Fabric/Fiber-Based Triboelectric Nanogenerators

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Triboelectric nanogenerator (TENG), as a green energy harvesting technology, has aroused tremendous interest across many fields, such as wearable electronics, implanted electronic devices, and human-machine interfaces. Fabric and fiber-structured materials are excellent candidates for TENG materials due to their inherent flexibility, low cost, and high wearing comfort. Consequently, it is crucial to combine TENG with fabric/fiber materials to simultaneously leverage their mechanical energy harvesting and wearability advantages.

triboelectric nanogenerator | fabric/fiber structure | wearable self-powered sensors

1. Introduction

In recent years, mobile wearable devices and wireless communication networks, as symbols of the new era, have gradually changed people's ways of life [1][2][3]. Particularly, flexible energy supply devices have attracted extensive attention with the development of wearable electronic markets. Although the external power supplies of wearable electronic products, such as small solid batteries, supercapacitors, lithium-ion batteries, etc., are becoming more and more miniaturized and portable, their rigid nature contradicts the flexibility of fabric, resulting in inferior comfort of wear [4][5]. In addition, these battery devices cannot provide a long-term energy supply during repeated charging/discharging. Moreover, a large amount of wasted electronics needs high disposal and recycling costs during the disposal and recycling process, which also lead to soil and water pollution [6][7][8]. What is more dangerous is that in complex working environments, they might easily cause leakage of electrolyte and oxidized materials within the battery, resulting in severe harm to users. Therefore, from the perspective of economic and sustainable development, rigid battery devices are a poor choice for the future development of wearable sensors [9][10]. Hence, it is of the utmost importance to select a sustainable green and environmentally friendly flexible power supply that is not only integrated and miniaturized, but also environmentally credible and will not accidentally harm the human body [11][12][13][14].

Collecting energy from the surrounding environment is one potential solution to this issue. As a revolutionary energy harvesting technology, triboelectric nanogenerators (TENGs) utilize simple construction and mechanisms to effectively harvest mechanical energy and play a crucial role in the construction of portable power sources or self-powered systems [15][16][17]. Moreover, compared to traditional power supply systems, TENGs have the advantages of light weight, simple structure, and strong material adaptability [18][19]. As one of the most abundant energies in the human living environment, mechanical energy possesses the qualities of continuity, independence, easy access, and widespread existence. It has significant application potential in the fields of smart wearables and biomedical engineering. As the human body is not only a rich source of green mechanical energy but also an application terminal for smart wearables, the acquisition and utilization of required energy can be accomplished through human movement by integrating nanogenerator and human movement [20][21]. Although some polymer films (e.g., polytetrafluoroethylene, polydimethylsiloxane) can also adhere to the human body (e.g., knees, arms) to harvest mechanical energy or monitor movements, the poor wearing comfort and durability remains a great challenge. By comparison, fabrics and fiber materials have natural wearability, inherent durability, and can withstand complex mechanical deformations such as stretch, twist, bend and tear, owning to its uniqueness. Thus, the integration of cutting-edge energy collection technology and fabric/fiber materials are advantageous for the development of wearable self-powered sensor [22][23].

The application advantages of fabric/fiber material in the fields of TENG and the feasibility of self-powered wearable sensors. Firstly, the structure design and operating mechanisms of TENG is introduced. Followed by the uniqueness of fabric/fiber materials based on TENG. Fabric/fiber materials are divided into three categories based on their preparation methods: fabric and textile fiber (spinning and weaving method), wet spinning fiber materials (wet spinning method), and electrospinning nanofibers (electrospun method). **Figure 1** depicts recent research progress of fabric/fiber-based TENGs made mainly through these methods [24][25][26][27][28]. In addition to energy harvesting, human motion detection and functional applications can also be incorporated. These applications fully confirm the vast potential of fabric/fiber-based TENG in the field of self-powered wearable sensors, bringing revolutionary changes to the future development of wearable technology and greatly promoting the robust growth of the wearable electronics market.

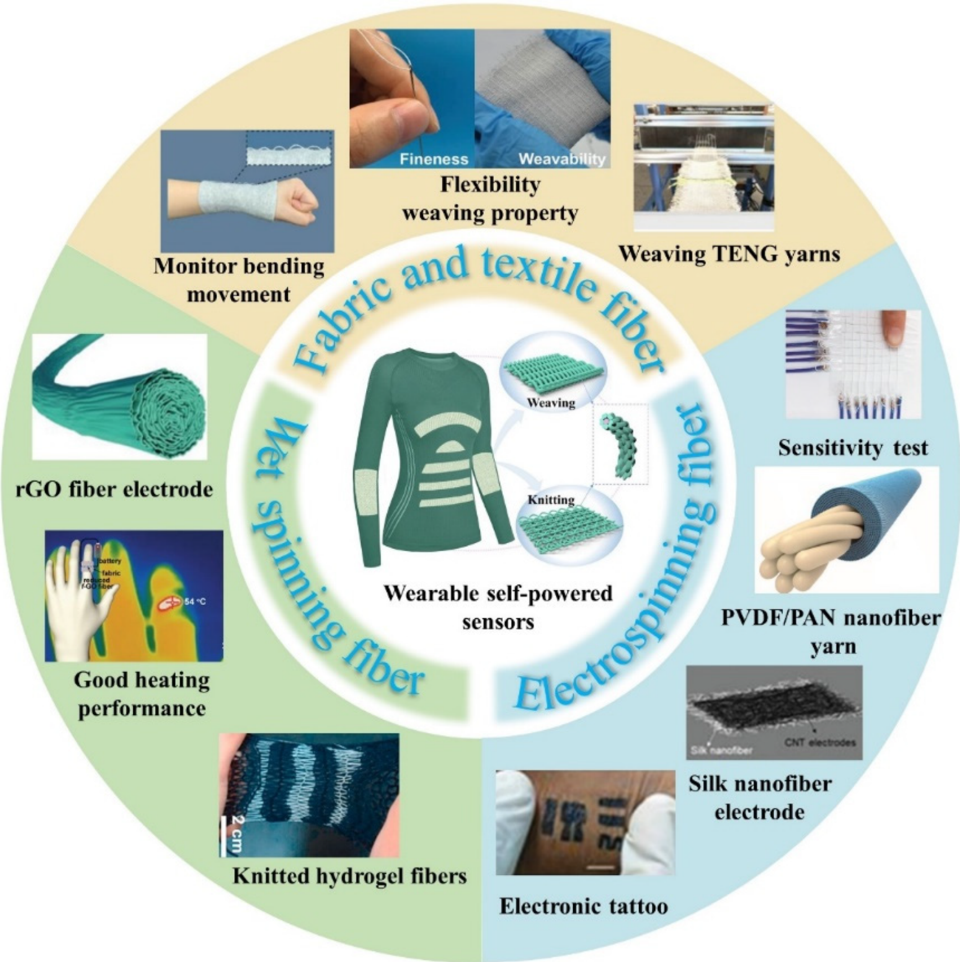

Figure 1. Schematic of recently reported fabric/fiber-based TENG.

2. The Mechanism and Structure Design of TENG

TENG is a new energy collection technology device proposed by Professor Wang in 2012 [29][30]. It can convert surrounding mechanical energy into electric energy by utilizing the dual effects of contact electrification (CE) and electrostatic induction (EI). Specifically, when two kinds of materials are in contact with each other under external force (**Figure 2**a(i),(iv)), the surface of the materials will produce positive or negative charges due to different polarities of triboelectric materials. When the two materials are separated (**Figure 2**a(ii),(iii)), the positive and negative static charges generated by contact electric charge are also detached, thus the induced potential difference is correspondingly produced on electrodes. If the two electrodes are in loaded or in a short-circuit state, the electrons driven by potential difference would flow in the external circuits, thus transform mechanic energy into electric energy. The difference in surface potential significantly affects the triboelectric property. In short, this CE phenomenon is closely related to electron transfer, which can be easily explained by the electron cloud/potential well mechanism (**Figure 2**b) [31]. Compared to piezoelectric nanogenerators (PENG) and pyroelectric nanogenerators, TENG have the advantages of high output power, a wide selection of materials, simple fabrication, low cost, and light weight [32][33][34]. In the past decade, TENG has attracted significant attention, and a number of research advancements have been accomplished in terms of device working mode design, physical mechanism disclosure, and study of practical applications.

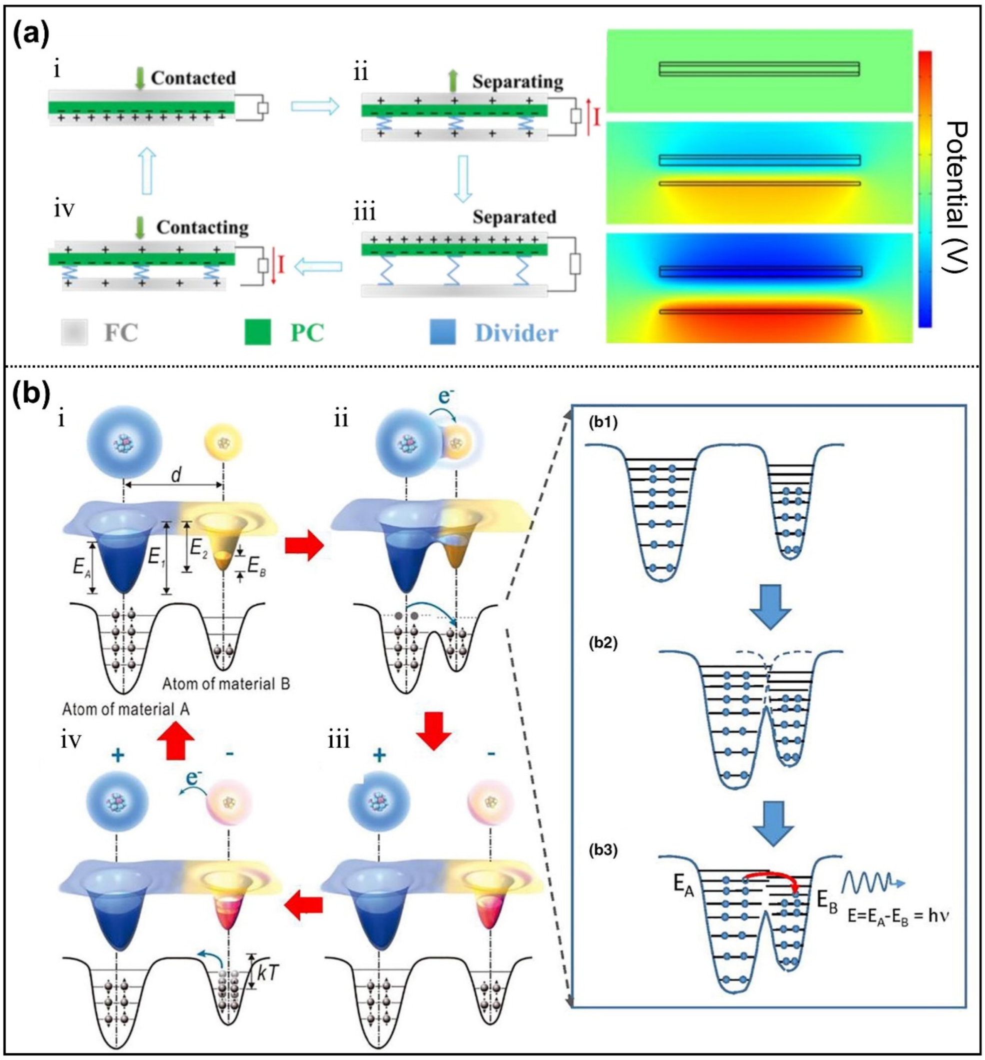

Figure 2. Working mechanism of TENG. (**a**) Working models, which include: (i) original state, (ii) separating state, (iii) fully separated, (iv) contacting each other. Reprinted with permission from Ref. [35]. Copyright 2020 American Chemical Society. (**b**) The electron cloud/potential well mechanism for the contact-electrification phenomenon. Reprinted with permission from Ref. [31]. Copyright 2022 Elsevier.

In particular, according to the polarization direction and electrode structure, as shown in **Figure 3**, the TENG can be mainly divided into four basic working modes: vertical contact-separation mode, single-electrode mode, horizontal sliding mode and freestanding triboelectric-layer mode [36][37]. Based on the different working modes of TENG, various forms of mechanical energy collection and self-powered sensors in various application scenarios can be realized. The basic working modes are as follows:

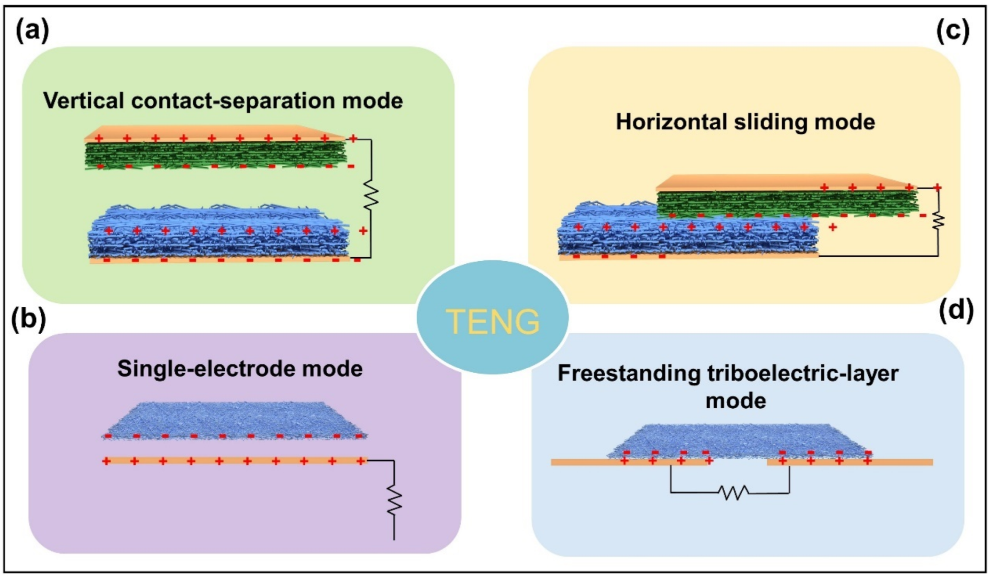

Figure 3. The basic structure mode of TENGs. (**a**) Vertical contact-separation model. (**b**) Single-electrode mode. (**c**) Horizontal sliding mode. (**d**) Freestanding triboelectric-layer mode.

2.1. Vertical Contact-Separation Mode

The vertical contact-separation model is the simplest and most widely studied of TENGs, with the highest instantaneous power output. Its typical structure consists of two kinds of dielectric films with electrodes assembled vertically on the back (**Figure 3**a). The working mechanisms are similar to what is depicted in **Figure 2**a. When the dielectric films make recontact, the potential difference caused by triboelectric charges disappears, and electrons flow in the opposite direction due to the dual effects of CE and EI [36]. Under the periodic external force, the vertical contact and separation between two triboelectric layers of TENG generate the periodic alternating current (AC).

2.2. Single-Electrode Mode

In daily life, it is inconvenient to attach electrodes onto the surface of triboelectric materials, especially when two moving materials contact each other, which would lead to uncertainty. To solve this problem, researchers proposed a single-electrode mode TENG with only one electrode attached onto the dielectric film, as shown in **Figure 3**b. In this way, only the chosen material is fixed with an electrode. The opposite dielectric material can be any other moving material, and can even be used as electrode [38]. However, due to the electrostatic shielding, the overall electric output of the single-electrode TENG is only half of the dual-electrodes mode. However, the advantage of single-electrode TENG affords it a wide range of application prospects in movement monitoring and energy collection of water droplets, intelligent sensing, human-computer interaction and other fields [39][40].

2.3. Horizontal Sliding Mode

The initial structure of the horizontal sliding mode TENG is similar to that of the vertical contact-separation mode, but the films of the two friction materials remain in close contact (**Figure 3**c). Driven by external forces, the two friction materials slip horizontally which is parallel to the surface and generate friction charges on the surface. The lateral separation of the center of the friction charge forms a potential difference that drives electrons through the external load to balance the electrostatic field of the friction charge. The horizontal sliding mode TENG is separated and closed by periodic sliding of two friction materials in the horizontal direction, producing AC output. However, the sliding friction between solid materials severely wears the materials and generates heat, which reduces the efficiency and durability of TENG [41].

2.4. Freestanding Triboelectric-Layer Mode

Freestanding triboelectric-layer mode TENG usually composed of an independent friction layer and a fixed electrode (**Figure 3**d), the periodical movement of the friction layer between two electrodes causes the potential difference, so as to drive the electron to reciprocate between two electrodes through circuits in order to equilibrate the changes of potential difference [42]. Similar to single-electrode TENG structure, the freestanding mode is simple in design and fabrication, besides, the independent friction layer can move periodically without restriction and is not affected by electrostatic shielding effect, so it has higher energy conversion efficiency.

References

1. Wei, X.; Li, H.; Yue, W.; Gao, S.; Chen, Z.; Li, Y.; Shen, G. A high-accuracy, real-time, intelligent material perception system with a machine-learning-motivated pressure-sensitive electronic skin. Matter 2022, 5, 1481–1501.
2. Dong, J.; Wang, D.; Peng, Y.; Zhang, C.; Lai, F.; He, G.; Ma, P.; Dong, W.; Huang, Y.; Parkin, I.P.; et al. Ultra-stretchable and superhydrophobic textile-based bioelectrodes for robust self-cleaning and personal health monitoring. Nano Energy 2022, 97, 107160.
3. Zhao, Y.; Gao, W.; Dai, K.; Wang, S.; Yuan, Z.; Li, J.; Zhai, W.; Zheng, G.; Pan, C.; Liu, C.; et al. Bioinspired Multifunctional Photonic-Electronic Smart Skin for Ultrasensitive Health Monitoring, for Visual and Self-Powered Sensing. Adv. Mater. 2021, 33, 2102332.
4. Liu, Y.; Mauter, M.S. Marginal energy intensity of water supply. Energy Environ. Sci. 2021, 14, 4533–4540.
5. Wang, Y.; Guo, T.; Tian, Z.; Bibi, K.; Zhang, Y.-Z.; Alshareef, H. MXenes for Energy Harvesting. Adv. Mater. 2022, 34, 2108560.
6. Long, Z.; Shi, C.; Wu, C.; Yuan, L.; Qiao, H.; Wang, K. Heterostructure Fe2O3 covalent organic framework for long cycling and high-rate lithium storage. Nanoscale 2022, 14, 1906–1920.
7. Long, Z.; Li, R.; Dai, Z.; Shi, C.; Wu, C.; Wei, Q.; Qiao, H.; Wang, K.; Liu, K. Necklace-like NiCo2O4@carbon composite nanofibers derived from metal–organic framework compounds for high-rate lithium storage. Mater. Chem. Front. 2021, 5, 5726–5737.

8. Ao, K.; Daoud, W. Facile controlled formation of CoNi alloy and CoO embedded in N-doped carbon as advanced electrocatalysts for oxygen evolution and zinc-air battery. Electrochim. Acta 2021, 395, 139204.
9. Huang, L.; Lin, S.; Xu, Z.; Zhou, H.; Duan, J.; Hu, B.; Zhou, J. Fiber-Based Energy Conversion Devices for Human-Body Energy Harvesting. Adv. Mater. 2020, 32, 1902034.
10. Long, Z.; Yuan, L.; Shi, C.; Wu, C.; Qiao, H.; Wang, K. Porous Fe2O3 nanorod-decorated hollow carbon nanofibers for high-rate lithium storage. Adv. Compos. Hybrid. Mater. 2022, 5, 370–382.
11. Jia, C.; Xia, Y.; Zhu, Y.; Wu, M.; Zhu, S.; Wang, X. High-Brightness, High-Resolution, and Flexible Triboelectrification-Induced Electroluminescence Skin for Real-Time Imaging and Human–Machine Information Interaction. Adv. Funct. Mater. 2022, 32, 2201292.
12. Fan, C.; Wang, D.; Huang, J.; Ke, H.; Wei, Q. A highly sensitive epidermal sensor based on triple-bonded hydrogels for strain/pressure sensing. Compos. Commun. 2021, 28, 100951.
13. Huang, J.; Zhao, M.; Cai, Y.; Zimniewska, M.; Li, D.; Wei, Q. A Dual-Mode Wearable Sensor Based on Bacterial Cellulose Reinforced Hydrogels for Highly Sensitive Strain/Pressure Sensing. Adv. Electron. Mater. 2020, 6, 1900934.
14. Ao, K.; Shi, J.; Zhang, X.; Daoud, W.A. Tuning oxygen vacancies in spinel nanosheets for binder-free oxygen cathodes with superior catalytic activity in zinc-air batteries. J. Power Sources 2022, 521, 230918.
15. Sun, J.; Tu, K.; Büchele, S.; Koch, S.M.; Ding, Y.; Ramakrishna, S.N.; Stucki, S.; Guo, H.; Wu, C.; Keplinger, T.; et al. Functionalized wood with tunable tribopolarity for efficient triboelectric nanogenerators. Matter 2021, 4, 3049–3066.
16. Wu, C.; Wang, A.C.; Ding, W.; Guo, H.; Wang, Z. Triboelectric Nanogenerator: A Foundation of the Energy for the New Era. Adv. Energy Mater. 2019, 9, 1802906.
17. Wu, C.; Tetik, H.; Cheng, J.; Ding, W.; Guo, H.; Tao, X.; Zhou, N.; Zi, Y.; Wu, Z.; Wu, H.; et al. Electrohydrodynamic Jet Printing Driven by a Triboelectric Nanogenerator. Adv. Funct. Mater. 2019, 29, 1901102.
18. Sun, J.; Guo, H.; Schadli, G.N.; Tu, K.; Schar, S.; Schwarze, F.W.M.R.; Panzarasa, G.; Ribera, J.; Burgert, I. Enhanced mechanical energy conversion with selectively decayed wood. Sci. Adv. 2021, 7, eabd9138.
19. Sun, J.; Guo, H.; Ribera, J.; Wu, C.; Tu, K.; Binelli, M.; Panzarasa, G.; Schwarze, F.W.M.R.; Wang, Z.L.; Burgert, I. Sustainable and Biodegradable Wood Sponge Piezoelectric Nanogenerator for Sensing and Energy Harvesting Applications. ACS Nano 2020, 14, 14665–14674.

20. Han, J.; Xu, C.; Zhang, J.; Xu, N.; Xiong, Y.; Cao, X.; Liang, Y.; Zheng, L.; Sun, J.; Zhai, J.; et al. Multifunctional Coaxial Energy Fiber toward Energy Harvesting, Storage, and Utilization. ACS Nano 2021, 15, 1597–1607.

21. Wu, C.; Jiang, P.; Li, W.; Guo, H.; Wang, J.; Chen, J.; Prausnitz, M.R.; Wang, Z.L. Self-Powered Iontophoretic Transdermal Drug Delivery System Driven and Regulated by Biomechanical Motions. Adv. Funct. Mater. 2020, 30, 1907378.

22. Liu, L.; Xu, W.; Ding, Y.; Agarwal, S.; Greiner, A.; Duan, G. A review of smart electrospun fibers toward textiles. Compos. Commun. 2020, 22, 100506.

23. Zhang, J.; Wang, H.; Blanloeuil, P.; Li, G.; Sha, Z.; Wang, D.; Lei, W.; Boyer, C.; Yu, Y.; Tian, R.; et al. Enhancing the triboelectricity of stretchable electrospun piezoelectric polyvinylidene fluoride/boron nitride nanosheets composite nanofibers. Compos. Commun. 2020, 22, 100535.

24. Ma, L.; Wu, R.; Patil, A.; Yi, J.; Liu, D.; Fan, X.; Sheng, F.; Zhang, Y.; Liu, S.; Shen, S.; et al. Acid and Alkali-Resistant Textile Triboelectric Nanogenerator as a Smart Protective Suit for Liquid Energy Harvesting and Self-Powered Monitoring in High-Risk Environments. Adv. Funct. Mater. 2021, 31, 2102963.

25. Ma, L.; Zhou, M.; Wu, R.; Patil, A.; Gong, H.; Zhu, S.; Wang, T.; Zhang, Y.; Shen, S.; Dong, K.; et al. Continuous and Scalable Manufacture of Hybridized Nano-Micro Triboelectric Yarns for Energy Harvesting and Signal Sensing. ACS Nano 2020, 14, 4716–4726.

26. Gogurla, N.; Kim, Y.; Cho, S.; Kim, J.; Kim, S. Multifunctional and Ultrathin Electronic Tattoo for On-Skin Diagnostic and Therapeutic Applications. Adv. Mater. 2021, 33, 2008308.

27. Tang, P.; Deng, Z.; Zhang, Y.; Liu, L.-X.; Wang, Z.; Yu, Z.-Z.; Zhang, H.B. Tough, Strong, and Conductive Graphene Fibers by Optimizing Surface Chemistry of Graphene Oxide Precursor. Adv. Funct. Mater. 2022, 32, 2112156.

28. Shuai, L.; Guo, Z.H.; Zhang, P.; Wan, J.; Pu, X.; Wang, Z. Stretchable, self-healing, conductive hydrogel fibers for strain sensing and triboelectric energy-harvesting smart textiles. Nano Energy 2020, 78, 105389.

29. Luo, J.; Gao, W.; Wang, Z.L. The Triboelectric Nanogenerator as an Innovative Technology toward Intelligent Sports. Adv. Mater. 2021, 33, 2004178.

30. Liang, C.; Gu, H.; Xia, Y.; Wang, Z.; Liu, X.; Xia, J.; Zuo, S.; Hu, Y.; Gao, X.; Hui, W.; et al. Two-dimensional Ruddlesden-Popper layered perovskite solar cells based on phase-pure thin films. Nat. Energy 2021, 6, 38–45.

31. Wang, Z.L.; Wang, A.C. On the origin of contact-electrification. Mater. Today 2019, 30, 34–51.

32. Li, X.M.; Ning, X.Y.; Li, L.X.; Wang, X.; Li, B.W.; Li, J.D.; Yin, J.; Guo, W.L. Performance and power management of droplets-based electricity generators. Nano Energy 2022, 92, 106705.

33. Dudem, B.; Dharmasena, R.D.I.G.; Riaz, R.; Vivekananthan, V.; Wijayantha, K.G.U.; Lugli, P.; Petti, L.; Silva, S.R.P. Wearable Triboelectric Nanogenerator from Waste Materials for Autonomous Information Transmission via Morse Code. ACS. Appl. Mater. Inter. 2022, 14, 5328–5337.
34. Zou, H.; Zhang, Y.; Guo, L.; Wang, P.; He, X.; Dai, G.; Zheng, H.; Chen, C.; Wang, A.C.; Xu, C.; et al. Quantifying the triboelectric series. Nat. Commun. 2019, 10, 1427.
35. Cheng, R.; Dong, K.; Liu, L.; Ning, C.; Chen, P.; Peng, X.; Liu, D.; Wang, Z. Flame-Retardant Textile-Based Triboelectric Nanogenerators for Fire Protection Applications. ACS Nano 2020, 14, 15853–15863.
36. Dong, K.; Peng, X.; Wang, Z. Fiber/Fabric-Based Piezoelectric and Triboelectric Nanogenerators for Flexible/Stretchable and Wearable Electronics and Artificial Intelligence. Adv. Mater. 2020, 32, 1902549.
37. Han, G.H.; Kim, S.W.; Kim, J.K.; Lee, S.H.; Jeong, M.H.; Song, H.C.; Choi, K.J.; Baik, J.M. 3D Multiple Triangular Prisms for Highly Sensitive Non-Contact Mode Triboelectric Bending Sensors. Nanomaterials 2022, 12, 1499.
38. Wu, H.; Wang, J.; Wu, Z.; Kang, S.; Wei, X.; Wang, H.; Luo, H.; Yang, L.; Liao, R.; Wang, Z. Multi-Parameter Optimized Triboelectric Nanogenerator Based Self-Powered Sensor Network for Broadband Aeolian Vibration Online-Monitoring of Transmission Lines. Adv. Energy Mater. 2022, 12, 2103654.
39. He, H.; Liu, J.; Wang, Y.; Zhao, Y.; Qin, Y.; Zhu, Z.; Yu, Z.; Wang, J. An Ultralight Self-Powered Fire Alarm e-Textile Based on Conductive Aerogel Fiber with Repeatable Temperature Monitoring Performance Used in Firefighting Clothing. ACS Nano 2022, 16, 2953–2967.
40. Zhao, Z.; Wei, B.; Wang, Y.; Huang, X.; Li, B.; Lin, F.; Ma, L.; Zhang, Q.; Zou, Y.; Yang, F.; et al. An Array of Flag-Type Triboelectric Nanogenerators for Harvesting Wind Energy. Nanomaterials 2022, 12, 721.
41. Wang, S.; Lin, L.; Xie, Y.; Jing, Q.; Niu, S.; Wang, Z. Sliding-Triboelectric Nanogenerators Based on In-Plane Charge-Separation Mechanism. Nano Lett. 2013, 13, 2226–2233.
42. Wang, S.; Xie, Y.; Niu, S.; Lin, L.; Wang, Z. Freestanding Triboelectric-Layer-Based Nanogenerators for Harvesting Energy from a Moving Object or Human Motion in Contact and Non-contact Modes. Adv. Mater. 2014, 26, 2818–2824.