Gold Nanoparticles: Enhancing the Sensitivity of Clinical Diagnostic Tests

Free Article Collection eBook

The current COVID-19 pandemic has brought much attention to the medical utility of rapid diagnostic test (RDTs). Although these assays are easy to use and provide fast diagnostic results at the point-of-care, one of the main limitations in their development has been the prevalence of false-positive and false-negative results. To improve their sensitivity, gold nanoparticle probes have been incorporated into the design of RDTs. Gold nanoparticles are highly regarded for their optoelectronic properties, biocompatibility, stability, and their ability to be synthesized into various shapes.

Taken together, these features can be utilized in various combinations to optimize the sensitivity and accuracy of clinical diagnostics. Our article collection "Gold Nanoparticles: Enhancing the Sensitivity of Clinical Diagnostic Tests" highlights several applications where gold nanoparticles were used to improve clinical biomarker or disease detection.

Through this research article collection, we hope to educate scientists on how gold nanoparticles can be used to enhance the sensitivity of clinical diagnostic tests.

Download here

nanoComposix | FORTIS LIFE SCIENCES

WIREs
Wiley Interdisciplinary Reviews

NANO · MICRO small
www.small-journal.com

Toward a New Era of Sustainable Energy: Advanced Triboelectric Nanogenerator for Harvesting High Entropy Energy

*Baodong Chen and Zhong Lin Wang**

Widely distributed across the environment, irregular micro-nano mechanical high entropy energy (HEE) is a new promising recoverable energy, in which the development of matched harvesting technology is imperative to fit in with the requirements of booming sustainable energy in the new era. The triboelectric nanogenerator (TENG) is a very efficient technology for harvesting micro-nano HEE, especially when converting irregular, low-frequency, weak mechanical energy into electricity. Here, the latest advancements are comprehensively reviewed in using TENGs for sustainable energy, sensing, and other applications. The fundamental theory and overwhelming superiority of TENG is systematically analyzed as a sustainable energy with four representative domains: micro-nano distributed power sources, self-powered sensing systems, direct high-voltage power sources, and large-scale blue energy. The review is concluded with a discussion of the challenges of leveraging TENGs for sustainable energy engineering. The striving directions of TENG technologies are proposed with a concentration on basic research and commercialization for the new ear of 5G and Internet of Things.

1. Introduction of TENG

With the booming era of Internet of Things, 5G, and future 6G, given the need for mobility of these billions of distributed electron devices and sensor network, forces researchers to develop a completely new form of sustainable energy sources. [1–4] This happened due to the rapid advance individual, randomly and vast numbers of the mobility electronics require the matched way of power supply. In practice, so that's that existing power structure and its unreasonable way led to the today' s information age urgent requirement.[5] Fortunately, widely distributed across the surrounding environment, random, irregular micro-nano mechanical high entropy energy (HEE) is a promising recyclable energy sources,[6–7] that could take this as a replaceable solution to meet the requirements.[8–9] Energy technologies with various working mechanisms have been developed to convert the mechanical energy into power or electrical signal, largely consist of electromagnetic and piezoelectric effect in existence.[10–11] In addition, triboelectric nanogenerator (TENG) based on the ancient triboelectrification effect presents as a potential but competitive emerging energy technology due to a series of unique advantages, such as high voltage and sensitivity,[12] good flexibility,[13] stretchability,[14] multistyle structure design,[15] light-weight,[16] easy processing,[17–18] low production cost,[19–20] wide selection of materials,[21–22] and applicability[23–25] for mechanical energy harvesting and self-powered sensing.

TENGs also called as Wang generator that has been invented by Wang in 2012 with the purpose of recycling and make use micro-nano mechanical HEE in the environment.[12] Based on the modified displacement current of Maxwell's equations as the acting force and to be able to effectively convert HEE into electricity or electric signal, which has an enormous application range and extended value in sustainable and distributed energy field.[26–27] Compared with fixed-line network of conventional power supply technology and a variety of batteries must face the frequent recharging, replacing and environmental pollution, TENG unit or integrated network can harvest environmental mechanical energy and serve as a high-efficiency distributed energy source, e.g., HEE.[28–29] In addition, TENGs with their ubiquitous physical effect, abundant choice of materials, simple structure, flexibility in design, easy fabrication, excellent universality, easy recovery, and low production cost are considered one of the ideal sustainable energy technologies, not only for sustainably powering electronic devices but also for the development of intelligent and active self-powered sensing

B. Chen, Z. L. Wang
CAS Center for Excellence in Nanoscience
Beijing Key Laboratory of Micro-nano Energy and Sensor
Beijing Institute of Nanoenergy and Nanosystems
Chinese Academy of Sciences
Beijing 101400, P. R. China
E-mail: zlwang@binn.cas.cn

B. Chen, Z. L. Wang
School of Nanoscience and Technology
University of Chinese Academy of Sciences
Beijing 100049, P. R. China

B. Chen
Institute of Applied Nanotechnology
Jiaxing, Zhejiang 314031, P. R. China

Z. L. Wang
School of Materials Science and Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0245, USA

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/smll.202107034.

DOI: 10.1002/smll.202107034

 © 2022 Wiley-VCH GmbH

system.[30] So far, the theoretical estimation of maximum instantaneous power density of TENG device is raised from 500 W m^{-2} to over 10 MW m^{-2} in special conditions,[31] and the energy conversion efficiency is growing steadily by continually optimized power management system, therefore it meets the personalize requirements of power for most miniaturized electronics. This new technology of energy conversion is generally applicable to all kinds of micro-nano HEE, including biomechanical energy, wind energy, water, and ocean wave.[32–33] **Figure 1** demonstrates the conceptual diagram and research development of TENG and a collection range of mechanical energy in the environment. Applicability of this technology can be widely used in the sky, sea and land field that to collect and convert different kinds of wind energy, blue energy (water or wave), and biomechanical, vibrational and sliding energy, and so on. (Figure 1a).[34] As a high-performance distributed power source or an active self-powered sensor system, it is widely applied by fields such as flexible electronics, medical rehabilitation, assistant sporting and training, artificial intelligence, mass-data acquisition, and human-computer interaction. The overall situation of publications directly involved with TENG was investigated, and the number of articles from different research institutes were detailed counted and analyzed. The published articles of TENG in the top 20-ranked in scientific journals is demonstrated in Figure 1b.[35] According to the impact factors from the "Journal Citation Reports" in 2017, the articles of nearly 15% were published with the factor value more than 10. In the previous researches, the statistics of TENG article's publication number from different research institutes and universities was reported, which some front-runners include Chinese Acad. Sci. (China), Georgia Inst. Technol. (United States), Natl. Ctr. Nanosci. Technol. (China), Univ. Chinese Acad. Sci. (China), Chongqing Univ. (China), etc., as shown in Figure 1c.[35] By December 2018, TENG research was covered

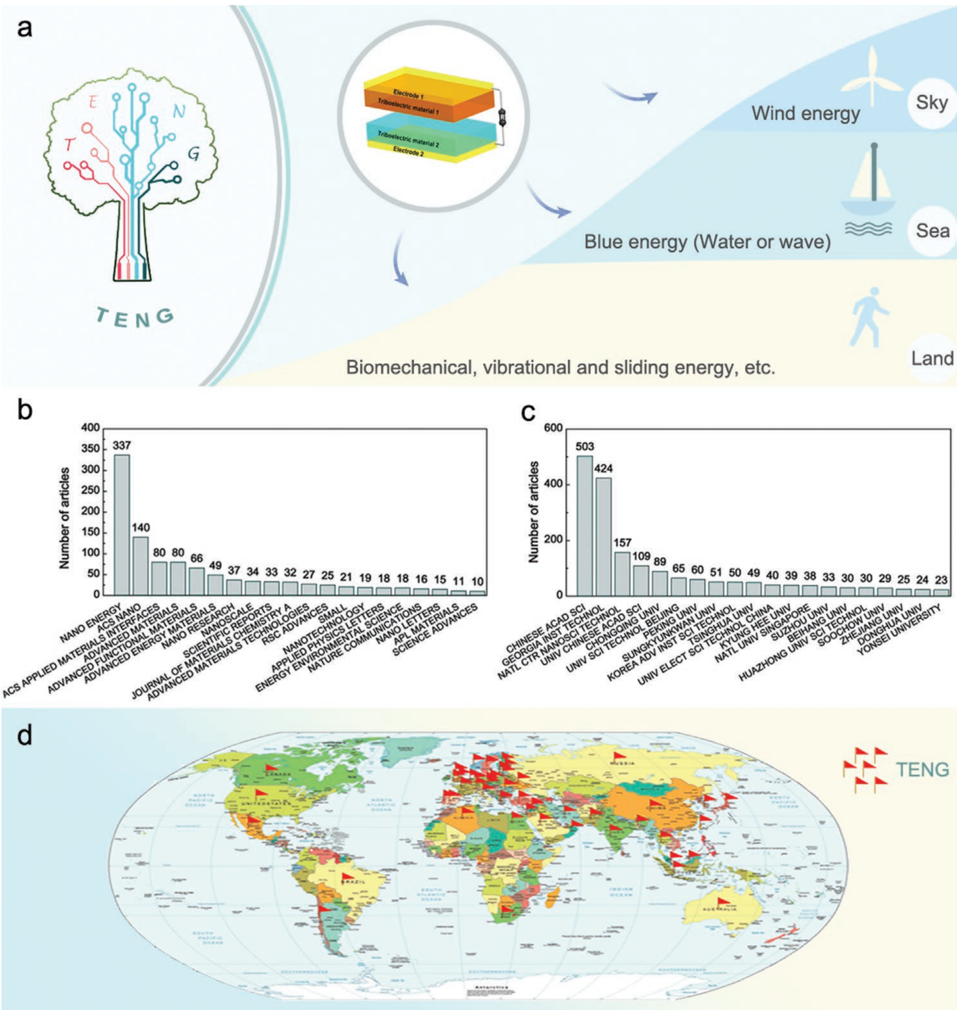

Figure 1. Conceptual diagram and research development of TENGs. a) Conceptual diagram of TENG for harvesting various mechanical energy from the environment. The inset shows the structure of a basic TENG composed by two materials with opposite triboelectric materials and two metallic electrodes. Reproduced with permission.[34] Copyright 2012, Royal Society of Chemistry. b) Number of articles of TENGs published in top 20 scientific journals. Reproduced with permission.[35] Copyright 2019, Wiley-VCH. c) Number of articles of TENGs from different research institutes. Reproduced with permission.[35] Copyright 2019, Wiley-VCH. d) TENGs research conducted by research institutes and universities across six continents globally. Reproduced with permission.[35] Copyright 2019, Wiley-VCH.

more than 40 countries and regions, including six continents of Africa, Asia, Australia, Europe, North America, and South America, as shown in Figure 1d.[35] With an ever-expanding range for researches and institutes, which the great potential of this sustainable energy technology recognized. Existing related work indicates that TENG not only is applicable for the present distributed energy demands, but the perfect example of the sustainable energy for stabilize emissions with carbon neutral in the future.

Although advanced TENGs have been extensively developed and reported for recycling micro-nano HEE so as to face the energy crisis of a new era, several fundamental issues, such as physics principle, working mode, overwhelming superiority, typical applications, and critical challenges etc., are still not comprehensively and systematically overviewed. For emerging TENGs, the basic functionality of this technology and the approaches to incorporate the micro-nano HEE recycling units into traditional electronics and devices are also not roundly summarized. In addition, it is still not clear about the challenges and face difficulties of TENGs in the batched processing. These urgent issues have seriously hindered the process of commercialization and industrialization of TENGs in future sustainable energy. Although this technology continues to progress, and more usable prototypes are continually being developed, there remains a large gap between the current power supply capacity and real energy demands.

Here, toward clean energy and carbon neutral requirements of the new era, a new sustainable energy technology with TENGs for recycling micro-nano HEE is reviewed. It is very necessary for giving periodic reviews of the rapid development in TENGs that for the field to progress. So that, the latest progress should be full-scale debated and provided a significant guidance to the related researchers and institutions, which will be helpful to deepening research and to move forward with the commercialization of this technology. This work also points out the existing challenges, and primary assume is done on the future research direction in the field. Our original intention is not just a summary of what has been achieved, but more importantly is expected to provide a guideline for future study and application.

2. Fundamentals Mechanisms of TENG

2.1. Theoretical Origin

Triboelectrification effect is a ubiquitous natural phenomenon in their natural environment, that's more than 2600 years old. The fundamental physical mechanism of TENG work is a coupled effect between triboelectrification of dielectric material and electrostatic induction of conductor. In which triboelectrification effect producing the positive or negative polarized charges on dielectric material surfaces, and the electrostatic induction causing the conversion of mechanical energy into electrical energy by external triggered in load circuit, which made the scientific breakthrough from 0 to 1. In the segment of the review, the theoretical origin, working modes, self-powered sensing, and power management for the TENGs are systematically discussed. The typical structural TENG is displayed in **Figure 2**a. It has two dielectric films and two corresponding electrode layers connected to load circuit, which could generate alternating current (AC) electrical signal when the contact and separation of the two dielectric materials can change cyclically.[36] The theoretical model of TENG is conforms to the fundamental physical field that the modified displacement current of Maxwell's equations can serve as an acting force for the energy conversion of HEE. In fact, the quantitative description provides a straightforward knowledge of TENGs on the macro-level study, but the theoretical mechanism of TENG has still unclear until it was originated in the displacement current from Maxwell's equations and is defined as

$$J_D = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}_S}{\partial t} \tag{1}$$

where $\boldsymbol{D}$ is a vector field of is the electric displacement, ε referred to as the permittivity and is dimensionless quantity, $\boldsymbol{E}$ call the electric field that defined as the electric force per unit charge, and $\boldsymbol{P}_S$ is the polarized contribution from triboelectrification effect in dielectric material surface. To recapitulate briefly, the time-varying surface polarization was built up by triboelectrification with two dielectric materials. In order to facilitate quantitative analysis and intuitively depiction, this physical model can be simplified as a capacitor model with time-varying capacitances, as shown in Figure 2b.[36] The key, theoretic source of the equivalent model originated in displacement current, so the mathematic expression of TENG's voltage is derived as

$$V = \frac{1}{C(z)} \times Q + V_{OC}(z) \tag{2}$$

This equivalent model is the most effective tool that prompts the quantitative research and development. In addition, triboelectrification phenomena on the micro-level was explained by the potential well model based on the electron cloud interaction,[37] as shown in Figure 2c. The advantage is that the model is appropriate for almost all general materials. At two dielectric materials (A and B) before contact, the electrons have not transfer due to the capture effect of the potential wells. The overlap of electron clouds occurs when A and B material contacts each other, then the electron could be possible to hop from the atom of A to the atom of B. At the A and B after separation, the most of the electrons transferred to B will be kept by the function of the surface barrier. In the proposed model, which is important to point out that reveals the mechanism of electron transfer as main theoretical origin for triboelectrification effect in a general case.

2.2. Four Working Modes

As mentioned above, due to the triboelectric polarities and electrodes configuration, which TENGs can be summarized in four fundamental working modes, as follows contact-separation (C-S), lateral-sliding (L-S), single-electrode (S-E), and freestanding triboelectric-layer (F-T-L), typical structures of these modes are schematically illustrated in **Figure 3**.[26] These four

 © 2022 Wiley-VCH GmbH

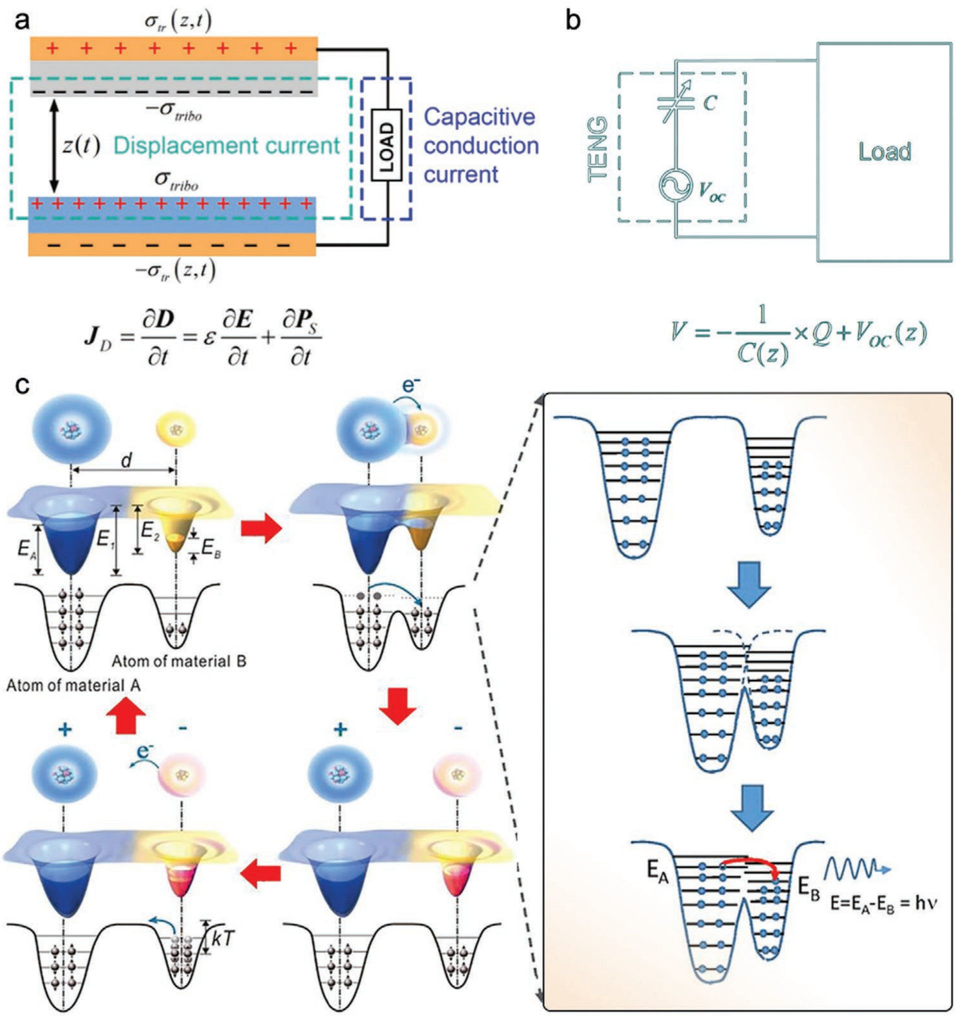

Figure 2. Displacement current model and electron-cloud–potential-well model of TENG. a) The displacement current model of a contact-separation mode TENG. Reproduced with permission.[36] Copyright 2018, Wiley-VCH. b) The simplified capacitive model of TENG. Reproduced with permission.[36] Copyright 2018, Wiley-VCH. c) Electron-cloud–potential-well model of TENG and charge transfer and release between two materials. Reproduced with permission.[37] Copyright 2018, Wiley-VCH.

modes can cover overwhelming majority of micro-nano HEE to achieve energy conversion, such as biomechanical energy, mechanical vibration/triggering/rotating/sliding, wind, flowing water and ocean wave. According to the structure and operation characteristics, while each of the four fundamental working modes have its own advantages, electrical output performances, scope of application and target requirements.

The C-S mode is the most typical structure of TENG, which the main characteristics of structure need to keep a relative movement and a large clearance. The advantages include pump output, higher open circuit voltage, and wide applications such as vibration, pressing and impacting, etc. The L-S mode has significant structural characteristics, including translational motion and rotation, which leads to advantages of high short-circuit current and high frequency. The S-E mode is most applicable to relatively independent object and inconvenient to process electrode on its surface, such as biological movement (walking, wings shaking, finger typing, panting, etc.), spinning car tires, electronic skin and more. The existing studies confirmed that the S-E mode has the advantages of easy fabrication, simplicity of structure, and therefore be more easily used on electronic skin and flexible electronics field. The F-T-L mode possess the advantages on micro-nano HEE harvesting from randomly moving with no grounding electrode compared to the S-L mode, which has a lower voltage, high current, and high conversion efficiency. Output performances of this mode strongly depend on the appropriate area of triboelectric layer, operating frequency, and the gap of electrode layer, which is suitable for different forms of micro-nano HEE such as sliding, vibratory and rotational. Overall, these four fundamental working modes and their advantages have been in-depth researched in published works, and thus are not to expand upon this discussion in detail here.

2.3. Self-Powered System (SPS)

As is known to all, TENG is fundamentally AC power sources due to own capacitive model does not conduct direct current

© 2022 Wiley-VCH GmbH

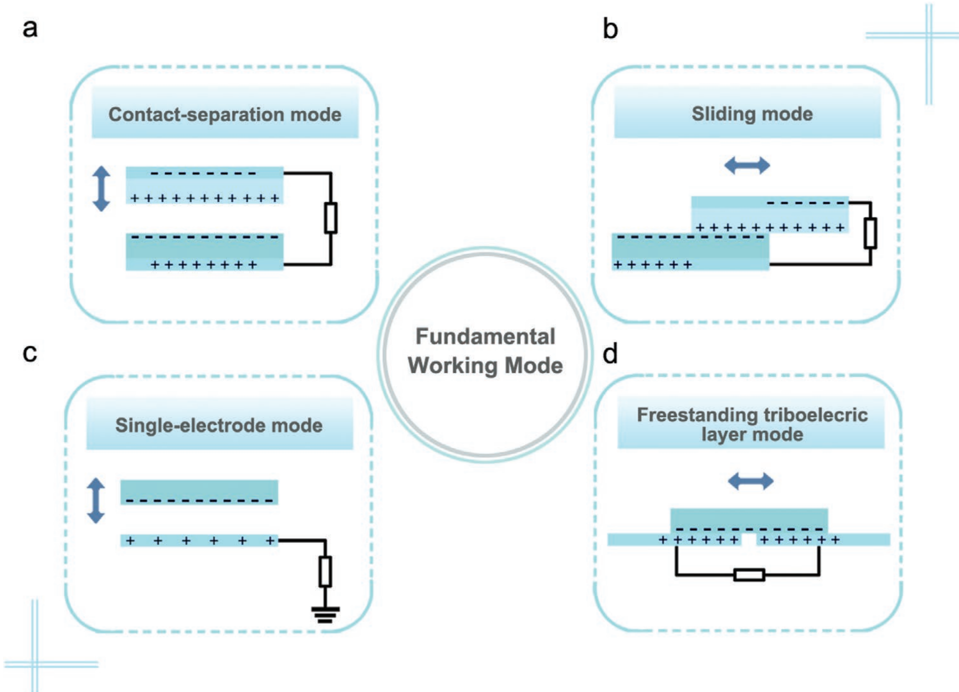

Figure 3. The four fundamental modes of TENG. a) The contact-separation mode. b) The lateral sliding mode. c) The single-electrode mode. d) The freestanding triboelectric-layer mode. Reproduced with permission.[26] Copyright 2016, Elsevier Ltd.

(DC), the resistance is infinite. From this, some AC loads such as commercial light emitting diodes (LEDs), light bulbs, electroluminescence devices, and low-temperature plasma through the TENGs direct drive. Since the instantaneous short-circuit current is lower, therefore it cannot be used as the power source directly to drive other electron devices, such as all kinds of chips, electronic thermometer, sensor, warning device, etc. If the TENG wants as a stable power source to use for all kinds of electronic products and chips, while a unit of energy storage by a charging battery or a high-capacity capacitor is necessary to serve the SPS.

Illustration of a completely TENG-based SPS is exhibited in **Figure 4**a, the concept by integrating an energy harvesting unit based on TENG, power management system, a unit of energy storage and loading circuits for various practical applications.[38] Firstly, TENG recycles all kinds of micro-nano HEE and converts it to AC electricity, then AC electricity is stored and converted to a DC output by the power management system and to form energy storage a unit of power storage. Finally, this sustainable power can serve as a stable DC electricity for the loading circuits, with it specifically consists of different sensors, microcontroller, processors, displays, single chip microcomputer, and wireless transmitters. In this chapter, the wireframes of self-powered system can provide a clear path for better cognition TENG for a lag between theoretical research and practical applications. There is no doubt that its industrialization should be coordinated with multidisciplinary of science and trades, and still depend on relative technical personnel and researchers to work together jointly to grow and develop. This TENG-based SPS for various extension of practical applications is displayed in Figure 4b. The example presented above have covered mobile and wearable electronic products, sensors, and chips, which have broad applications in health, medical rehabilitation, big data, safety monitoring, and Internet of Things.[39] Besides harvesting biomechanical HEE, this conceptual design also applies to other mechanical HEE in the environment, even high-frequency mechanical vibration/oscillation, such as moving vehicles, vibrating mechanical equipment, wind, water, and oceans waves.

2.4. Power Management System (PMS)

Based on the above, it is noticed that a universal PMS is critical for any practical application of TENG. It is used to converting intermittent and pump alternating current electrical outputs of TENG to steady direct current for improving conversion efficiency and energy storage in high efficiency. Due to the randomness of micro-nano HEE, PMS plays a critical role between distributed TENG and hundreds of millions of electronic devices. Because of the TENG always mismatches with the impedance of load, and thus leading an inefficient of energy efficiency in real-world applications, when directly powering electronics and storing generated power. Therefore, a PMS with high-efficiency and universality is urgently needed and has important implications for the actual applications of a TENG-based sustainable power source.

The rapid development of HEE harvesting technology put forward higher requirement for the transformation efficiency of PMS. In the recent years, various types of PMS are developed based on the s switched-capacitor convertor principle that well improving the output behavior of TENG and their main topological structures are basically identical. Their main different is the design of logical discharge switch. A self-charging power system is developed by exploiting biomechanical HEE, which reached the instantaneous efficiency of nearly 90% and total efficiency of 60% for sustainable working of low-power wearable electronics, as shown

 © 2022 Wiley-VCH GmbH

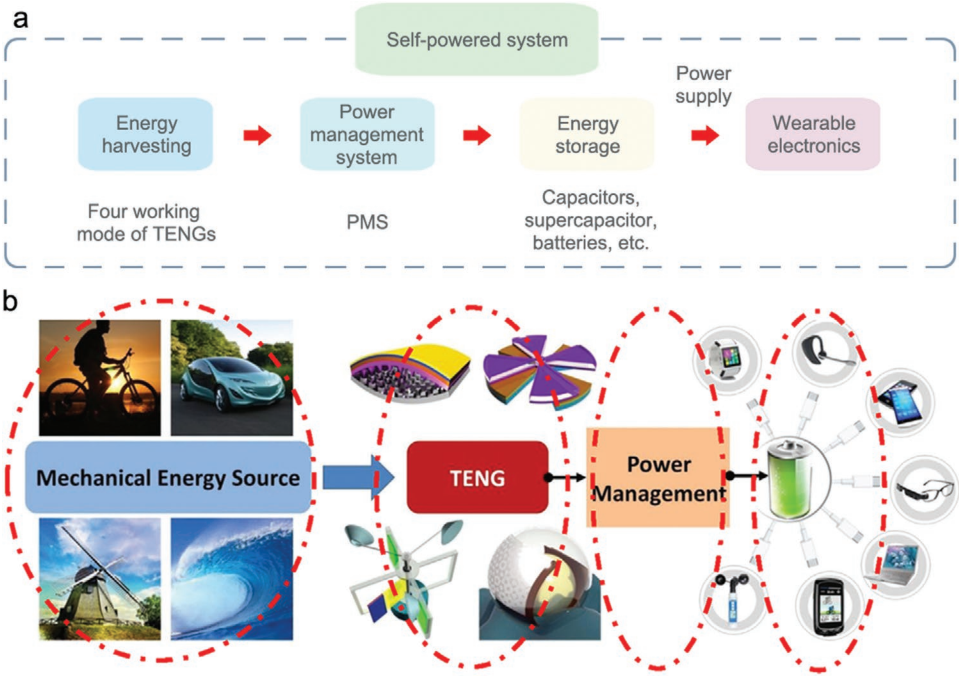

Figure 4. Illustration and application extension of TENG-based self-powered system. a) System diagram of a TENG-based self-powered system. b) The concept of self-powered system by integrating a triboelectric nanogenerator, power management circuit, energy storage unit for various applications as a universal adaptable power source. Reproduced with permission.[38] Copyright 2015, Springer Nature.

in **Figure 5**a.[38] Fractal design based switched-capacitor-convertors is fabricated, and it possesses over 94% conversion efficiency and a great feature of multistage reducing voltage (Figure 5b).[40] With tendency of high-frequency and high-integration, this design principle has displayed tremendous potential applications. However, existing various topology structures of PMS are hard to meet all requirements of practical application, which commercialization is a long way from being reality yet, these factors include acceptable performance, cost, durability, size, technological process, etc.

3. Progress in Applications of TENG

3.1. Micro-Nano Distributed Power Sources (MDPS)

Trillions of distributed wireless nodes need to be powered one by one with the rapidly expanding of the Internet of Things. New technology based on TENG that can harvest micro-nano mechanical HEE and as a self-sufficient MDPS which is newly emerging field that is typical applications of nanomaterial

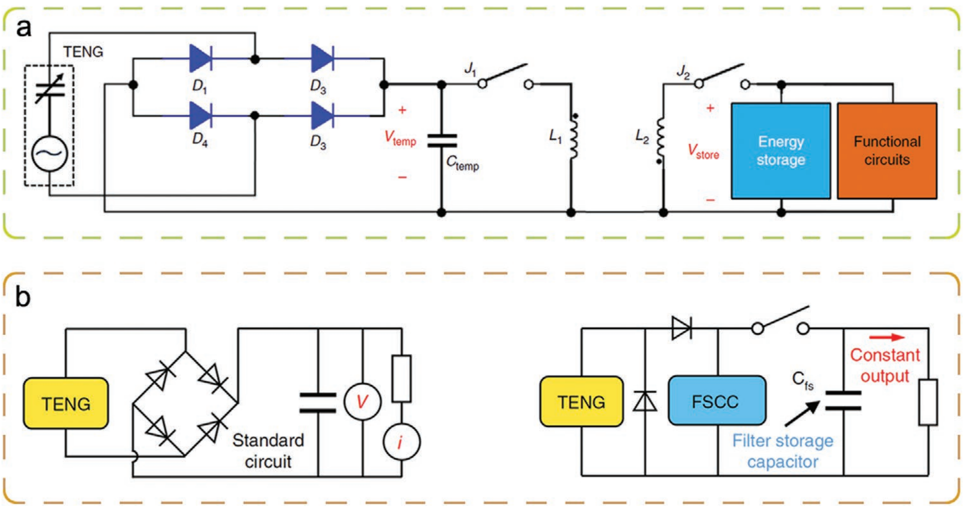

Figure 5. Typical designs of power management system to improve energy conversion efficiency. a) Circuit diagram of self-charging power system with 90% board efficiency and 60% total efficiency. Reproduced with permission.[38] Copyright 2015, Springer Nature. b) Circuit diagram of fractal design based switched-capacitor-convertors with over 94% conversion efficiency and step-down function. Reproduced with permission.[40] Copyright 2020, Springer Nature.

 © 2022 Wiley-VCH GmbH

and nanoenergy for powering billions of electronics. Representative structures of TENG are used in MDPS by harvesting mechanical energy coming from the sky, sea, and ground, as shown in **Figure 6**, which including converting human biomechanical energy into electricity,[41] from ocean waves energy to electricity,[42] from wind energy to electricity.[43] For a MDPS example, a flexible 3D TENG is developed by 3D printing that can be integrated into the shoes to power wearable electronics by harvest biomechanical HEE from human walking (Figure 6a). Wang et al. reported a flexible seaweed-like TENG to harvest ocean wave HEE, which the device is converted to electricity under wave excitations by bending and wiggling (Figure 6b). Furthermore, the electrical output was systematic tested, which a S-TENGs network have confirmed to be effective in powering hundreds of commercial LEDs. The C-S mode TENG is designed and optimized by Liu et al. to harvest wind energy in the environment (Figure 6c). Above all, only a few typical applications of TENG are presented when seen as a MDPS from the point of application scenarios. Even so, the TENG-based MDPS played an important role by utilizing mechanical HEE from environment.

3.2. Self-Powered Sensing System (SPSS)

TENG can produce matched electrical signal with the external response from the ambient mechanical HEE. Further studies confirmed that the amplitude and frequency of electrical signal reflect the strength of the mechanical HEE, which can direct transform the trigging of mechanical HEE to electrical signals

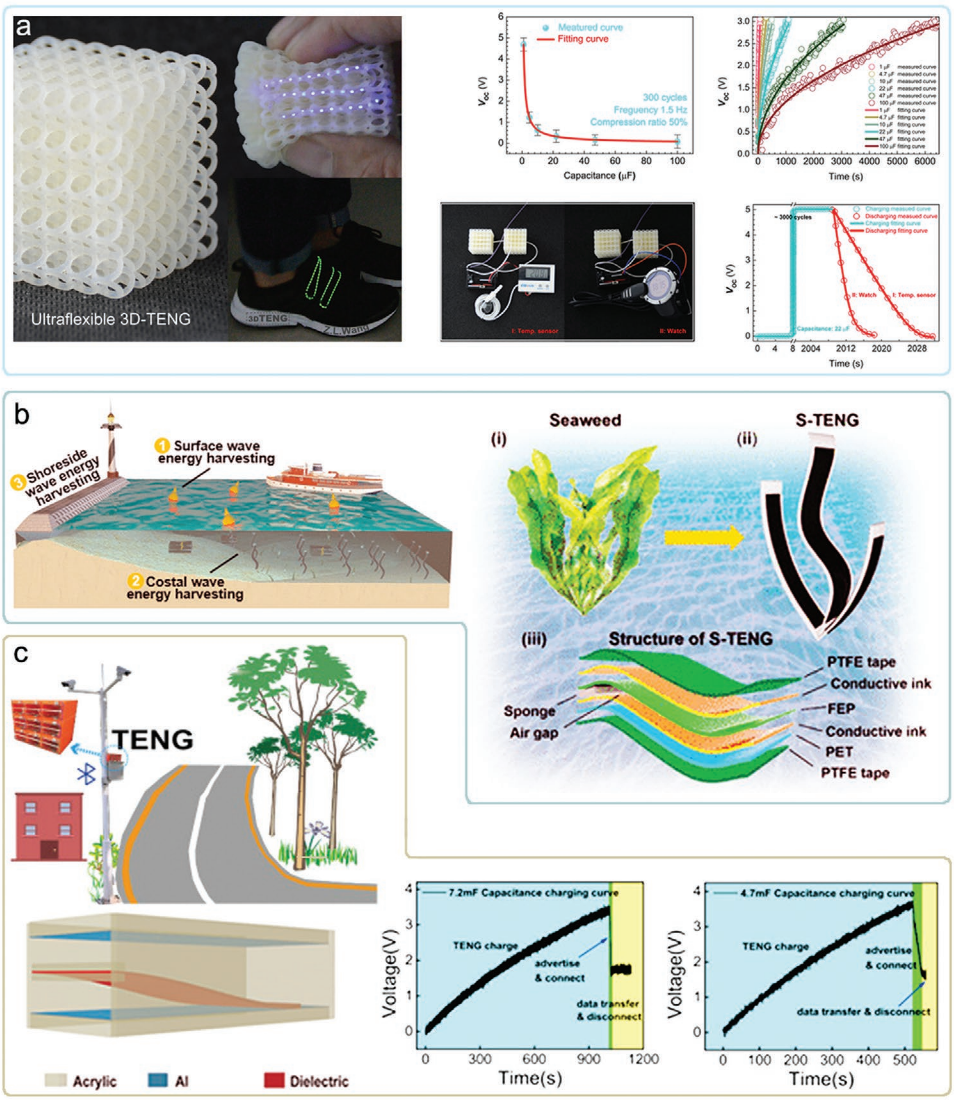

Figure 6. Representative application instances of TENG for distributed power sources by harvesting mechanical energy in the environment. a) Schematic diagram of ultraflexible and 3D triboelectric nanogenerator for harvesting biomechanical energy. Reproduced with permission.[41] Copyright 2018, Elsevier Ltd. b) Schematic diagram of flexible seaweed-like triboelectric nanogenerator for harvesting wave energy. Reproduced with permission.[42] Copyright 2021, American Chemical Society. c) Schematic diagram of wind-driven self-powered wireless environmental sensing system. Reproduced with permission.[43] Copyright 2020, Elsevier Ltd.

 © 2022 Wiley-VCH GmbH

without additional the signal conversion circuit, characterizing it as a SPSS. In addition, the number of transferred charges in triboelectric material surface are one of the surest indicators of the sensing performance. Therein the characteristic of mechanical input could be obtained by analyzing the generated voltage or current signal, such as like pressure, motion, vibration, sliding, etc. The exploitation and utilization of the active SPSS hold tremendous potential, which requires extremely low standby power or without, most simplified circuits, thinner structure, and lower cost than traditional passive sensing systems.

Related highlighting SPSS works, such angle sensors, touch sensors, acoustic sensors, acceleration sensors, chemical sensors, and all kinds of electronic skin and technical issue are discussed. The results indicated that the active TENG-based sensor can operate as a sensitive triboelectric angle sensor, which high resolution with 2.03 nanoradian by a systematic optimization is exhibited in **Figure 7**a. This active angle sensor can be integrated into a medical device to monitor the activities of knee, and may be conducive to promoting rehabilitation of knee disease.[44] The real-time respiratory and sleep SPSS is reported based on a specially designed TENG by Peng et al., which has plenty of advantages, such as breathable, highly sensitive and stability, high air permeability and self-powered operation, as shown in Figure 7b. The result showed that the peak power density is 330 mW m^{-1} and the sensitivity of pressure is 0.217 kPa. This design offers a practical scheme for respiration and sleep SPSS to achieve the timely breathing diseases clinical monitoring.[45] Furthermore, a triboelectric auditory sensor with SPSS function is proposed, which strategy might even find its

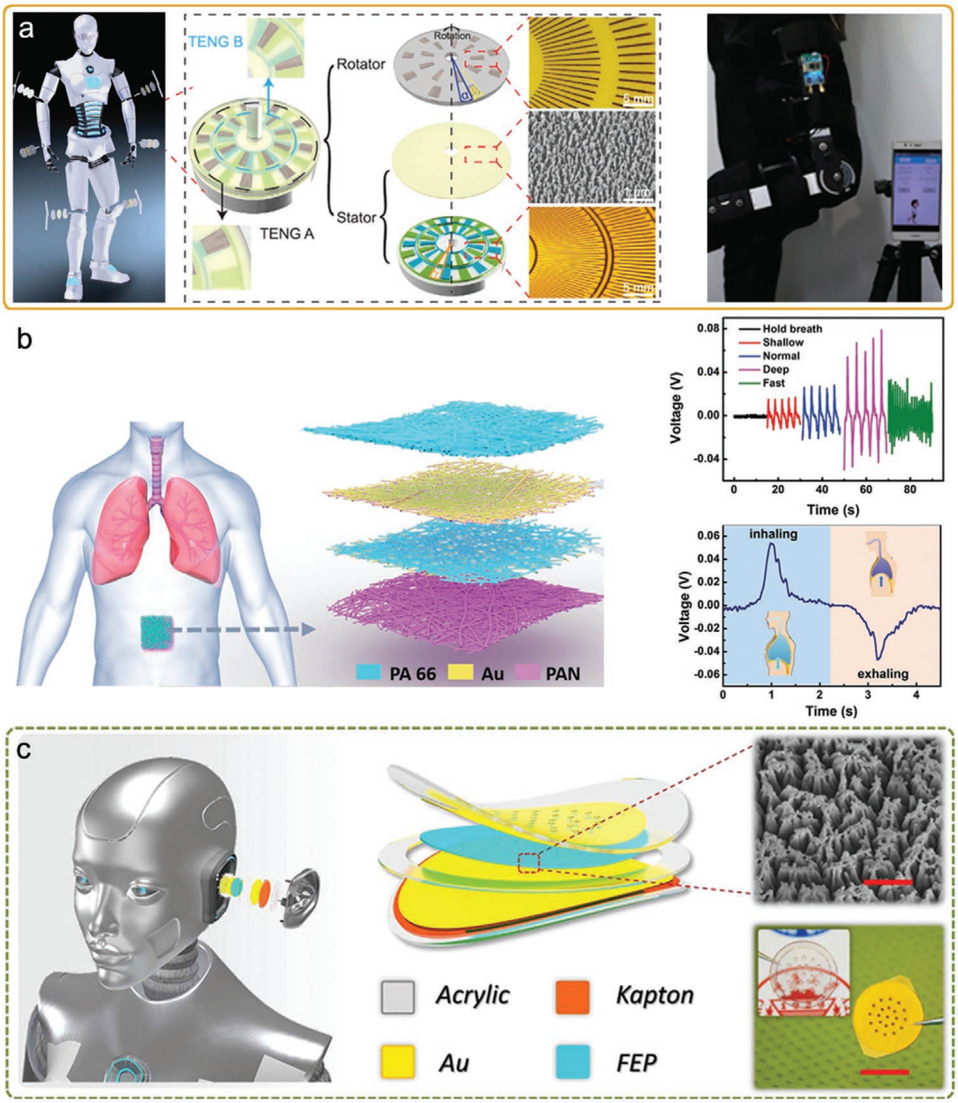

Figure 7. Representative application instances of TENG for active sensing and self-powered sensors by harvesting mechanical energy in the environment. a) Schematic diagram of triboelectric self-powered angle sensor. Reproduced with permission.[44] Copyright 2020, Wiley-VCH. b) Schematic diagram of self-powered electronic skin based on a triboelectric nanogenerator. Reproduced with permission.[45] Copyright 2021, Wiley-VCH. c) Schematic diagram of self-powered triboelectric auditory sensor for constructing an electronic auditory system and an architecture for an external hearing aid in intelligent robotic applications. Reproduced with permission.[46] Copyright 2018, AAAS.

 © 2022 Wiley-VCH GmbH

way into bioinspired robot design by this active auditory system (Figure 7c). A broadband SPSS with the response range of 100–5000 Hz was developed by comprehensively optimizing design, and a series of issues such as high energy-consuming, complexity and cost were improved.[46]

3.3. High-Voltage Power Source (HVPS)

TENG is aiming at harnessing much underutilized and wasted mechanical HEE, it's not only a sustainable and high conversion efficiency energy technology, but also has high sensibility of mechanical triggering. Beyond that, the exclusive advantages of high voltage and low current make TENG as a new candidate technology of existing HVPS due to then-unheard-of safety and portability. The potential applications of HVPS have been developed with various types, such as indoor air purification, triboelectric plasma, catalysis, electrochemistry and electroluminescence. Especially, as a direct HVPS which has the ability of driving electrostriction materials, that indicates this characteristic of high-voltage has broad application foreground. In 2021, a practicable application demo, the triboelectric soft robot (TSR) system is proposed by Liu et al. (**Figure 8**a). The research shows that the TSR with bioinspired soft body and two adhesion feet, which is driven from the triboelectrification effect caused by mechanical energy, and the speeds up to 14.9 mm s^{-1}.[47] Cheng et al. present a concept of triboelectric microplasma (TEMP) based on the high-voltage TENG (Figure 8b). The TEMP has been used to luminescence and surface preparation by detailed experiments, and the practical results shows the concept is

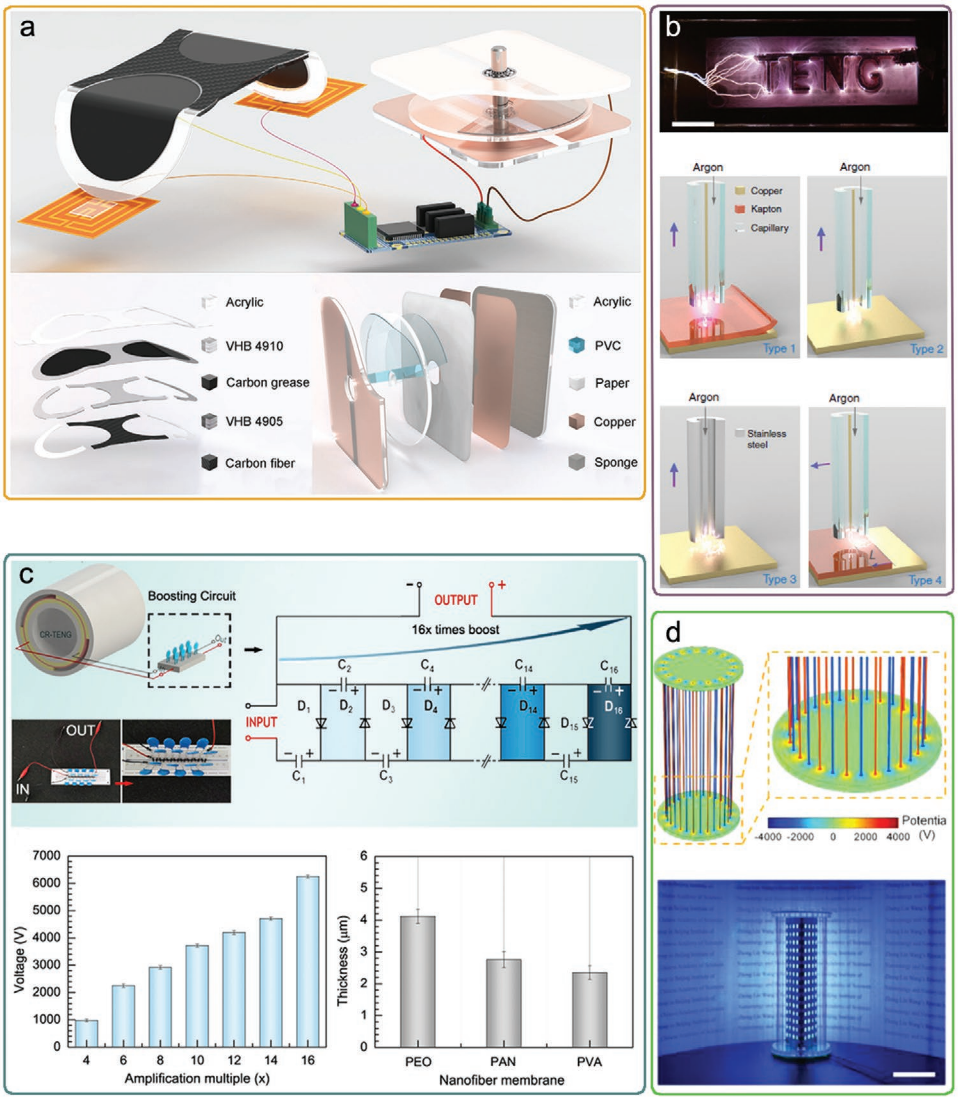

Figure 8. Representative application instances of TENG for direct high-voltage power sources. a) Schematic diagram of triboelectric soft robot (TESR) system. Reproduced with permission.[47] Copyright 2021, Wiley-VCH. b) Schematic diagram of triboelectric micro-plasma by integrating TENG. Reproduced with permission.[48] Copyright 2018, Springer Nature. c) Schematic diagram of electro-blown spinning (EBS) methodology based on a cylindrical rotating (CR) TENG. Reproduced with permission.[49] Copyright 2020, Elsevier Ltd. d) Schematic diagram of high-performance and durable TENG for self-powered medical health improvement. Reproduced with permission.[50] Copyright 2021, Elsevier Ltd.

© 2022 Wiley-VCH GmbH

feasible and effective. In particular, this new technology may provide a effective program to deal with plasma with no additional HVPS required.[48] Liu et al. report an new electro-blown spinning methodology based on a cylindrical rotating TENG, which is high-voltage, fast, efficient and low cost for fabricating the polymer nanofiber. The drical rotating TENG serves both as a direct high-voltage power source and as a receiver of fabricated nanofibers (Figure 8c). The study achieve combination of assisted blowing and high-voltage TENG, give a new novel supplement to the future spinning technologies.[49] For the last two years, the prevention and control of contagious disease are really urgency for public health challenges around the world. A high performance medical improvement system with a durable high-voltage TENG is developed by Luo et al., the electrical output performance of double triboelectric layers is improved by nearly 65% compared to single layer (Figure 8d). In this study, the high-voltage TENG driven by wind energy as a direct power sources, which is further used to fabricated the mosquito killing and ultraviolet sterilization system, while the mosquito population and bacterial reproduction can be controlled, therebyr educing the risk of disease transmission.[50] The above typical appliacation shows TENG performance highlighting, structure simple, light weight, and run stableness in whole self-powered system and proves the sustainability, validity and feasibility of this direct high-voltage power source.

3.4. Large-Scale Blue Energy (LSBE)

Water wave is one of the abundant low- frequency HEE sources and widely distributed in rivers, lakes, and seas, which can collectively be called "blue energy," but existing harvesting technology of blue energy are still relying on relies on electromagnetic generator now. This traditional approach has a few limitations for harvesting LSBE, which it cost is high and its conversion efficiency is low due to the high-quality materials and low frequency mechanical energy (<3 Hz). Therefore, a high conversion efficiency and low-cost technology that can harvest LSBE is greatly desirable to face the above difficulties.

Toward LSBE harvesting, a lot of work is focused on this new route with TENG in the past nearly 5 years which aiming to deal with simple, reliable, cost-effective. Compared with existing study results, a ball-TENG networks based on coupling design in for these difficulties is reported by Xu in 2018, which the number of transferred charges is improved over 10 times (**Figure 9**a). [51] In which, the way of flexible connection designs and show better performance in the networks of three different connecting. Zhang et al. report an active resonance system based on TENG by using complex tumbler-pendulum design, which can harvest low-frequency and varying, poly-directional LSBE (Figure 9b). The entire system has benefited what the electrical output of this device can be obvious enhanced by the complex tumbler-pendulum design[52] In 2021, a new TENG is fabricated by the design of segmented structure for harvesting underwater LSBE (Figure 9c), which the maximum peak power and average power reaches 6.2 and 0.74 mW, respectively.[53] Furthermore, a self-powered example of application is verified for LSBE harvesting and laid a solid foundation for smart oceans. In addition, the low wear resistance of existing triboelectric materials limits its practical applications and may undermines stability and reliability. The electric output more than 10 times is observed by animal furs compared with the conventional TENG, which owing to their superiorities of low-wear and humidity resistance (Figure 9d).[54] In brief, the various energies were recycled by TENG from all kinds of HEE, is not only new energy harvesting technology, but will become a new self-sufficient sustainable power source of Internet of Things, 5G, and future 6G.

4. Overwhelming Superiority and Challenges

Above all, the ubiquitous triboelectrification effect prompts TENGs with more applicability, controllability, diversification, and more significant that the designed possibilities and material's universality are more practicability and has greater potential. Self-sufficient MDPS and SPSS based on TENG technologies will impact the development of wearable technologies, micro-electronics, and Internet of Things, and the future holds even brighter prospects. The frame diagram of TENG's overwhelming superiority is shown in **Figure 10**a, which cover three main aspects: including universal applicable structure, wide choice of materials and low-frequency working conditions. Here, the overwhelming superiorities are demonstrated, as follows:

4.1. Universal Applicable Structure

Numerous typical structures of TENG devices cover the latest research progress. So far, a plentiful structure of TENGs have been fabricated for various applications in MDPS, SPSS, HVPS, and LSBE. Representative structures of TENGs in practical application are indicated in Figure 10b. In view of the gratifying performance and potential, and one is that benefit by a universal structure, including i) thin film, ii) grid shaped turntable, iii) arched, iv) array, v) thread, and vi) multilayer.[55–60] In order to deal with different occasions, it all has owing to universal triboelectrification effect offers the infinite possibilities of diversified design for the various structures.

4.2. Wide Choice of Triboelectric Materials

With the building of standardized surface charge density conception, the triboelectrification series is widely used to choose best-matched triboelectric materials for optimizing performance (Figure 10b). Thus, this contributed to the functional triboelectric materials are extended to the field of conventional materials, such as semiconductors (SiO_2, TiO_2, HfO_2, ZnO, SnO_2, MgO, HfO_2, Ta_2O_5, $BaTiO_3$) and polymers (styrene, polyethylene, polylactic acid, nylon, polyethylene glycol, polytetrafluoroethylene, polydimethylsiloxane, poly tetra fluoroethylene).[61–62] In a word, all kinds of performance of triboelectric materials had been extensively researched, and are used for fabrication of the multifarious TENG devices and an encouraging result has been achieved in last nearly 10 years.

 © 2022 Wiley-VCH GmbH

Figure 9. Representative application instances to capture the energy from water or ocean waves using TENG. a) Schematic diagram of coupling design in TENG networks. Reproduced with permission.[51] Copyright 2018, American Chemical Society. b) Schematic diagram of active resonance triboelectric nanogenerator (AR-TENG). Reproduced with permission.[52] Copyright 2021, Elsevier Ltd. c) Schematic diagram of segmented swing-structured fur-based TENG (SSF-TENG). Reproduced with permission.[53] Copyright 2021, Wiley-VCH. d) Schematic diagram of the fur-brush triboelectric nanogenerator (FB-TENG). Reproduced with permission.[54] Copyright 2021, Wiley-VCH.

4.3. Low-Frequency Working Conditions

Besides the light-weight and low-cost in the process of collecting micro-nano mechanical HEE, TENG is much adaptive and high conversion efficiency than electromagnetic generator. Most importantly, TENGs have a high conversion efficiency at less than 3 Hz of operating frequency, as shown in Figure 10c. [63–65] The output voltage depends on the generated triboelectric charges on the material surface and systemic capacitance. In addition, the short-circuit current and output power is proportional to its operating frequency, and the output power is much higher than electromagnetic generator at low-frequency.

In the process of researches in HEE harvesting and SPSS, that a series of great achievements of TENGs have been achieved. It is foreknowing that the sustainable energy technology will have a significant impact in SPSS. Existing difficulties of TENGs are concluded from eight principal aspects, as shown in **Figure 11**, including a) electrical output performance, b) power management system, c) mechanical stability and durability, d) new type of triboelectric materials, e) applications and market promotion, f) fabrication process, h) principles and mechanisms, i) surface charge density.[66,57,67,68,41,24,47,69,62] The next striving continues to achieves the aims of commercial TENG with high-efficiency, reliability and practicality revolves around the eight indispensable aspects.

5. Conclusion and Perspective

Since in 1831, the invention of electromagnetic induction by Faraday, which electromagnetic generator can be converting

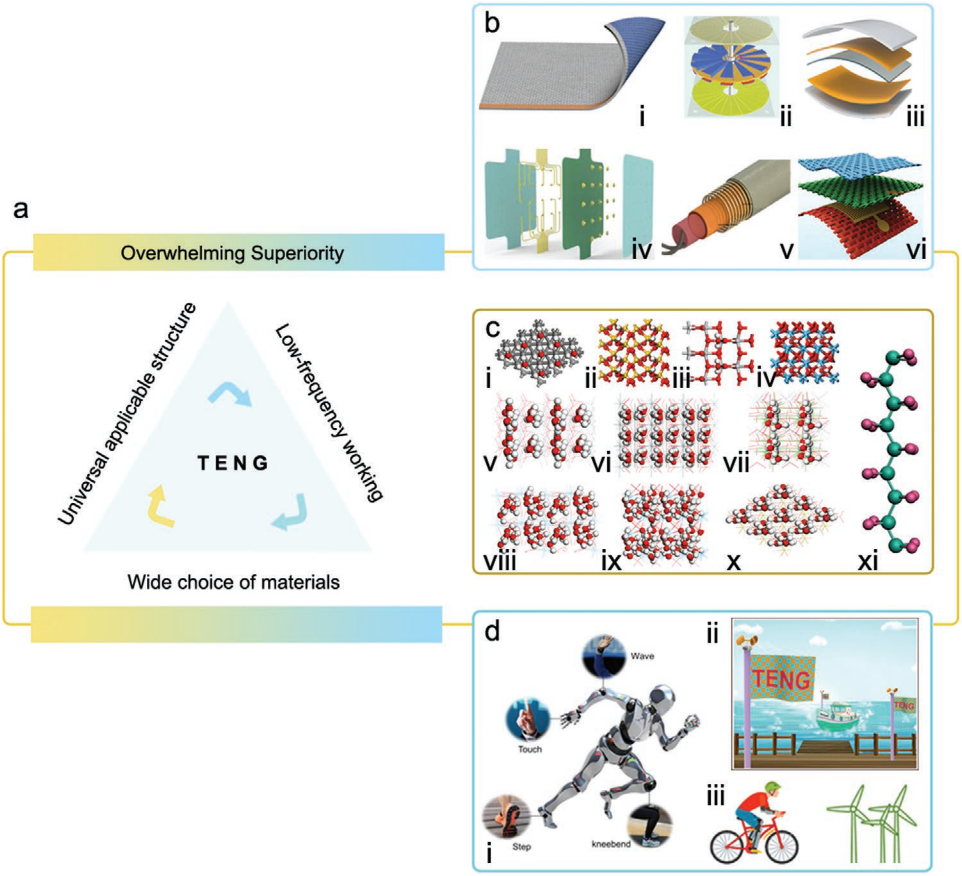

Figure 10. Overwhelming superiorities of the TENG technology and its own typical examples. a) Concept sketch of the TENG's overwhelming superiorities, which mainly cover universal applicable structures, wide choice of materials and low-frequency working. b) Universal applicable structures of the TENGs in practical applications. bi) Reproduced with permission.[55] Copyright 2021, Royal Society of Chemistry. bii) Reproduced with permission.[56] Copyright 2021, American Chemical Society. biii) Reproduced with permission.[57] Copyright 2021, Wiley-VCH. biv) Reproduced with permission.[58] Copyright 2021, AAAS. bv) Reproduced with permission.[59] Copyright 2021, American Chemical Society. bvi) Reproduced with permission.[60] Copyright 2021, Springer. c) Wide choice of materials for the fabrication of the TENGs include C (i), SiO_2 (ii), TiO_2 (iii), HfO_2 (iv), ZnO (v), SnO_2 (vi), MgO (vii), HfO_2 (viii), Ta_2O_5 (ix), $BaTiO_3$ (x), and PTFE (xi). ci-cx) Reproduced with permission.[61] Copyright 2021, Springer Nature. cxi) Reproduced with permission.[62] Copyright 2017, Springer. (d) Low-frequency working range of the TENGs involve with biomechanical energy, water wave and ocean energy, weak and irregular wind energy, and other micro-nano mechanical energy. di) Reproduced with permission.[63] Copyright 2019, Elsevier Ltd. dii) Reproduced with permission.[64] Copyright 2021, American Chemical Society. diii) Reproduced with permission.[65] Copyright 2020, Elsevier Ltd.

high-frequency mechanical energy into electricity. In fact, the physical mechanism of TENG is dominated by the modified displacement current equation, and is also owning more high conversion efficiency at several Hertz. In regards to irregular, random, and low-frequency HEE, and TENGs are most effective, which is what a new era needs toward the sustainable energy.

From the discovery of TENG (also called as Wang generator) in 2012 by Wang, its rapid development has quickly excited many researchers and institutions, which change the way of power supply from traditional concentrated to distributed energy. By Aug. 2021, it has more than 60 countries and regions, over 800 research units and by more than 6000 top engineers and scientists on research filed of TENGs, self-powered sensors and system, as well as the numbers are rising. According to statistics, TENG is mainly face the four major fields in practical application, as shown in **Figure 12**a. First, TENG is a MDPS for building a SPSS by integrated with existing sensors, electronic components, and functional circuit. As a sustainable self-sufficient power supply, distributed TENGs can form a sensor network for sensing and monitoring, including forest/prairie fire prevention, climate change/coastal/hydrological monitoring, health-care monitoring, animal tracking, etc. These disordered sensor network could be powered by the TENG-based MDPS, which it only need to harvest mechanical energy from its surroundings (Figure 12b).[69] Second, TENG can be used as an active SPSS for sensing motion and trigger in many kinds of new technology domains, such as artificial intelligence, human-computer interface, robotics, precaution, assistance, and security. Third, TENG can be a HVPS with a range of 1–10 kV in interrelated application scenarios, such as indoor air purification, triboelectric plasma, catalysis, electrochemistry and electroluminescence, electrostriction and more. Finally, integrate TENG units into a giant array that can be widely applied to the lakes, seas, and rivers for wave energy harvesting, and is referred as LSBE. To deal with global climate change and to be carbon neutral, it is inevitable to harvest LSBE to combat climate change and to meet ever-increasing

 © 2022 Wiley-VCH GmbH

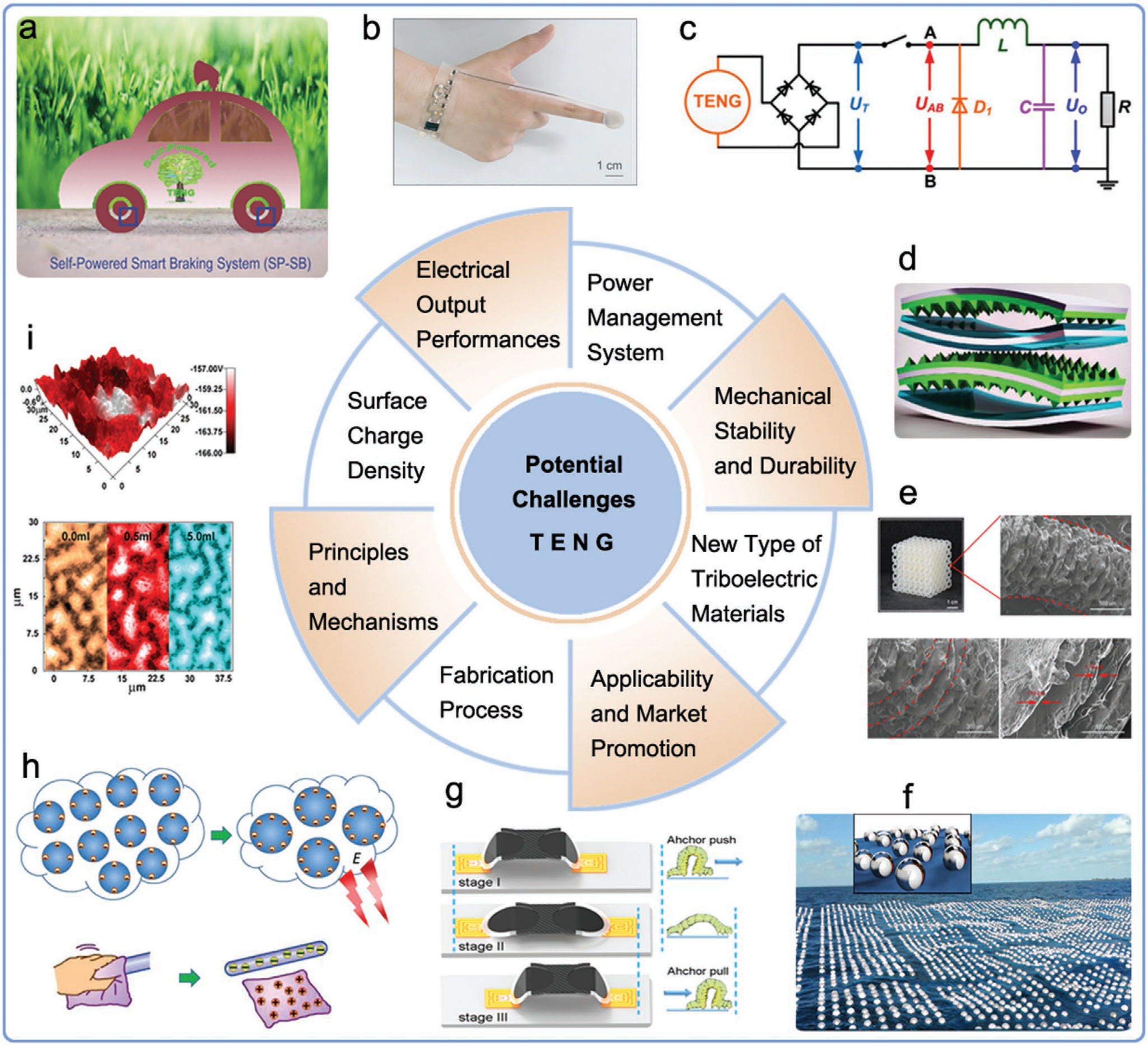

Figure 11. Potential challenges of TENG from eight principal aspects. a) Schematic diagram of harsh-environmental-resistant TENG. Reproduced with permission.[66] Copyright 2018, Wiley-VCH. b) Schematic diagram of integrated elastic-arched TENG. Reproduced with permission.[57] Copyright 2018, Wiley-VCH. c) Universal power management strategy for TENG. Reproduced with permission.[67] Copyright 2017, Elsevier Ltd. d) Investigation of power generation based on stacked TENG. Reproduced with permission.[68] Copyright 2013, Elsevier Ltd. e) Schematic diagram of 3D ultraflexible TENG. Reproduced with permission.[41] Copyright 2018, Elsevier Ltd. f) Schematic diagram of the blue energy dream by TENG networks. Reproduced with permission.[24] Copyright 2017, Elsevier Ltd. g) Bioinspired triboelectric soft robot driven by mechanical energy. Reproduced with permission.[47] Copyright 2021, Wiley-VCH. h) On the origin of contact-electrification. Reproduced with permission.[69] Copyright 2019, Elsevier Ltd. i) Au nanocomposite enhanced electret film for TENG. Reproduced with permission.[62] Copyright 2018, Springer.

energy demand. This is a brand-new understanding for the sustainable energy field.

The challenges and difficulties of TENGs are still too daunting face toward industrialized markets at this stage. Although this technology consistent innovation and toward a more applied goal progress, the greater disparity still exists between the power supply capacity, durability and stability with real demands. In addition, another critical challenges for large-scale applications of TENG is how to provide the most effective and economic approach to realize a good compatibility with existing electronic industry and engineering technologies. Based on the above, a striving direction of TENG development is proposed for summarized: design innovation, device & performance, industrialization, and system & integration, as shown in Figure 12c. These urgent issues have greatly bound the development of commercialization and industrialization of TENGs in future sustainable energy, which results in large gap between the current devices and real applications. In the first

© 2022 Wiley-VCH GmbH

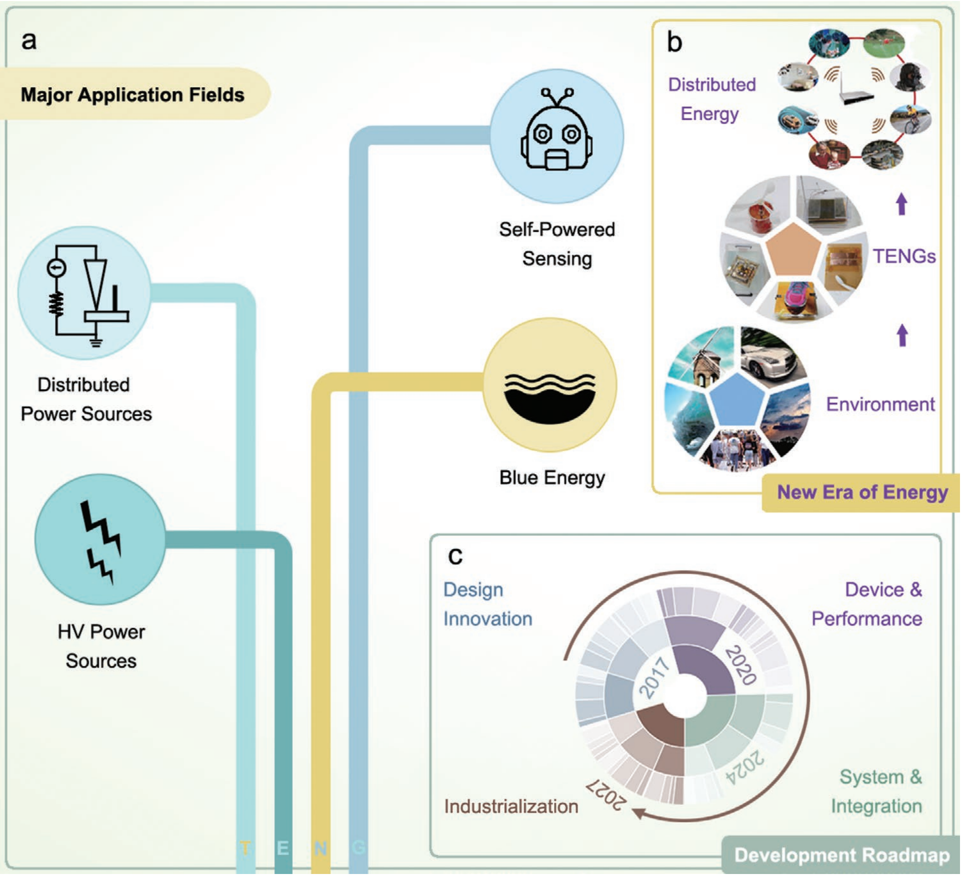

Figure 12. Promising application fields and striving direction of TENG development. a) The major application fields of TENG involve four key respects: micro-nano distributed power sources, self-powered sensing, direct high-voltage power sources, large-scale blue energy. b) Environmental mechanical energy harvesting by various TENGs with the PMM, such as human walking, natural wind, vibration, wave and raindrop for distributed wireless sensor networks and new era of energy. Reproduced with permission.[69] Copyright 2017, Elsevier Ltd. c) Development roadmap of TENGs involve four key respects: design innovation, device & performance, industrialization, and system & integration.

place, the design innovation is demanded, it is how to optimize the configuration and structure of TENG for conjoining the market needs.[70] In the second place, for the device & performance, the most suitable triboelectric material is chosen and its preparation for achieving optimum performance, durability, and stability.[71] In the third place, the system integration is essential to effective harvesting HEE, which the prototype testing and pilot product development of TENGs are necessary process of growth.[72] In the fourth place, industrialization is the goal of any technology, and may a chance to change the world like the industrial revolution and this is just as true for TENGs.

In brief, with the world's entry into rapidly information new age, the traditional way of power supply may not meet the all needs of intelligence and big data. The fossil fuels, hydroelectric and sun energy technologies are still indispensable for inherent in the existing world order, while other energy conversion technologies are valuable supplement to energy shortage, and including TENGs. Therefore, it can be predicted that the future world is to be co-powered by concentrated power and MDPS. Despite these advancements, TENG development still face several challenges. In order to achieve such high goals, some questions related to TENG technologies have been summarized in the past, and here are listed a few crucial problems. These critical problems in this area are briefly recapitulated as follows: 1) fundamental physics of triboelectrification, 2) high-performance triboelectric materials, 3) preparation processes and system integration, 4) power management and energy storage, 5) commercialization and environment-friendly impact. Faced with these critical problems, which it offers a lot of opportunities for engineers and scientists and people who develop TENG on applications. We truly believe that considering the growing advancements in this field and more attentions for TENGs received from the research community. It is predicted that research TENG and its application exploitation will continue its rapid growth and possibly forming a TENG dominated industrial chain, it would become a series of workable commercial products in the future.

Acknowledgements

The authors acknowledge the support from Natural Science Foundation of Beijing Municipality (2192062), supported by National Natural Science Foundation of China (51502147, 51702018 and 11704032).

© 2022 Wiley-VCH GmbH

Conflict of Interest

The authors declare no conflict of interest.

Keywords

carbon neutrality, high entropy energy, self-powered sensing, sustainable energy, triboelectric nanogenerators

Received: November 15, 2021
Revised: February 25, 2022
Published online:

[1] Q. Huang, D. Wang, Z. Zheng, *Adv. Energy Mater.* **2016**, *6*, 1600783.
[2] G. Schwartz, B. C. Tee, J. Mei, A. L. Appleton, D. H. Kim, H. Wang, Z. Bao, *Nat. Commun.* **2013**, *4*, 1859.
[3] M. Gao, P. Wang, L. Jiang, B. Wang, Y. Yao, S. Liu, D. Chu, W. Cheng, Y. Lu, *Energy Environ. Sci.* **2021**, *14*, 2114.
[4] W. Liu, Z. Wang, G. Wang, G. Liu, J. Chen, X. Pu, Y. Xi, X. Wang, H. Guo, C. Hu, Z. L. Wang, *Nat. Commun.* **2019**, *10*, 1426.
[5] S. Wang, L. Lin, Z. L. Wang, *Nano Lett.* **2012**, *12*, 6339.
[6] X. Pu, H. Guo, J. Chen, X. Wang, Y. Xi, C. Hu, Z. L. Wang, *Sci. Adv.* **2019**, 30.
[7] P. Chen, J. An, S. Shu, R. Cheng, J. Nie, T. Jiang, Z. L. Wang, *Adv. Energy Mater.* **2021**, *11*, 2003066.
[8] F. Liu, Y. Liu, Y. Lu, Z. Wang, Y. Shi, L. Ji, J. Cheng, *Nano Energy* **2019**, *56*, 482.
[9] J. Wang, S. Li, F. Yi, Y. Zi, J. Lin, X. Wang, Y. Xu, Z. L. Wang, *Nat. Commun.* **2016**, *7*, 12744.
[10] Maxwell, J. C. Maxwell, in (Eds: R. Flood, M. McCartney, A. Whitaker), Oxford University Press, Oxford **1904**, p. 178.
[11] Z. L. Wang, J. Song, *Science* **2006**, *312*, 242.
[12] F. R. Fan, Z. Q. Tian, Z. L. Wang, *Nano Energy* **2012**, *1*, 328.
[13] Z. L. Wang, J. Chen, L. Lin, *Energy Environ. Sci.* **2015**, *8*, 2250.
[14] Y. Zou, P. Tan, B. Shi, H. Ouyang, D. Jiang, Z. Liu, H. Li, M. Yu, C. Wang, X. Qu, L. Zhao, Y. Fan, Z. L. Wang, Z. Li, *Nat. Commun.* **2019**, *10*, 2695.
[15] Z. Wang, J. An, J. Nie, J. Luo, J. Shao, T. Jiang, B. Chen, W. Tang, Z. L. Wang, *Adv. Mater.* **2020**, *32*, 2001466.
[16] J. Luo, Z. Wang, L. Xu, A. C. Wang, K. Han, T. Jiang, Q. Lai, Y. Bai, W. Tang, F. R. Fan, Z. L. Wang, *Nat. Commun.* **2019**, *10*, 5147.
[17] Y. Tang, H. Zhou, X. Sun, N. Diao, J. Wang, B. Zhang, C. Qin, E. Liang, Y. Mao, *Adv. Funct. Mater.* **2020**, *30*, 1907893.
[18] J. Shao, Y. Yang, O. Yang, J. Wang, M. Willatzen, Z. L. Wang, *Adv. Energy Mater.* **2021**, *11*, 202100065.
[19] S. Lin, L. Xu, C. Xu, X. Chen, A. C. Wang, B. Zhang, P. Lin, Y. Yang, H. Zhao, Z. L. Wang, *Adv. Mater.* **2019**, *31*, 1808197.
[20] J. Wang, C. Yan, K. J. Chee, P. S. Lee, *Adv. Mater.* **2015**, *27*, 2876.
[21] H. Shin, B. K. Sharma, S. W. Lee, J. B. Lee, M. Choi, L. Hu, C. Park, J. H. Choi, T. W. Kim, J. H. Ahn, *ACS Appl. Mater. Interfaces* **2019**, *11*, 14222.
[22] D. H. Lien, M. Amani, S. B. Desai, G. H. Ahn, K. Han, J. H. He, J. W. Ager3rd, M. C. Wu, A. Javey, *Nat. Commun.* **2018**, *9*, 1229.
[23] X. Y. Wei, X. Wang, S. Y. Kuang, L. Su, H. Y. Li, Y. Wang, C. Pan, Z. L. Wang, G. Zhu, *Adv. Mater.* **2016**, *28*, 6656.
[24] Z. L. Wang, T. Jiang, L. Xu, *Nano Energy* **2017**, *39*, 9.
[25] Z. L. Wang, G. Zhu, Y. Yang, S. Wang, C. Pan, *Mater. Today* **2012**, *15*, 532.
[26] Z. L. Wang, *Mater. Today* **2017**, *20*, 74.
[27] Z. L. Wang, *Nano Energy* **2019**, *68*, 104272.
[28] S. Niu, S. Wang, Y. Liu, Y. S. Zhou, L. Lin, Y. Hu, K. C. Pradel, Z. L. Wang, *Energy Environ. Sci.* **2014**, *7*, 2339.
[29] X. Pu, M. Liu, L. Li, C. Zhang, Y. Pang, C. Jiang, L. Shao, W. Hu, Z. L. Wang, *Adv. Sci.* **2015**, *3*, 1500255.
[30] Y. Zou, X. Hu, H. Ma, S. E. Li, *J. Power Sources* **2015**, *273*, 793.
[31] H. Wu, S. Wang, Z. wang, Y. Zi, *Nat. Commun.* **2021**, *12*, 5470.
[32] Y. Zhang, F. Wan, S. Huang, S. Wang, Z. Niu, J. Chen, *Nat. Commun.* **2020**, *11*, 2199.
[33] H. Guo, Z. Wen, Y. Zi, M. H. Yeh, J. Wang, L. Zhu, C. Hu, Z. L. Wang, *Adv. Energy Mater.* **2016**, *6*, 1501593.
[34] C. Rodrigues, D. Nunes, D. Clemente, N. Mathias, J. M. Correia, P. Rosa-Santos, F. Taveira-Pinto, T. Morais, A. Pereira, J. Ventura, *Energy Environ. Sci.* **2020**,*13*, 2657.
[35] T. Cheng, Q. Gao, Z. L. Wang, *Adv. Mater. Technol.* **2019**, *4*, 1800588.
[36] C. Wu, A. C. Wang, W. Ding, H. Guo, Z. L. Wang, *Adv. Energy Mater.* **2019**, *9*, 1802906.
[37] C. Xu, Y. Zi, A. C. Wang, H. Zou, Y. Dai, X. He, P. Wang, Y. C. Wang, P. Feng, D. Li, Z. L. Wang, *Adv. Mater.* **2018**, *30*, 1706790.
[38] S. Niu, X. Wang, F. Yi, Y. S. Zhou, Z. L. Wang, *Nat. Commun.* **2015**, *6*, 8975.
[39] X. Cheng, W. Tang, Y. Song, H. Chen, H. Zhang, Z. L. Wang, *Nano Energy* **2019**, *61*, 517.
[40] W. Liu, Z. Wang, G. Wang, Q. Zeng, W. He, L. Liu, X. Wang, Y. X, H. Guo, C. Hu, Z. L. Wang, *Nat. Commun.* **2020**, *11*, 1883.
[41] B. Chen, W. Tang, T. Jiang, L. Zhu, X. Chen, C. He, L. Xu, H. Guo, P. Lin, D. Li, J. Shao, Z. L. Wang, *Nano Energy* **2018**, *45*, 380.
[42] Y. W, X. Liu, Y. Wang, H. Wang, H. Wang, S. L. Zhang, T. Zhao, M. Xu, Z.h. L. Wang, *Nano Energy* **2021**, *15*, 15700.
[43] D. Liu, B. Chen, J. An, C. Li, G. Liu, J. Shao, W. Tang, C. Zhang, Z. L. Wang, *Nano Energy* **2020**, *73*, 104819.
[44] Z. Wang, J. An, J. Nie, J. Luo, J. Shao, T. Jiang, B. Chen, W. Tang, Z. L. Wang, *Adv. Mater.* **2020**, *32*, 2001466.
[45] X. Peng, K. Dong, C. Ning, R. Cheng, J. Yi, Y. Zhang, F. Sheng, Z. Wu, Z. L. Wang, *Adv. Funct. Mater.* **2021**, *31*, 2103559.
[46] H. Guo, X. Pu, J. Chen, Y. Meng, M. H. Yeh, G. Liu, Q. Tang, B. Chen, D. Liu, S. Qi, C. Wu, C. Hu, J. Wang, Z. L. Wang, *Sci. Adv.* **2018**, *3*, 2516.
[47] Y. Liu, B. Chen, W. Li, L. Zu, W. Tang, Z. L. Wang, *Adv. Funct. Mater.* **2021**, *31*, 2104770.
[48] J. Cheng, W. Ding, Y. Zi, Y. Lu, L. Ji, F. Liu, C. Wu, Z. L. Wang, *Nat. Commun.* **2018**, *9*, 3733.
[49] Y. Liu, J. W, B. Chen, M. Zheng, D. Liu, Y. Liu, W. Tang, J. Liu, D. Nan, Z. L. Wang, *Appl. Mater. Today* **2020**, *19*, 100631.
[50] J. Luo, K. Han, X. Wu, H. Cai, T. Jiang, H. Zhou, Z. L. Wang, *Nano Energy* **2021**, *88*, 106313.
[51] L. Xu, T. Jiang, P. Lin, J. Shao, C. He, W. Zhong, X. Chen, Z. L. Wang, *ACS Nano* **2018**, *12*, 1849.
[52] C. Zhang, L. He, L. Zhou, O. Yang, W. Yuan, X. Wei, Y. Liu, L. Lu, J. Wang, Z. L. Wang, *Joule* **2021**, *5*, 1613.
[53] H. Pang, Y. Feng, J. An, P. Chen, J. Han, T. Jiang, Z. L. Wang, *Adv. Funct. Mater.* **2021**, *31*, 2106398.
[54] P. Chen, J. An, S. Shu, R. Cheng, J. Nie, T. Jiang, Z. L. Wang, *Adv. Energy Mater.* **2021**, *11*, 2003066.
[55] R. Cheng, K. Dong, P. Chen, C. Ning, X. Peng, Y. Zhang, D. Liu, Z. L. Wang, *Energy Environ. Sci.* **2021**, *14*, 2460.
[56] C. Zhang, Y. Liu, B. Zhang, O. Yang, W. Yuan, L. He, X. Wei, J. Wang, Z. L. Wang, *ACS Energy Lett.* **2021**, *6*, 1490.
[57] L. Zu, D. Liu, J. Shao, Y. Liu, S. Shu, C. Li, X. Shi, B. Chen, Z. L. Wang, *Adv. Mater. Technol.* **2021**, 2100787, https://doi.org/10.1002/admt.202100787.
[58] Y. Shi, F. Wang, J. Tian, S. Li, E. Fu, J. Nie, R. Lei, Y. Ding, X. Chen, Z. L. Wang, *Sci. Adv.* **2021**, *7*, 2943.
[59] J. Han, C. Xu, J. Zhang, N. Xu, Y. Xiong, X. Cao, Y. Liang, L. Zheng, J. Sun, J. Zhai, Q.i. Sun, Z. L. Wang, *ACS Nano* **2021**, *15*, 1597.
[60] J. Yi, K. Dong, S. Shen, Y. Jiang, X. Peng, C. Ye, Z. L. Wang, *Nano-Micro Lett.* **2021**, *13*, 103.
[61] M. Sun, Q. Lu, Z. L. Wang, B. Huang, *Nat. Commun.* **2021**, *12*, 1752.

© 2022 Wiley-VCH GmbH

[62] B. Chen, W. Tang, C. Zhang, L. Xu, L. Zhu, L. Yang, C. He, J. Chen, L. Liu, T. Zhou, Z. L. Wang, *Nano Res.* **2018**, *11*, 3096.
[63] J. Huang, X. Yang, J. Yu, J. Han, C. Jia, M. Ding, J. Sun, X. Cao, Q. Sun, Z. L. Wang, *Nano Energy* **2020**, *69*, 104419.
[64] C. Ye, K. Dong, J. An, J. Yi, X. Peng, C. Ning, Z. L. Wang, *ACS Energy Lett.* **2021**, *6*, 1443.
[65] W. Harmon, D. Bamgboje, H. Guo, T. Hu, Z. L. Wang, *Nano Energy* **2020**, *71*, 104642.
[66] J. Wen, B. Chen, W. Tang, T. Jiang, L. Zhu, L. Xu, J. Chen, J. Shao, K. Han, W. Ma, Z. L. Wang, *Adv. Energy Mater.* **2018**, *8*, 1801898.
[67] F. Xia, Y. Pang, W. Lia, T. Jiang, L. Zhang, T. Guo, G. Liu, C. Zhang, Z. L. Wang, *Nano Energy* **2017**, *37*, 168.
[68] W. Tang, B. Meng, H. Zhang, *Nano Energy* **2013**, *2*, 1164.
[69] Z. L. Wang, A. C. Wang, *Mater. Today* **2019**, *30*, 34.
[70] Y. Xie, J. Hu, H. Li, H. Mi, G. Ni, X. Zhu, X. Jing, Y. Wang, G. Zheng, C. Liu, C. Shen, *Nano Energy* **2022**, *93*, 106827.
[71] G. Ni, X. Zhu, H. Mi, P. Feng, J. Li, X. Jing, B. Dong, C. Liu, C. Shen, *Nano Energy* **2021**, *87*, 106148.
[72] P. Feng, Z. Xia, B. Sun, X. Jing, H. Li, X. Tao, H. Mi, Y. Liu, *ACS Appl. Mater. Interfaces* **2021**, *13*, 16916.

Baodong Chen is an associate professor in Beijing Institute of Nanoenergy and Nanosystems (BINN), Chinese Academy of Sciences (CAS); School of Nanoscience and Technology, University of Chinese Academy of Sciences. He received his Ph.D. degree from School of Materials Science and Engineering in 2015, from Inner Mongolia University of Technology, China. Prior to joining the faculty at BINN in 2018, he was a postdoctoral fellow at National Center for Nanoscience and Technology. His research interests include nanocomposite materials, nanogenerator, self-powered sensing systems, distributed energy, and 2D and 3D printed flexible electronics.

Zhong Lin Wang received his Ph.D. degree from Arizona State University in physics. He now is the Hightower Chair in Materials Science and Engineering, Regents' Professor at Georgia Tech, the chief scientist and director of the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. His discovery and breakthroughs in developing nanogenerators and self-powered nanosystems establish the principle and technological road map for harvesting mechanical energy for powering personal electronics. He coined and pioneered the fields of piezotronics and piezophototronics by introducing piezoelectric potential gated charge transport process in fabricating new electronic and optoelectronic devices.

 © 2022 Wiley-VCH GmbH