Electrification Mechanism of Smart Textile Triboelectric Nanogenerators

Subjects: Physics, Applied

Contributor: Kai Dong

Triboelectrification or contact electrification is a universal phenomenon in which two materials contact each other. A triboelectric nanogenerator (TENG) is a new type of energy collection technology first invented by Wang's team in 2012. By coupling triboelectric charging and electrostatic induction, various forms of irregular, low-frequency, and distributed mechanical energy, which is common in daily life but usually wasted, can be effectively converted into electric energy, including human movement, vibration, wind, mechanical triggering, water waves, and so on.

smart textiles triboelectric nanogenerators electricity generation

1. Introduction

The rapid consumption of fossil energy and the increasing urgency of environmental security precipitate us to reshape the current energy utilization structures that depend on oil and coal [1]. In addition, ubiquitous wearable electronics and the Internet of Things (IoTs) pose a great challenge to the present energy supply modes in the centralized, fixed, ordered, and high energy density forms, which rely heavily on traditional power plants and cable transmission networks [2]. In general, the power needed to operate millions of wearable sensors is very small, typically at the microwatt to watt level. Although orderly energy supply modes can provide a part of the power for distributed electronic devices, the rest of the power must be provided by random energy sources in our living environment, including solar energy, vibration, motion, wind energy, and other resources [3][4][5][6][7][8][9]. What is expected is to make full use of any available resources in the environment where the device is deployed. Therefore, the idea of a self-powered system is proposed, which is one of the most feasible schemes for low power electronic devices by effectively acquiring environmental energy [10][11][12][13][14][15][16][17][18].

Triboelectrification or contact electrification is a universal phenomenon in which two materials contact each other. A triboelectric nanogenerator (TENG) is a new type of energy collection technology first invented by Wang's team in 2012. By coupling triboelectric charging and electrostatic induction, various forms of irregular, low-frequency, and distributed mechanical energy, which is common in daily life but usually wasted, can be effectively converted into electric energy, including human movement, vibration, wind, mechanical triggering, water waves, and so on [19][20][21][22][23][24]. With the merits of lightweight, cost-effectiveness, universal availability, abundant materials choice, and especially high conversion efficiency at low frequency, TENGs exhibit a great application prospect in wearable emergency power supply, multifunctional self-powered sensors, healthcare apparatus, and artificial intelligence [25][26][27][28][29][30][31][32][33][34][35]. TENG's fundamental theory can be traced back to Maxwell's equations, which shows that the second term in Maxwell's displacement current has a direct relationship to the output electric current of

TENGs [36]. Recently, expanded Maxwell's equations were also derived by assuming that the medium is moving as a rigid translation in space [37]. The expanded Maxwell's equations not only largely expand their applications in various fields but also serve as the fundamental theory of the NGs, including output current and associated electromagnetic radiation.

By combining the traditional flexible and wearable textile materials with emerging and advanced TENG science, a new type of intelligent textile technology, namely textile TENG, is developed, which has two outstanding functions: independent energy collection and active self-powered energy-sensing (**Figure 1**) [38][39][40][41][42]. With the help of wearable intelligent systems with no burden and self-sufficiency, individuals can easily obtain and make efficient use of electric energy, which will help promote the development of people-centered portable electronics and artificial intelligence in the future [43][44][45][46][47]. However, the low power density and high internal impedance are still the two main factors that hinder the effective commercial utilization of textile TENGs. The maximum energy output per cycle has a quadratic relationship with the charge density of the triboelectric surface and is positively correlated with the average output power and energy conversion efficiency of TENGs. According to Paschen's law, the breakdown effect of high-pressure air has a great influence on the maximum surface charge density [48]. Due to the restriction of high-pressure air breakdown, most of the surface charge densities enhanced by material optimization or external ion implantation are easy to diffuse into the atmosphere and internal triboelectric layer, resulting in charge loss and reduction of surface charge density [49][50]. Breaking through the limitation of air breakdown and prolonging the time of charge decay is especially important for improving the output of TENGs [51]. In order to improve the electromechanical conversion performance of TENGs, people adopted various methods to improve its output performance and expand the applications, such as physical surface modification, chemical surface modification, the embedding of charge trap layer, switching realization, active charge excitation, and so on. Although a large number of reviews summarized these methods to enhance the power output performance of TENGs [52][53][54][55][56][57][58], there is a little comprehensive summary about the improvement of the output performance of textile TENGs. Due to the high aspect ratio, complex curved configuration, and surface micro-to-nano structural defects of 1D fiber structure, it is hard and also unreasonable to directly apply these strategies of improving the power output of the common planar membrane structural TENGs to textile TENGs. In addition, because of the limited effective contact area in textile TENGs, their mechanical-to-electrical conversion efficiency is much lower than that of common planar membrane structures. Therefore, it is extremely necessary to make a comprehensive summary and constructive discussion on the potential strategies to improve the electromechanical conversion output performance of textile TENGs, so as to make their power generation meet the actual use demand.

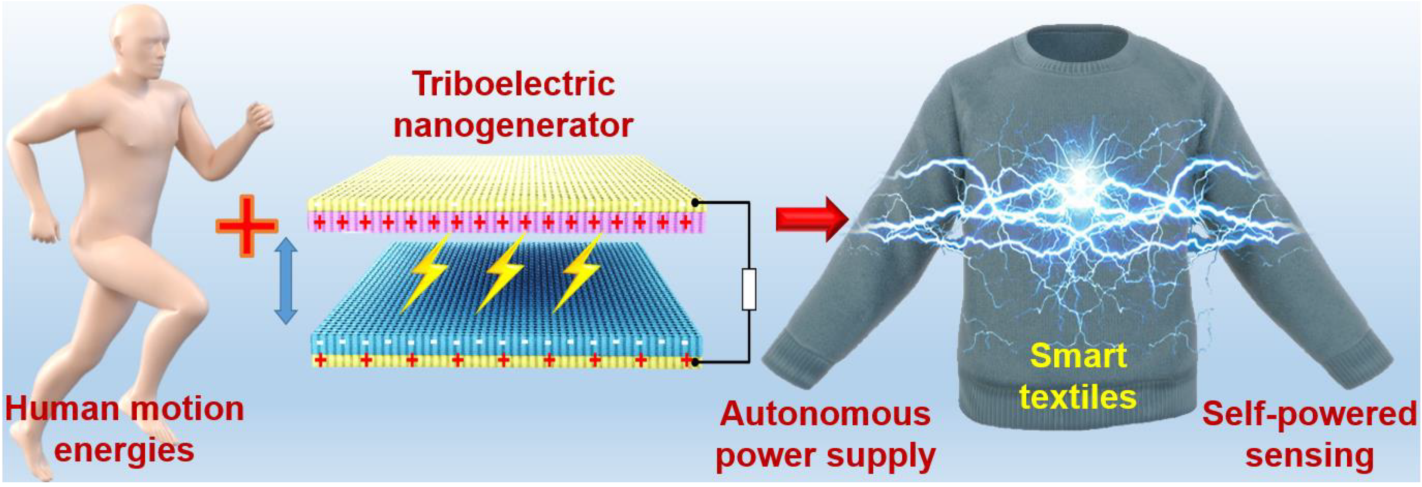

Figure 1. Schematic illustration of smart textile TENGs by converting human motion energies into electric energy through TENG technology.

2. Electrification Mechanism

Contact electrification (CE) or triboelectrification means that two different materials or materials of the same chemical type will be charged after physical contact. However, the underlying mechanism was debated for a long time, but no conclusion was reached. Recently, some researchers used a variety of experimental methods to explore the atomic-scale contact or friction behaviors as well as their induced electrification phenomena. For example, the combination of in situ high-resolution transmission electron microscope (TEM) and atomic force microscope (AFM) measurements can provide direct real-time observation of atomic-level interface structure in the processes of friction and the formation of a loosely stacked interface layer between two metal asperities can result in low friction under tensile stress (**Figure 2**a) [59]. In addition, using Kelvin probe force microscope (KPFM) technology and properly functionalized probes, carbon monoxide molecules can be imaged in σ-real space with anisotropic holes and quadrupole charges (**Figure 2**b) [60]. This method is expected to expand the possibility of characterizing complex molecular systems and surface charge distribution. The atomic-scale motion of nanotubes on a graphene substrate are also investigated based on DFT simulations to explore their atomic-scale rolling friction behavior and induced charge-transfer mechanism [61]. As shown in **Figure 2**c, a simplified physical model is established to the theoretical basis on atomic-scale rolling and sliding friction behaviors. The typical maximum and minimum energy positions during the rolling and sliding process are selected to characterize its corresponding charge-transfer morphology (**Figure 2**d). It can be found that the charge interaction is mainly concentrated in the contact area of the moving object, and there is no charge redistribution beyond the contact area. The charge is completely accumulated at the bottom of the carbon nanotube and depleted at the top of the flat graphene substrate, which indicates that selecting the rod rather than the flat structure as a strategy can effectively increase the induced charge density of the triboelectric interface.

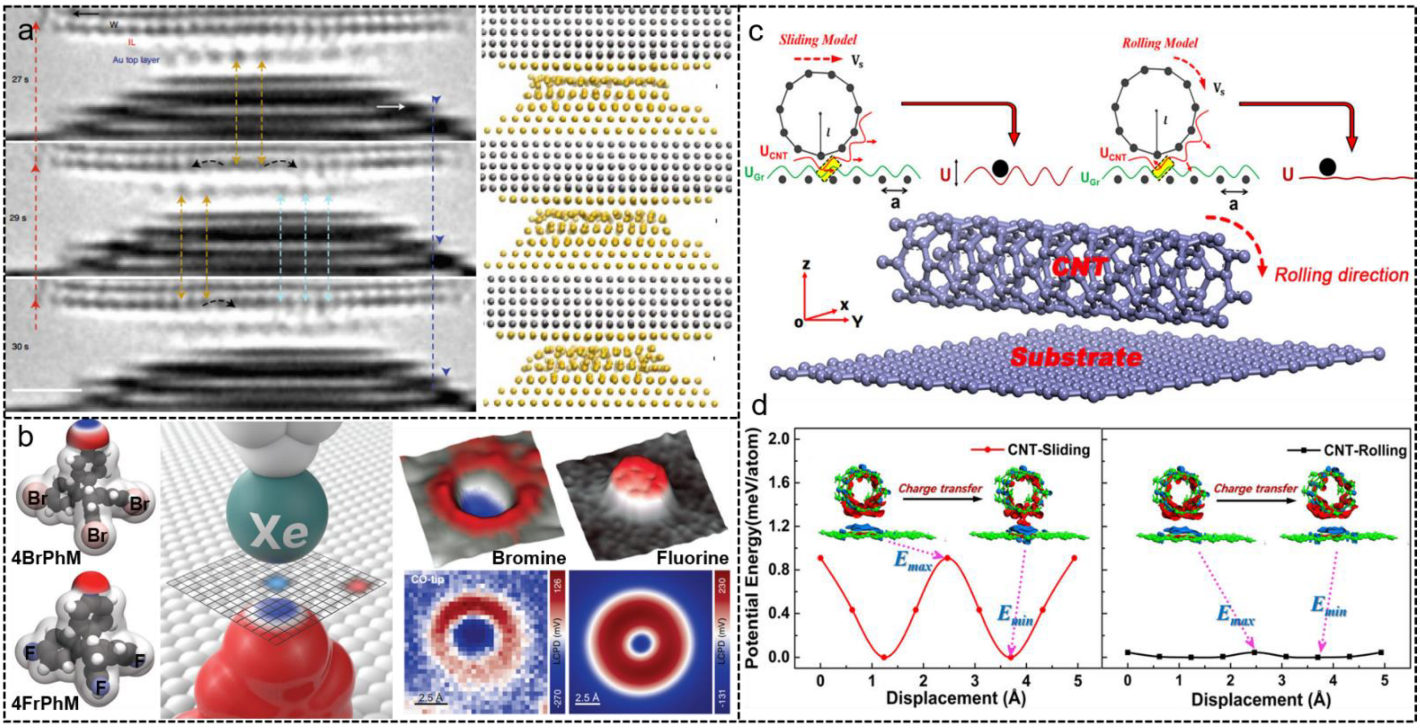

Figure 2. Experimental characterization of atomic-scale contact or friction behaviors as well as their induced electrification phenomena. (**a**) The atomic-scale interface structure in the friction process was observed directly and in real-time. Through in situ high-resolution transmission electron microscopy (TEM) and atomic force microscopy (AFM) measurements, it was found that a loosely stacked interface layer was formed between the two metal micro bumps [59]. (**b**) Real-space images of the anisotropic charge distribution of the σ-hole and the quadrupolar charge of a carbon monoxide molecule obtained by KPFM [60]. (**c**) Atomic-scale rolling and sliding friction behaviors between CNT and graphene substrate. (**d**) The corresponding potential energy distribution during the rolling and sliding process. (**c**,**d**) [61].

Contact electrification or triboelectrification mechanism is particularly important for TENGs. As usual, a macro-scale electron or charge transfer model during two friction layers in a complete contact and separation cycle is used to reveal the electrification mechanism (**Figure 3**a). Taking the typical vertical contact-separation model as an example, when the two friction materials A and B make contact with each other, the same amount of charges are generated on their interface with opposite polarities (**Figure 3**a(i)). When the two friction materials begin to separate, static charges are induced in the electrodes, generating an instantaneous electrical current (**Figure 3**a(ii)). When the two friction layers are completely separated, the charges on the friction layers are fully equilibrated by the electrostatic induced charges on their attached electrodes (**Figure 3**a(iii)). In the reverse case, if the two frictional materials gradually approach each other, the electrons or charges will be transferred in the reverse trend (**Figure 3**a(iv)). After the whole system returns to the initial state, the charges on the electrodes will be offset by the frictional layers. The contact and separation process in **Figure 3**a will form an alternative potential or current signal. In addition to the widely used macro-scale charge transfer model, Wang et al. proposed an atomic-scale electron cloud potential well or wave function overlapping model based on the electron-emission-dominated charge transfer mechanism to attempt to describe the CE process between any two materials and even atoms [62][63]. As shown in **Figure 3**b, once the two atoms approach and make contact with each other, the electron clouds will overlap between the two atoms to form ionic or covalent bonds, resulting in the initial single potential wells becoming an asymmetric double-well potential. Due to the strong overlap of electron clouds, the energy barrier between the two decreases. Then, electrons can then be transferred from one atom to the other, resulting in CE (**Figure 3**b(ii)). Due to the existence of surface potential barriers that bind the electrons tightly in specific orbits and prevent the charge generated by CE from flowing back, the charges generated in CE can be readily retained by the material as the electrostatic charges for several hours at room temperature (**Figure 3**b(iii)) [64]. The process presented in **Figure 3**b is referred to as the Wang transition, which has laid a solid foundation for exploring the meso-scale and macro-scale contact electrification or triboelectrification of textile TENGs.

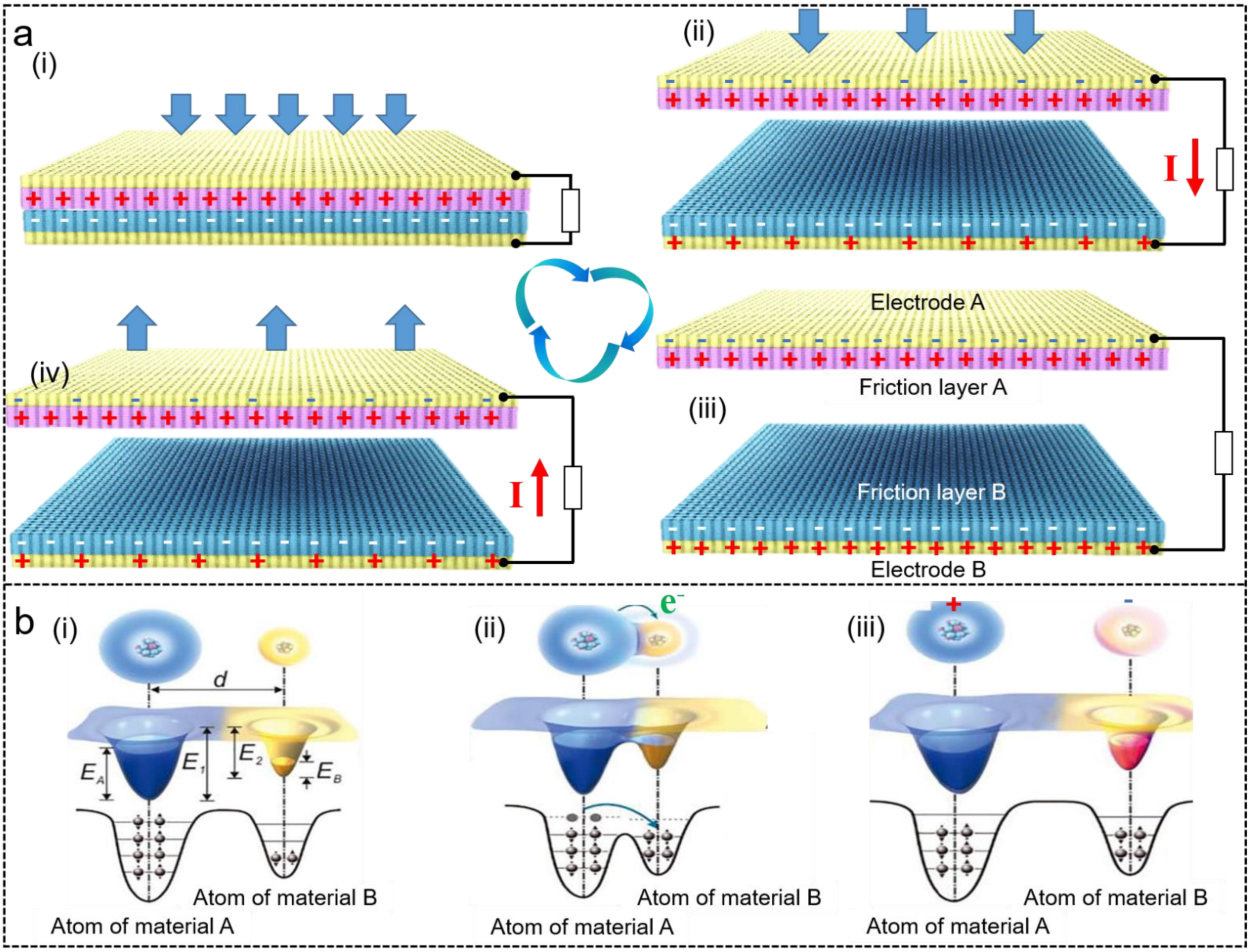

Figure 3. Electrification mechanism of mechanical-to-electrical conversion during contact or friction process. (**a**) Classic electron or charge transfer process in a complete contact and separation cycle. (**b**) An electron-cloud-potential-well model was proposed for explaining CE and Charge transfer between two materials that may not have a well-specified energy band structure [65].

References

1. Davis, S.J.; Lewis, N.S.; Shaner, M.; Aggarwal, S.; Arent, D.; Azevedo, I.L.; Benson, S.M.; Bradley, T.; Brouwer, J.; Chiang, Y.-M.; et al. Net-zero emissions energy systems. Science 2018, 360, eaas9793.
2. Hittinger, E.; Jaramillo, P. Internet of Things: Energy boon or bane? Science 2019, 364, 326–328.
3. Liu, L.; Guo, X.; Lee, C. Promoting smart cities into the 5G era with multi-field Internet of Things (IoT) applications powered with advanced mechanical energy harvesters. Nano Energy 2021, 88, 106304.
4. Dharmasena, R.D.I.G.; Jayawardena, K.D.G.I.; Mills, C.A.; Deane, J.H.B.; Anguita, J.V.; Dorey, R.A.; Silva, S.R.P. Triboelectric nanogenerators: Providing a fundamental framework. Energy Environ. Sci. 2017, 10, 1801–1811.
5. Ryu, H.; Park, H.-M.; Kim, M.-K.; Kim, B.; Myoung, H.S.; Kim, T.Y.; Yoon, H.-J.; Kwak, S.S.; Kim, J.; Hwang, T.H.; et al. Self-rechargeable cardiac pacemaker system with triboelectric nanogenerators. Nat. Commun. 2021, 12, 4374.
6. Wang, H.; Han, M.; Song, Y.; Zhang, H. Design, manufacturing and applications of wearable triboelectric nanogenerators. Nano Energy 2021, 81, 105627.
7. He, W.; Fu, X.; Zhang, D.; Zhang, Q.; Zhuo, K.; Yuan, Z.; Ma, R. Recent progress of flexible/wearable self-charging power units based on triboelectric nanogenerators. Nano Energy 2021, 84, 105880.
8. Feng, H.; Bai, Y.; Qiao, L.; Li, Z.; Wang, E.; Chao, S.; Qu, X.; Cao, Y.; Liu, Z.; Han, X.; et al. An Ultra-Simple Charge Supplementary Strategy for High Performance Rotary Triboelectric Nanogenerators. Small 2021, 17, 2101430.
9. Huang, L.-B.; Dai, X.; Sun, Z.; Wong, M.-C.; Pang, S.-Y.; Han, J.; Zheng, Q.; Zhao, C.-H.; Kong, J.; Hao, J. Environment-resisted flexible high performance triboelectric nanogenerators based on ultrafast self-healing non-drying conductive organohydrogel. Nano Energy 2021, 82, 105724.
10. Yin, L.; Kim, K.N.; Trifonov, A.; Podhajny, T.; Wang, J. Designing wearable microgrids: Towards autonomous sustainable on-body energy management. Energy Environ. Sci. 2022, 15, 82–101.
11. Karan, S.K.; Maiti, S.; Lee, J.H.; Mishra, Y.K.; Khatua, B.B.; Kim, J.K. Recent Advances in Self-Powered Tribo-/Piezoelectric Energy Harvesters: All-In-One Package for Future Smart Technologies. Adv. Funct. Mater. 2020, 30, 2004446.
12. Mahapatra, S.D.; Mohapatra, P.C.; Aria, A.I.; Christie, G.; Mishra, Y.K.; Hofmann, S.; Thakur, V.K. Piezoelectric Materials for Energy Harvesting and Sensing Applications: Roadmap for Future Smart Materials. Adv. Sci. 2021, 8, 2100864.

13. Sahu, M.; Hajra, S.; Kim, H.-G.; Rubahn, H.-G.; Kumar Mishra, Y.; Kim, H.J. Additive manufacturing-based recycling of laboratory waste into energy harvesting device for self-powered applications. Nano Energy 2021, 88, 106255.

14. Parandeh, S.; Etemadi, N.; Kharaziha, M.; Chen, G.; Nashalian, A.; Xiao, X.; Chen, J. Advances in Triboelectric Nanogenerators for Self-Powered Regenerative Medicine. Adv. Funct. Mater. 2021, 31, 2105169.

15. Dang, C.; Shao, C.; Liu, H.; Chen, Y.; Qi, H. Cellulose melt processing assisted by small biomass molecule to fabricate recyclable ionogels for versatile stretchable triboelectric nanogenerators. Nano Energy 2021, 90, 106619.

16. Zhong, W.; Xu, B.; Gao, Y. Engraved pattern spacer triboelectric nanogenerators for mechanical energy harvesting. Nano Energy 2022, 92, 106782.

17. Durukan, M.B.; Cicek, M.O.; Doganay, D.; Gorur, M.C.; Çınar, S.; Unalan, H.E. Multifunctional and Physically Transient Supercapacitors, Triboelectric Nanogenerators, and Capacitive Sensors. Adv. Funct. Mater. 2022, 32, 2106066.

18. Jiang, M.; Li, B.; Jia, W.; Zhu, Z. Predicting output performance of triboelectric nanogenerators using deep learning model. Nano Energy 2022, 93, 106830.

19. Fan, F.-R.; Tian, Z.-Q.; Wang, Z.L. Flexible triboelectric generator. Nano Energy 2012, 1, 328–334.

20. Wu, C.; Wang, A.C.; Ding, W.; Guo, H.; Wang, Z.L. Triboelectric Nanogenerator: A Foundation of the Energy for the New Era. Adv. Energy Mater. 2019, 9, 1802906.

21. Ye, C.; Liu, D.; Peng, X.; Jiang, Y.; Cheng, R.; Ning, C.; Sheng, F.; Zhang, Y.; Dong, K.; Wang, Z.L. A Hydrophobic Self-Repairing Power Textile for Effective Water Droplet Energy Harvesting. ACS Nano 2021, 15, 18172–18181.

22. Chen, J.; Wang, Z.L. Reviving Vibration Energy Harvesting and Self-Powered Sensing by a Triboelectric Nanogenerator. Joule 2017, 1, 480–521.

23. Xu, W.; Zheng, H.; Liu, Y.; Zhou, X.; Zhang, C.; Song, Y.; Deng, X.; Leung, M.; Yang, Z.; Xu, R.X.; et al. A droplet-based electricity generator with high instantaneous power density. Nature 2020, 578, 392–396.

24. Rodrigues, C.; Nunes, D.; Clemente, D.; Mathias, N.; Correia, J.M.; Rosa-Santos, P.; Taveira-Pinto, F.; Morais, T.; Pereira, A.; Ventura, J. Emerging triboelectric nanogenerators for ocean wave energy harvesting: State of the art and future perspectives. Energy Environ. Sci. 2020, 13, 2657–2683.

25. Dong, K.; Peng, X.; Wang, Z.L. Fiber/Fabric-Based Piezoelectric and Triboelectric Nanogenerators for Flexible/Stretchable and Wearable Electronics and Artificial Intelligence. Adv.

Mater. 2020, 32, 1902549.

26. Wang, Z.L.; Chen, J.; Lin, L. Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors. Energy Environ. Sci. 2015, 8, 2250–2282.
27. Dong, K.; Wang, Z.L. Self-charging power textiles integrating energy harvesting triboelectric nanogenerators with energy storage batteries/supercapacitors. J. Semicond. 2021, 42, 101601.
28. Guan, X.; Xu, B.; Wu, M.; Jing, T.; Yang, Y.; Gao, Y. Breathable, washable and wearable woven-structured triboelectric nanogenerators utilizing electrospun nanofibers for biomechanical energy harvesting and self-powered sensing. Nano Energy 2021, 80, 105549.
29. Gunawardhana, K.R.S.D.; Wanasekara, N.D.; Dharmasena, R.D.I.G. Towards Truly Wearable Systems: Optimizing and Scaling Up Wearable Triboelectric Nanogenerators. iScience 2020, 23, 101360.
30. Zou, Y.; Raveendran, V.; Chen, J. Wearable triboelectric nanogenerators for biomechanical energy harvesting. Nano Energy 2020, 77, 105303.
31. Shen, S.; Xiao, X.; Xiao, X.; Chen, J. Wearable triboelectric nanogenerators for heart rate monitoring. Chem. Commun. 2021, 57, 5871–5879.
32. Zhang, S.; Bick, M.; Xiao, X.; Chen, G.; Nashalian, A.; Chen, J. Leveraging triboelectric nanogenerators for bioengineering. Matter 2021, 4, 845–887.
33. Tat, T.; Libanori, A.; Au, C.; Yau, A.; Chen, J. Advances in triboelectric nanogenerators for biomedical sensing. Biosens. Bioelectron. 2021, 171, 112714.
34. Pan, M.; Yuan, C.; Liang, X.; Zou, J.; Zhang, Y.; Bowen, C. Triboelectric and Piezoelectric Nanogenerators for Future Soft Robots and Machines. iScience 2020, 23, 101682.
35. Elbanna, M.A.; Arafa, M.H.; Bowen, C.R. Experimental and Analytical Investigation of the Response of a Triboelectric Generator Under Different Operating Conditions. Energy Technol. 2020, 8, 2000576.
36. Wang, Z.L. On Maxwell’s displacement current for energy and sensors: The origin of nanogenerators. Mater. Today 2017, 20, 74–82.
37. Wang, Z.L. On the expanded Maxwell’s equations for moving charged media system—General theory, mathematical solutions and applications in TENG. Mater. Today 2021.
38. Dong, K.; Hu, Y.; Yang, J.; Kim, S.W.; Hu, W.; Wang, Z.L. Smart textile triboelectric nanogenerators: Current status and perspectives. MRS Bull. 2021, 46, 512–521.
39. Chen, G.; Au, C.; Chen, J. Textile Triboelectric Nanogenerators for Wearable Pulse Wave Monitoring. Trends Biotechnol. 2021, 39, 1078–1092.

40. Huang, T.; Zhang, J.; Yu, B.; Yu, H.; Long, H.; Wang, H.; Zhang, Q.; Zhu, M. Fabric texture design for boosting the performance of a knitted washable textile triboelectric nanogenerator as wearable power. Nano Energy 2019, 58, 375–383.
41. Liu, J.; Gu, L.; Cui, N.; Xu, Q.; Qin, Y.; Yang, R. Fabric-Based Triboelectric Nanogenerators. Research 2019, 2019, 1091632.
42. Tcho, I.-W.; Kim, W.-G.; Choi, Y.-K. A self-powered character recognition device based on a triboelectric nanogenerator. Nano Energy 2020, 70, 104534.
43. Zhao, Z.; Yan, C.; Liu, Z.; Fu, X.; Peng, L.-M.; Hu, Y.; Zheng, Z. Machine-Washable Textile Triboelectric Nanogenerators for Effective Human Respiratory Monitoring through Loom Weaving of Metallic Yarns. Adv. Mater. 2016, 28, 10267–10274.
44. Paosangthong, W.; Torah, R.; Beeby, S. Recent progress on textile-based triboelectric nanogenerators. Nano Energy 2019, 55, 401–423.
45. Hu, Y.; Zheng, Z. Progress in textile-based triboelectric nanogenerators for smart fabrics. Nano Energy 2019, 56, 16–24.
46. Kwak, S.S.; Yoon, H.-J.; Kim, S.-W. Textile-Based Triboelectric Nanogenerators for Self-Powered Wearable Electronics. Adv. Funct. Mater. 2019, 29, 1804533.
47. De Medeiros, S.M.; Chanci, D.; Moreno, C.; Goswami, D.; Martinez, R.V. Waterproof, Breathable, and Antibacterial Self-Powered e-Textiles Based on Omniphobic Triboelectric Nanogenerators. Adv. Funct. Mater. 2019, 29, 1904350.
48. Zi, Y.; Wu, C.; Ding, W.; Wang, Z.L. Maximized Effective Energy Output of Contact-Separation-Triggered Triboelectric Nanogenerators as Limited by Air Breakdown. Adv. Funct. Mater. 2017, 27, 1700049.
49. Liu, W.; Wang, Z.; Hu, C. Advanced designs for output improvement of triboelectric nanogenerator system. Mater. Today 2021, 45, 93–119.
50. Chen, L.; Shi, Q.; Sun, Y.; Nguyen, T.; Lee, C.; Soh, S. Controlling Surface Charge Generated by Contact Electrification: Strategies and Applications. Adv. Mater. 2018, 30, 1802405.
51. Xie, X.; Chen, X.; Zhao, C.; Liu, Y.; Sun, X.; Zhao, C.; Wen, Z. Intermediate layer for enhanced triboelectric nanogenerator. Nano Energy 2021, 79, 105439.
52. Kim, W.-G.; Kim, D.-W.; Tcho, I.-W.; Kim, J.-K.; Kim, M.-S.; Choi, Y.-K. Triboelectric Nanogenerator: Structure, Mechanism, and Applications. ACS Nano 2021, 15, 258–287.
53. Zhou, Y.; Deng, W.; Xu, J.; Chen, J. Engineering Materials at the Nanoscale for Triboelectric Nanogenerators. Cell Rep. Phys. Sci. 2020, 1, 100142.

54. Khandelwal, G.; Maria Joseph Raj, N.P.; Kim, S.-J. Materials Beyond Conventional Triboelectric Series for Fabrication and Applications of Triboelectric Nanogenerators. Adv. Energy Mater. 2021, 11, 2101170.

55. Nurmakanov, Y.; Kalimuldina, G.; Nauryzbayev, G.; Adair, D.; Bakenov, Z. Structural and Chemical Modifications Towards High-Performance of Triboelectric Nanogenerators. Nanoscale Res. Lett. 2021, 16, 122.

56. Yu, Y.; Wang, X. Chemical modification of polymer surfaces for advanced triboelectric nanogenerator development. Extreme Mech. Lett. 2016, 9, 514–530.

57. Yang, H.; Fan, F.R.; Xi, Y.; Wu, W. Design and engineering of high-performance triboelectric nanogenerator for ubiquitous unattended devices. EcoMat 2021, 3, e12093.

58. Wang, Z.; Tang, Q.; Shan, C.; Du, Y.; He, W.; Fu, S.; Li, G.; Liu, A.; Liu, W.; Hu, C. Giant performance improvement of triboelectric nanogenerator systems achieved by matched inductor design. Energy Environ. Sci. 2021, 14, 6627–6637.

59. He, Y.; She, D.; Liu, Z.; Wang, X.; Zhong, L.; Wang, C.; Wang, G.; Mao, S.X. Atomistic observation on diffusion-mediated friction between single-asperity contacts. Nat. Mater. 2021, 21, 173–180.

60. Mallada, B.; Gallardo, A.; Lamanec, M.; de la Torre, B.; Špirko, V.; Hobza, P.; Jelinek, P. Real-space imaging of anisotropic charge of σ-hole by means of Kelvin probe force microscopy. Science 2021, 374, 863–867.

61. Zhang, B.; Cheng, Z.; Lu, Z.; Zhang, G.; Ma, F. Atomic-Scale Rolling Friction and Charge-Transfer Mechanism: An Integrated Study of Physical Deductions and DFT Simulations. J. Phys. Chem. C 2020, 124, 8431–8438.

62. Wang, Z.L. From contact electrification to triboelectric nanogenerators. Rep. Prog. Phys. 2021, 84, 096502.

63. Lin, S.; Chen, X.; Wang, Z.L. Contact Electrification at the Liquid-Solid Interface. Chem. Rev. 2021.

64. Xu, C.; Zi, Y.; Wang, A.C.; Zou, H.; Dai, Y.; He, X.; Wang, P.; Wang, Y.C.; Feng, P.; Li, D.; et al. On the electron-transfer mechanism in the contact-electrification effect. Adv. Mater. 2018, 30, 1706790.

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