. 13 TENG as the chemical sensor for IoT applications. (a) Upper left is the schematic illustration of the WR-TENG. Upper right is the sequence of electrostatic anions and water molecules. Bottom is a chemical reaction cycle and diagram for rust protection. Reproduced with permission[79]. Copyright 2019, American Chemical Society. (b) Structural design of the self-powered water quality measurement devices. Reproduced with permission[80]. Copyright 2019, Elsevier. (c) Structural design of non-contact magnetic field Liquid-Liquid interfacing TENG (LLi-TENG). Reproduced with permission[78]. Copyright 2020, Elsevier.

measurement.

(7) Sensing system in human-machine interfacing The TENG-enabled sensor is distinctive and innovative in its fundamental mechanism in human-machine interfacing with signal processing techniques, offering a modern architecture model for smart sensor technology and showing great potential in IoT applications[152].

A TENG-based micromotion sensor, utilizing two opposing tribomaterials and an indium tin oxide layer, was described in 2017 by Pu et al.[83], as illustrated in Fig. 14a. The proposed lightweight and translucent sensor can efficiently catch eye twitch activity with an extremely-high signal level (~750 mV) as opposed to the conventional electrooculogram solution (~1 mV). In 2018, Wu et al.[84] built a two-factor, keystroke-based, pressurized, and authentication framework that can authenticate clients and also recognize them by their unique style behavior, as shown in Fig. 14b. The framework is composed of a logically constructed triboelectric keystroke unit that transforms typing actions to analog signals and an algorithm-based user classification approach by Support Vector Machine (SVM). Kiaghadi et al.[85] also developed two types of textile-based sensors in 2019, which is demonstrated in Fig. 14c, attaining a ballistic signal from respiratory and cardiac activity. They developed a signal processing system that melds input from the multiple sensors to calculate biological patterns in a number of sleep positions and postures. In addition, as shown in Fig. 14d, Luo et al.[86] mentioned a versatile and translucent Self-Charging Power Film (SCPF), which either acts as an energy harvester or as a self-powered data processing framework. During a sliding movement, the film was capable of recognizing its unique characteristics by capturing electrical signals relevant to a person's particular bioelectricity, sliding speeds, the applied pressure, etc.

3.3 Wireless power transfer and information transmission

Due to consumer market demand and technological difficulty, Wireless Power Transfer (WPT) has gained considerable attention[164–166]. If it is feasible to capture

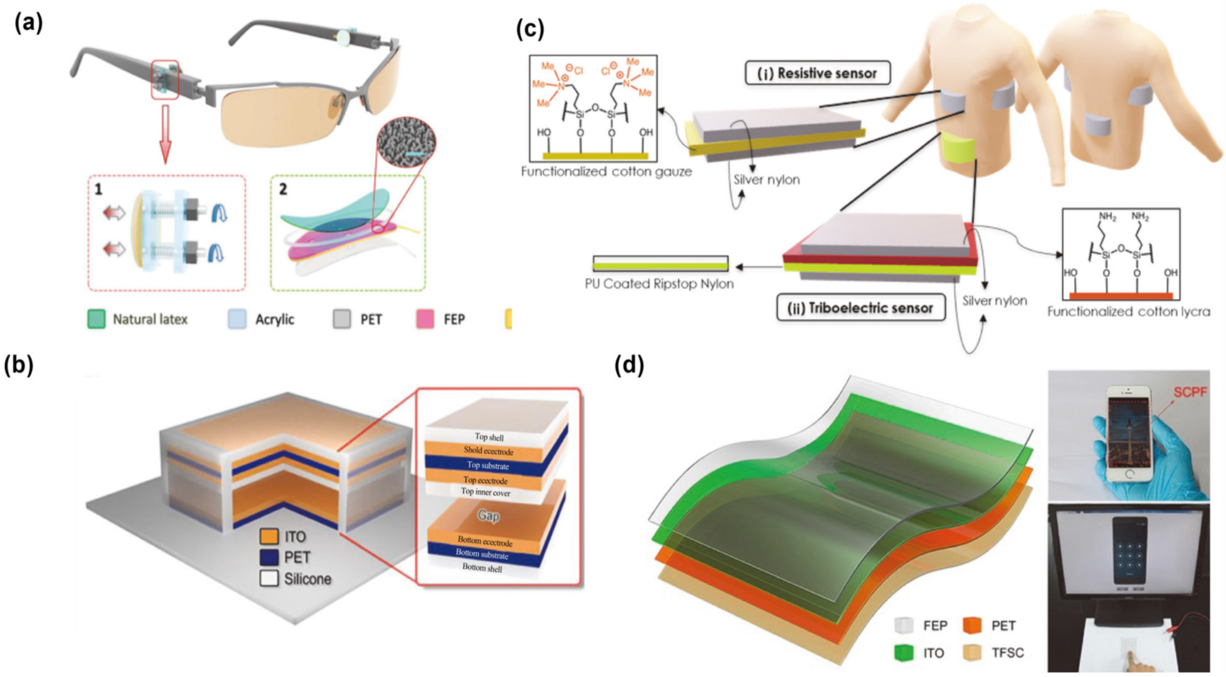

Fig. 14 TENG as sensing system with human-machine interfacing for IoT applications. (a) Schematic of the arrangement of a pair of ordinary mechnosensational TENG (msTENG)-mounted glasses. Lower left is the adjusting device framework for convenient modification. The downright side is the msTENG graphical schematic. Inset: an illustration SEM of nano-wires from FEP. Size bar: 5 mm. Reproduced with permission[83]. Copyright 2017, The American Association for the Advancement of Science. (b) Exploded structure design of a single triboelectric key. Reproduced with permission[84]. Copyright 2018, Elsevier. (c) Phyjama consists of a decentralized collection of four resistive (i) sensors and one triboelectric (ii) sensor. Reproduced with permission[85]. Copyright 2019, Association for Computing Machinery. (d) Schematic diagram of the SCPF being translucent and versatile. Pictures of an SCPF show its translucency and versatility on the top right side. Photo with smart unlocks sliding device on the top downside. Reproduced with permission[86]. Copyright 2016, American Chemical Society.

the power output of TENG wirelessly, its use may be expanded to a significant range, in particular for self-powered environmental monitoring devices[67, 83, 167]. The TENG-based Optical Wireless Communication (OWC), which utilizes large optical bandwidth, can efficiently solve the spectrum scarcity and large-scale deployment issue of implementation for such distributed and ubiquitous sensors in IoT applications[168–170]. Furthermore, the TENG also has a potential of driving off-the-shelf low power wireless Radio Frequency (RF) communication modules. Zigbee and Bluetooth Low Energy (BLE) are two most popular wireless RF communications protocols for IoT applications, both use cyclic sleep and awake mechanism to achieve overall low power consumption. For instance, the average power consumption on standard Zigbee and BLE setup under 120 s sleep-awake cycle setting are 51.8 and 33.3 μW, respectively[171]. Therefore, it would be more than useful to develop TENGs with wireless power transfer and information transmission capability.

In 2018, Ding et al.[87] incorporated the LEDs with TENGs as a wireless transmitter, transferring information relevant to physical stimulation without external energy supply, as shown in Fig. 15a. The entire device could be separated into two parts, namely, the transmitter and the receiver. The transmitter consisted primarily of the TENG system and the LED array. The TENG served as both the actively stimulus and the energy supply for OWC transmission. Besides, a photodetector or a camera could be utilized as a receiver to collect optical information in such systems. Three applications of the pressure sensor, optical remote control, and biometric verification were illustrated in the article with the specialized TENG systems and the assistance of machine learning and image processing technologies.

During the same year, as demonstrated in Fig. 15b, Cao et al.[88] illustrated a new method for wireless

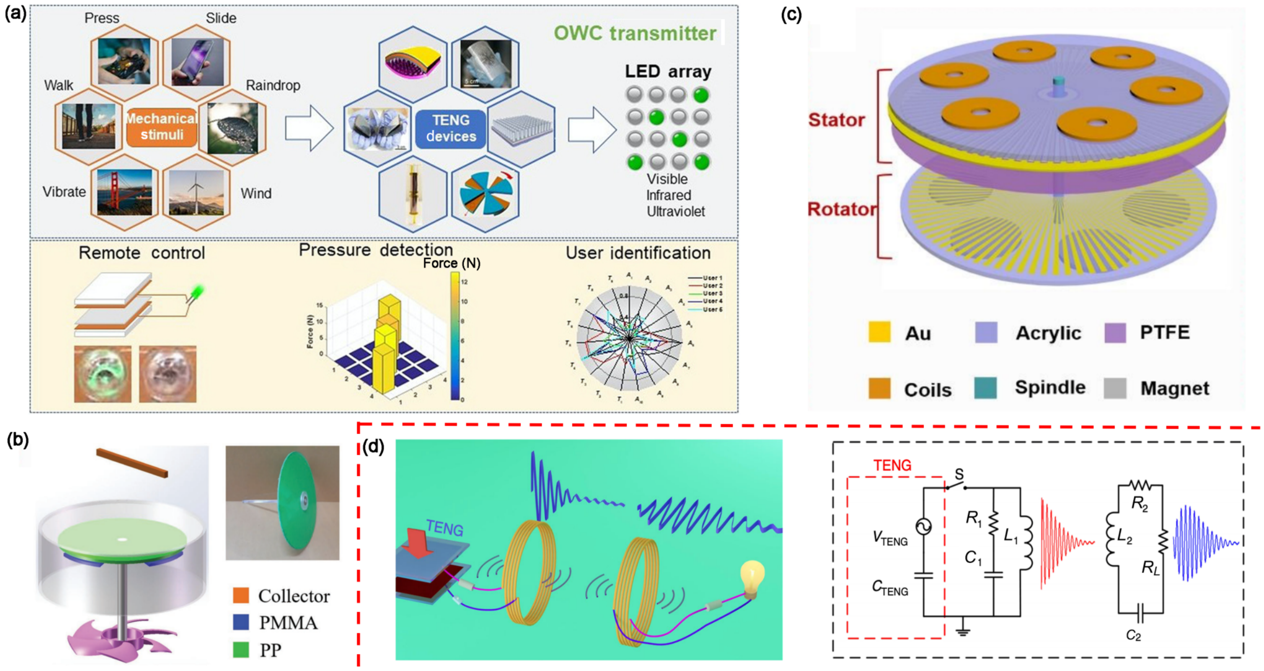

Fig. 15 TENG-enabled wireless power transfer and information transmission for IoT applications. (a) Structural design of the self-powered optical wireless communications OWC operated by TENG and its application scenarios. Reproduced with permission[87]. Copyright 2018, Elsevier. (b) Structural design of the rotary electrodeless TENG with collectors. Reproduced with permission[88]. Copyright 2018, John Wiley and Sons. (c) Schematic illustration of the hybridized nanogenerator. Reproduced with permission[89]. Copyright 2019, Royal Society of Chemistry. (d) Diagram (left) and corresponding circuit (right) of the wireless power transfer network combined with magnetic resonance. Reproduced with permission[90]. Copyright 2020, Springer Nature.

energy transmission by utilizing the displacement current produced by electrodeless TENG. Wireless current density and voltage of the device exceed 7 μA/cm^2, at a distance of 3 cm and 65 V, respectively. As shown in Fig. 15c, Chen et al.[89] presented a hybrid TENG with rotating-disk for harvesting rotating power and transmitting wireless power continuously by utilizing roller coils. The energy could be transferred wirelessly in real time to a length of ~60 cm, relying on helical coils. In 2020, Zhang et al.[90] demonstrated a wireless TENG based on magnetic resonance coupling, which is shown in Fig. 15d. The pulsed voltage signal was transformed into a sinusoidal message with a static rate by combining an inductor and a microswitch with the TENG. This could be wirelessly transferred at an efficiency of 73% over a gap of 5 cm between two devices (10 cm in diameter). In the same year, Liu et al.[172] proposed a wind-powered wireless environmental sensing system and quantified the wireless communication power needed in this wireless remote sensing scene. A carbon monoxide (CO) sensor ran sustainably at a wind speed of 4.5 m/s and sent a signal every 18 min from a distance of 1.5 km by means of radio transmission at an ultra-high frequency of 433 MHz, which is one of the typical frequency bands of Sub-1 GHz (the electromagnetic wave with frequency below 1 GHz). Another humidity and temperature hybrid sensor can send the monitoring data in the range of 50 m every 9 min via Bluetooth (2.4 GHz).

4 Summary and perspective

TENG-based technologies could provide various applications with numerous devices. TENG is a powerful and environmentally friendly device that can harvest energy from a wide variety of renewable energy sources and function as self-powered sensing networks and wireless information transmission systems. Furthermore, the involvement of TENGs in intelligent IoT systems has been demonstrated to offer superior output compared to other energy harvesting and sensor technologies via a large number of detailed studies. The attributes for future smart cities, intelligent building designs, and modern urban development have been addressed, and are topics of considerable concern in this emerging IoT era. However, this technology still appears to be new, and there remains much space for improvement under the current principles for developing as well as standardizing the existing innovations on TENG, which are outlined as follows.

Effective power management and energy storage: Environmental energy harvesting has a lot of variables that make it unpredictable and time-dependent, but the conventional IoT electronics require the electric power source with stable current and voltage output. Hence, it is necessary to store the harvested energy in a capacitor or battery so that the system can be operated in an organized manner. Besides, effective power management solutions are required to boost the produced current with minimal energy losses.

Miniaturization and integration: The current TENG-enabled IoT systems which have been demonstrated so far, are primarily focused on individual and separated devices. Further research may target for reducing the module size and incorporating a multitude of these devices into a functioning network structure. Prospective approaches are focused on the advancement of modern materials science and advanced fabrication technologies. Therefore, one trend in the future is to resolve the problem of integration and miniaturization of different multifunction systems.

Longevity and robustness: TENG-based systems remain constrained by longevity and robustness related challenges, like reliability and durability, as such systems are fundamentally limited by current materials, such as metallic organic polymers and manufacturing methods. In order to address these problems, further research is necessary to enhance material quality and packaging techniques.

Wearable health monitoring: In recent years, wearable electronics relying on TENG have been increasingly introduced owing to their unusual and efficient energy harvesting from biomechanical movements. Wearable TENG cases have been applied from *in vitro* to *in vivo*. Since TENGs are newly evolving energy harvesting solutions, comprehensive and in-depth research does need to be carried out in order to satisfy the requirements of different applications in the future.

Underwater IoT: The IoUT will be used as a worldwide network of intelligently linked underwater artifacts to track broad undiscovered water conditions. Challenges and future concerns, such as biological impact, chemical contamination, environmental sustainability, and cable connections, need to be continuously investigated.

In general, the power density is still the most vital parameter that determines the final application of TENGs and defines whether TENGs can be used in IoT applications, such as sensing, communication, and computation. Today, TENGs have shown power densities of up to 500 W/m^2, with an instantaneous conversion efficiency of 85%[173,174]. While that is adequate for many applications, it still needs further developments before to be more competitive in this field. We believe that the contact region mainly controls the density of power. Therefore, it is crucial to explore the interfacial region in order to understand the critical parameters from molecular to macroscopic levels, such as the contact design, interfacial zone, and interfacial chemistry. Secondly, the TENG voltage output is very high while its current output is low, meaning that TENG needs much higher impedance for matching than other harvesters[175]. Voltage transformers may be an approach for voltage reduction and current boosting. Furthermore, the packaging of the TENG can be more sophisticated designed to increase the output current and decrease the output voltage without reducing the power of many small size units. Thirdly, to reduce the cost of maintenance while keeping the sensing sensitivity, the output stability and durability of the device should be improved[176]. For millions of cycles, the performance of the material surface could be changed, particularly in contact sliding mode, which influences the performance of TENG and affects the result of sensor calibration and sensing accuracy. These problems could be tackled by choosing more durable materials and developing advanced structures.

With further improvements of this technology in the aforementioned areas, and by developing strategies to address these challenges, we firmly believe that there is a significant potential for the TENG to become a low cost, adaptable and sustainable power source, and an efficient autonomous sensing system for future IoT systems.

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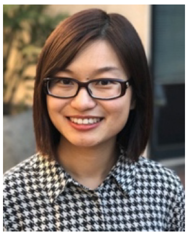

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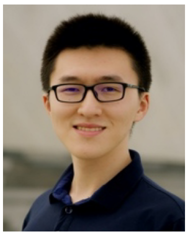

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