

Charge engineering in contact electrification and triboelectric nanogenerators: From fundamental mechanisms to performance enhancement

Kunming Shi¹✉, Bin Chai¹, Pingkai Jiang¹, and Xingyi Huang^{1,2}

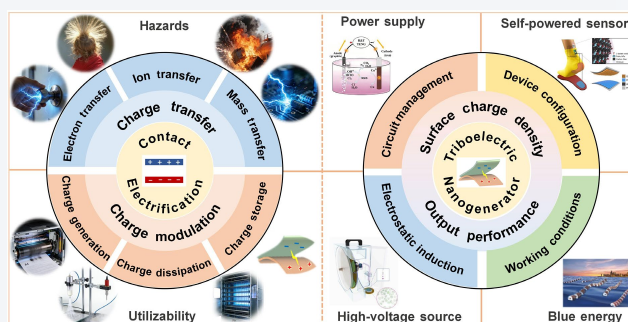
¹Department of Polymer Science and Engineering, School of Chemistry and Chemical Engineering, Shanghai Key Laboratory of Electrical Insulation and Thermal Aging, State Key Laboratory of Polyolefin Catalyst and High-Performance Materials, Shanghai Jiao Tong University, Shanghai 200240, China

²Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT: Contact electrification-derived triboelectric nanogenerators (TEGs) have emerged as a promising technology for energy harvesting. In either contact electrification or TENGs, charge engineering plays a crucial role in realizing their specific demands. Here, this review provides a comprehensive overview of the recent advances in contact electrification and TENGs, with a specific focus on the fundamental charge behavior during contact electrification and the strategies for improving surface charge density and TENG performance. Since the steady-state charge density is governed by both charge generation and dissipation, different charge transfer mechanisms and dissipation pathways are individually discussed, along with the effective approaches to enhance charge storage capability. Furthermore, this review outlines the strategies for boosting surface charge density and overall TENG performance from multiple perspectives, including material design, device architecture, circuit management, and working conditions. The versatile applications of high-performance TENGs are also highlighted in areas, such as power supplies, self-powered sensors, high-voltage sources, and blue energy harvesting. Finally, we present perspectives on the remaining challenges and future development of TENGs, aiming to inspire further research efforts in addressing these issues. Hopefully, this review will provide a better and more comprehensive understanding of contact electrification and TENG technology.

KEYWORDS: contact electrification, charge transfer, charge dissipation, surface charge density, triboelectric nanogenerators



1 Introduction

As a universal physical phenomenon, contact electrification has been known for thousands of years and is widely observed in both natural environments and daily life, including lightning, electrostatic shock, hair standing up, electrostatic discharge in electronic circuits, and electrostatic spark-induced explosion [1–3]. Essentially, contact electrification involves charge transfer (e.g., electron, ion, and mass transfer) between two materials in either solid, liquid, or gas phase upon their contact or friction, leading to

the materials charged with equal amounts of opposite polar charges [4–6]. The resulting electrostatic charges accumulate and discharge, leading to discomfort to the human body and posing risks to microelectronics, circuit systems, and industrial production. On the other hand, contact electrification can be harnessed beneficially in technologies, such as electrostatic precipitation, laser printing/photocopying, electrostatic spraying, and triboelectric energy harvesting [7, 8], as shown in Fig. 1(a). Through rational regulation of contact interface, electrostatic charges can be engineered (suppressing or enhancing) via charge generation and charge dissipation/storage according to different specific scenarios [9–11]. Therefore, it is of great significance to understand the underlying mechanisms of contact electrification and modulate the properties of contact interface for its practical utilization.

Electricity is of vital importance to the national economy and

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✉ Address correspondence to skmhuaxue@sjtu.edu.cn

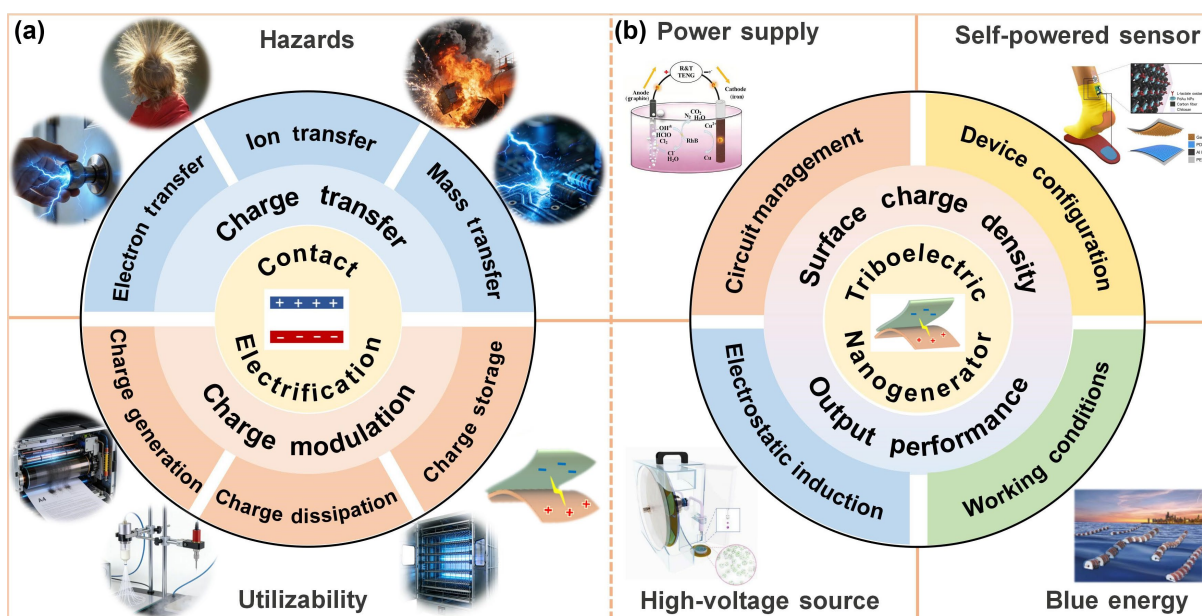


Figure 1 Schematic overview of contact electrification and triboelectric nanogenerator. (a) Charge transfer, charge engineering, and the dual characters of contact electrification. (b) Performance influencing factors and applications of TENG. Image for “power supply”. Reproduced with permission from Ref. [31], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2016. Image for “self-powered sensor”. Reproduced with permission from Ref. [32], © Elsevier Ltd. 2017. Image for “high-voltage source”. Reproduced with permission from Ref. [33], © Huo, H. N. et al. 2019. Image for “blue energy”. Reproduced with permission from Ref. [34], © Elsevier Inc. 2022.

human life, and it is of great significance to acquire sustainable electrical energy from ambient environment [12, 13]. Triboelectric nanogenerators (TENGs), based on contact electrification and electrostatic induction, can efficiently convert irregular, low-frequency, high-entropy mechanical energy that is ubiquitously available in the environment into usable low-entropy electrical energy [14, 15]. Though thermoelectric devices can also acquire electrical energy from ambient environment, they operate on the Seebeck effect and rely on the temperature differential across the device's spatial structure [16–19]. Different working principles lead to their distinct application scenarios. However, TENGs represent one of the most available applications of contact electrification in energy harvesting technology. This emerging nano-micro energy technology offers a viable approach to harvest mechanical energy and has been regarded as an alternative energy source to conventional batteries for powering intelligent electronic devices and systems [20, 21]. In principle, any two materials can constitute a TENG, with contact interface spanning solid–solid, solid–liquid, solid–gas, and liquid–gas configurations. The general working mechanism of TENGs is as follows: When two triboelectric materials contact or are subjected to friction under external force, their surfaces acquire opposite polar charges. Upon separation, the sustained charges create an electrostatic field, driving free electrons to flow through electrodes and external circuits, thereby generating electricity. According to relative motion and electrode configuration, TENGs can be classified into vertical contact–separation, lateral sliding, single-electrode, and freestanding triboelectric-layer modes [22]. The wide material choosability and diverse operation modes benefit the considerable application potential of TENGs.

Currently, TENGs are attracting significant attention and are being extensively studied in the fields of power supply, self-powered sensors, high-voltage sources, and blue energy [23–26], as shown in Fig. 1(b). Through sustained research and multifaceted strategies (including material design, device architecture, circuit management,

and working conditions), the output performance of TENGs has been progressively enhanced to meet their practical requirements [27–30]. Understanding the fundamental mechanisms of contact electrification and engineering the surface charge of triboelectric materials are crucial to constructing high-performance TENGs, thereby promoting the development of new applied technologies for TENGs.

2 Charge transfer and dissipation during contact electrification

Charge transfer at contact interface is the essence of contact electrification and the main source of charge generation. However, transferred charges (i.e., electrostatic charges) on the material surface will undergo dissipative decay, the extent of which depends on the material's charge storage/retention capacity and environmental factors [35]. Consequently, the steady-state electrostatic charge density on material surface is governed by two key competing factors: charge generation and charge dissipation [36–38], as depicted in Fig. 2. Therefore, the surface charge density and TENG performance can be significantly enhanced through charge engineering, for instance, boosting charge transfer while simultaneously inhibiting charge dissipation or improving charge storage in triboelectric materials.

2.1 Charge transfer mechanisms

Contact electrification is a complex process, and current understanding of the phenomenon is largely derived from experimental observations. To date, there is still no unified physical description or model for charge transfer during contact electrification. The prevailing mechanisms for interfacial charge transfer include electron transfer, ion transfer, and mass transfer [39]. The dominant mechanism varies significantly depending on the phase state, electron affinity, surface physicochemical properties, and micro-mechanical characteristics

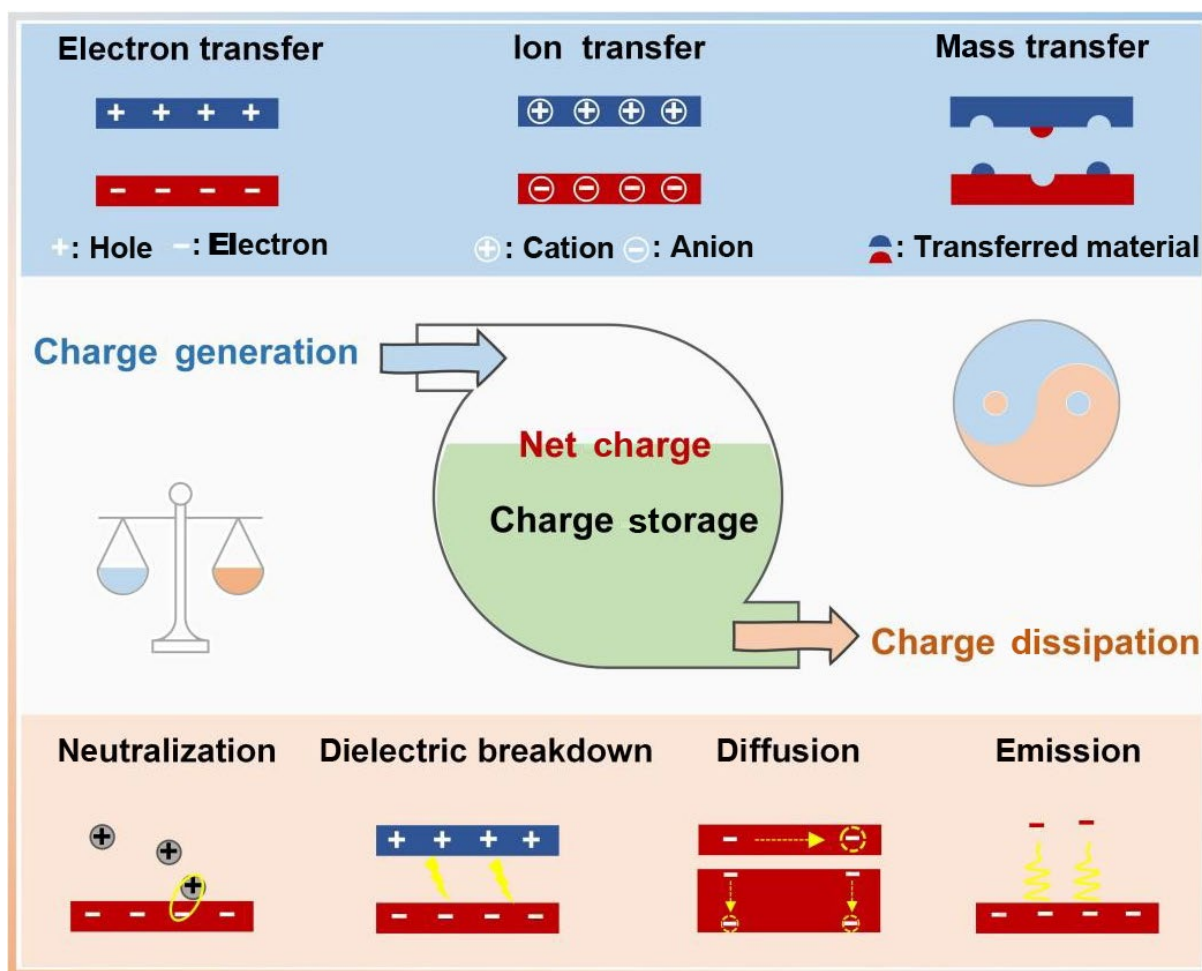


Figure 2 Schematic overview of charge generation, charge dissipation, and their relationship in contact electrification.

of the triboelectric materials [39–43]. Each of these mechanisms is discussed below to establish a comprehensive understanding of charge transfer in contact electrification.

2.1.1 Electron transfer mechanism

Electron transfer is widely regarded as the primary mechanism for contact electrification between metals or semiconductors, dominated by differences in work function or Fermi level [44, 45]. In such cases, electrons tend to transfer from the material with a low work function to that with a higher one. Namely, electrons of the material with a high Fermi level transfer to the material with a low Fermi level until their Fermi level achieve the same height, as shown in Fig. 3(a). For dielectric insulators, the surface state model is commonly used to explain electron transfer [4, 46, 47]. Although the wide bandgap of insulating materials presents a high energy barrier for electrons to transfer, the intermediate states provided by defects or surface states may bridge the bandgap for electrons [1, 48]. Moreover, it has been proposed that the close approach of surface atoms can reduce the interfacial potential barrier due to the superposition principle, thereby facilitating the electron transfer process [49].

Wang et al. demonstrated that when the distance between two materials exceeds the molecular bond length (0.15 to 0.2 nm), atoms in different materials attract each other (Fig. 3(b)), and charge transfer occurs once the distance decreases below the bond length, that is, when atoms enter the potential repulsion

zone [4, 54]. In 2014, Zhou et al. performed nanoscale contact electrification experiments via Kelvin probe force microscopy (KPFM), showing that the charge transferred from a metal tip to an insulator surface can be modulated by a bias voltage (Fig. 3(c)), which effectively shifts the Fermi level of the metal [50]. In 2018, Lin et al. reported that hotter solids tend to acquire positive triboelectric charges, whereas cooler solids tend to be negatively charged. This phenomenon was attributed to the thermionic emission effect as shown in Fig. 3(d), whereby thermally excited electrons transfer from the hotter to the cooler surface [51]. The study also revealed that the dissipation behavior of transferred charges at high temperature follows the electron-thermionic emission model. Additional evidence of electron transfer has been observed under photon excitation [52], as demonstrated in Fig. 3(e). It was found that the triboelectric charges can be released from the dielectric surface when photons exhibit a threshold photon energy. Thus, a photoelectron emission model was proposed to describe the light-induced charge decay on a dielectric surface. Moreover, photon emission detected during contact electrification, along with spectral analysis, has been confirmed to result from electron transfer and transition processes [55, 56]. These experimental results strongly support the existence and dominance of electron transfer in contact electrification.

The electron cloud model in Fig. 3(f) offers a general framework for understanding electron transfer. In the initial state, electron clouds of two materials are independent before they contact.

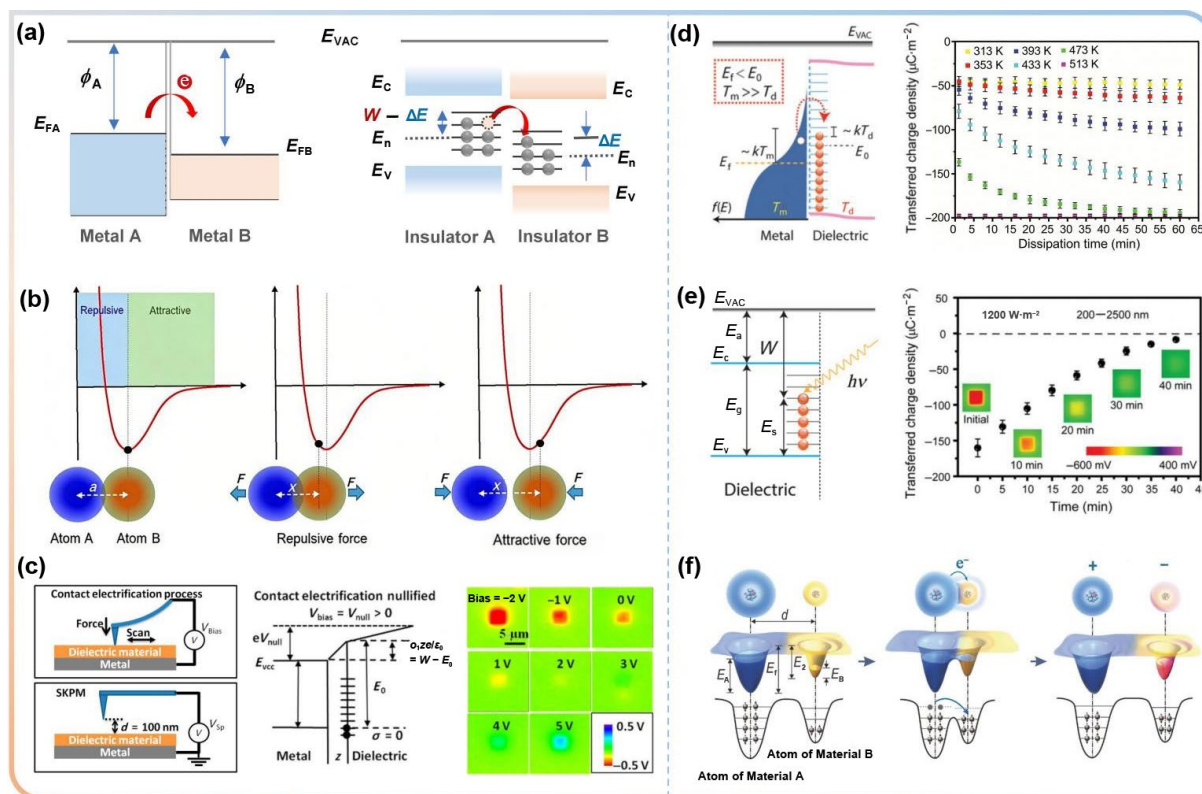


Figure 3 Electron transfer mechanism for contact electrification. (a) Schematics of electron transfer mechanism based on energy band model and surface state model for contact electrification of metal-metal and insulator-insulator pairs. (b) Interatomic interaction potential of two atoms at the equilibrium, repulsive, and attractive positions. Reproduced with permission from Ref. [4], © Elsevier Ltd. 2019. (c) Contact electrification of metal-insulator case using Kelvin probe force microscopy. Reproduced with permission from Ref. [50], © American Chemical Society 2014. (d) The band-structure model of the temperature-induced charge transfer, and the decay of transferred charge density on dielectric surface at different temperatures. Reproduced with permission from Ref. [51], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2019. (e) The photoexcitation of the electrons from surface states of the dielectric, and the decay of transferred charge density on dielectric surface under the irradiation of the xenon light with wavelengths from 200 to 2500 nm. Reproduced with permission from Ref. [52], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2019. (f) Electron-cloud-potential-well model of electron transfer mechanisms for contact electrification. Reproduced with permission from Ref. [53], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2018.

During mechanical contact, atoms from both materials approach each other, and their electron clouds start to overlap, leading to a reduced potential barrier and interatomic electron transfer [53]. Applied mechanical force can reduce the interatomic distance, further lower the interfacial potential barrier, and maximize electron cloud overlap. As the materials separate, the potential barrier rises again, trapping the transferred electrons and resulting in macroscopic charge polarity on the contacting surfaces. This model provides a universal description applicable to contact electrification between diverse material types [49].

2.1.2 Ion transfer mechanism

Ion transfer has been established as a viable mechanism in contact electrification, as mobile ions can migrate across material interface upon contact [57]. In ionic polymers (e.g., ionic conductive hydrogels), the polymer matrix and mobile ions exhibit opposite charge polarity [58, 59]. As depicted in Fig. 4(a), the dissociation of ions from the matrix during separation results in opposite polar charges on the separated material surfaces, contributing significantly to the overall charge transfer process [60, 61]. Whitesides and colleagues investigated contact electrification between glass beads and functionalized polystyrene (PS) microspheres (comprising covalently bound molecules with ionic functional groups and mobile counterions) [62]. Their findings

revealed that the polystyrene surfaces acquired charges matching the polarity of ionic functional groups, while the glass beads exhibited the same polarity as the mobile counterions, distinctly demonstrating the involvement of mobile ion transfer in polymer electrification. In terms of the preferential transfer of a specific polarity of ion, Soh's research claimed that polymers with higher Lewis basicity tend to stabilize cations and become positively charged, while those with higher Lewis acidity stabilize anions and become negatively charged [63].

In the case of non-ionic polymers, the polymer surface can absorb OH^- and H^+ ions from water molecules in the air. Ion transfer occurs when different non-ionic polymers contact due to their different ion adsorption affinities [66]. In 1994, a "water bridge" model was proposed by Diaz's group to describe the contact electrification between non-ionic polymers [60], as shown in Fig. 4(a). It was announced that the chemical potential formed inside the "water bridge" forces the ions to be asymmetrically distributed. Interestingly, ion transfer mechanism involving asymmetric dissociation of OH^- and H^+ species offers a plausible explanation for certain electrification phenomena (especially the electrification at the solid-liquid interface) that cannot be interpreted by electron transfer alone [57]. However, charge transfer persists at material interfaces even in anhydrous environment, demonstrating that ion transfer is condition-

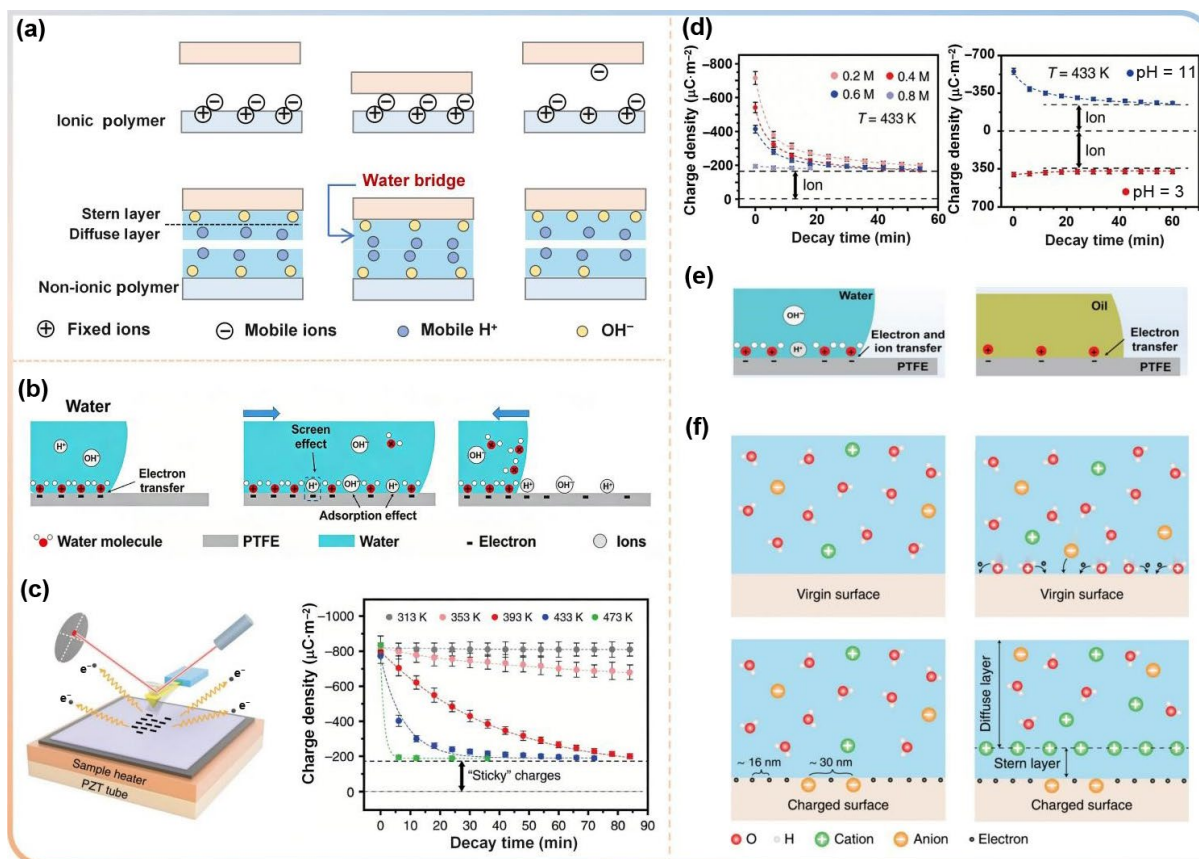


Figure 4 Ion transfer mechanism for contact electrification. (a) Schematic representation of ion transfer model of contact electrification for ionic polymers, and the water bridge model to explain ion transfer mechanism of contact electrification for non-ionic polymers. (b) Contact electrification between PTFE and deionized water. Reproduced with permission from Ref. [64], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2019. (c) The setup of AFM platform for the thermionic emission experiments, and the decay of surface charge (induced by contacting with deionized water at room temperature) on SiO₂ surface at different substrate temperatures. ((c), (d), and (f)) Reproduced with permission from Ref. [65], © Lin, S. Q. et al. 2020. (d) The influence of NaCl solution concentration and pH (pH = 3 HCl solution and pH = 11 NaOH solution) on the charge decay at 433 K. (e) Charge transfer between PTFE and deionized water, PTFE and oil. Reproduced with permission from Ref. [64], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2019. (f) Mechanism of liquid–solid contact electrification and formation of electric double layer.

dependent [67]. This implies that the relative contribution of ion transfer to overall charge transfer is governed by both the intrinsic properties of triboelectric materials and their working environment.

Experimental studies have demonstrated the coexistence of ion and electron transfer at liquid–solid interfaces [64, 68–71], as illustrated in Fig. 4(b). Since electrons can be removed due to thermionic emission, ionic charges remain as sticky charges after electron excitation. Therefore, the contribution of electrons and ions to the total surface charges can be quantitatively analyzed by elaborated thermionic emission experiments, as shown in Fig. 4(c). It has been demonstrated that the presence of dissolved ionic species (e.g., Na⁺ and Cl⁻) in aqueous solutions tends to suppress electron transfer across the interface, whereas ion transfer is highly sensitive to solution pH and ionic concentration [64, 65], as displayed in Fig. 4(d). Otherwise, the surface hydrophilicity of the solid also influences the charge transfer pathway: Hydrophilic surface favors ion transfer, while hydrophobic surface promotes electron transfer during aqueous contact electrification [4, 64], as depicted in Fig. 4(e).

Generally, electrical double layer (EDL) will build at liquid–solid contact interface [72]. In 2018, a two-step model was proposed by Wang's group integrating both electron transfer and ion adsorption processes (Fig. 4(f)) [65]. In the first step, during initial contact, solution species (H₂O molecules, cations, anions) collide with the

solid surface due to thermal motion and hydrodynamic pressure. Electrons transfer between solid and liquid atoms due to the overlap of their electron clouds, and ionization reactions may also occur simultaneously. Otherwise, the molecular fragments divorced from the solid surface can convert into mobile ions in the solution. In the second step, the liquid molecules close to the solid surface leave the contact interface due to liquid flow or turbulence, and most of the electrons transferred to the surface will remain if their energy fluctuation is below the interfacial energy barrier. Finally, the electrostatic-driven counterions in the liquid migrate to the charged surface, establishing the EDL at liquid–solid interface.

2.1.3 Mass transfer mechanism

Compared to electron and ion transfer, mass transfer/material transfer has received relatively little attention in previous studies on contact electrification mechanisms. Moreover, it has been difficult to establish a direct correlation between mass transfer and charge transfer, and the contribution of mass transfer to contact electrification remains controversial. In 2011, Baytekin et al. demonstrated that polymer–polymer contact electrification induces spatially heterogeneous charge distribution at the nanoscale (Fig. 5(a)) [73]. They attributed these mosaic-like charge patterns to material transfer accompanied by charge transfer. In an experiment of contact electrification between flat gold and a microdome-

patterned polydimethylsiloxane (PDMS) film, KPFM revealed that the circular patterns of transferred charge on gold were identical to the surface pattern of PDMS [74], as displayed in Fig. 5(b). These transferred charges were also shown to drive electrochemical reactions. These findings suggested the presence of immobile charges that are distinct from electrons on the gold surface, which originate from material transfer during contact electrification.

Bond cleavage is a usual phenomenon accompanying material transfer in polymer contact electrification [75, 76]. When polymer chains fracture into segments, mechanoions are generated via heterolytic cleavage, producing negative and positive charges at the fractured chain ends. Meanwhile, mechanoradicals can be generated via homolytic cleavage without charge separation, as depicted in Fig. 5(c). Therefore, material transfer is closely related to ion transfer, which involves the transfer of charged ionic fragments, as shown in Fig. 5(d). The generated mechanoions transferred along with polymer segments have been reported to contribute significantly to charge transfer and contact electrification [77, 78]. Baytekin's research in 2013 further revealed that mechanoions and mechanoradicals can achieve mutual stabilization through orbital

hybridization [79]. Additionally, electron transfer may occur between mechanoions and mechanoradicals, suggesting their important roles in both electron and material transfer models [80].

The tendency for material transfer during contact electrification is strongly influenced by the mechanical properties of polymer materials. Softer polymers, or those with weak intramolecular forces and strong surface adhesion, are more prone to material transfer during contact electrification [83]. In 2018, Pandey et al. showed that softer PDMS with low cross-linking ratio yields more triboelectric charge (Fig. 5(e)), accompanied by distinct PDMS segments transferred to a polyvinyl chloride (PVC) surface [82]. In 2019, Šutka et al. found that polymers with lower moduli exhibit higher surface charge values than those with higher moduli (Fig. 5(f)) [83]. In addition, larger adhesion force between contacted surfaces resulted in larger force to separate them and larger surface charge density. Furthermore, adhesive polymers have been demonstrated to exhibit significant material transfer coupled with substantial charge entrainment [84–87]. When used as triboelectric materials in TENGs, adhesive polymers can enhance the charge density by an order of magnitude compared to non-adhesive

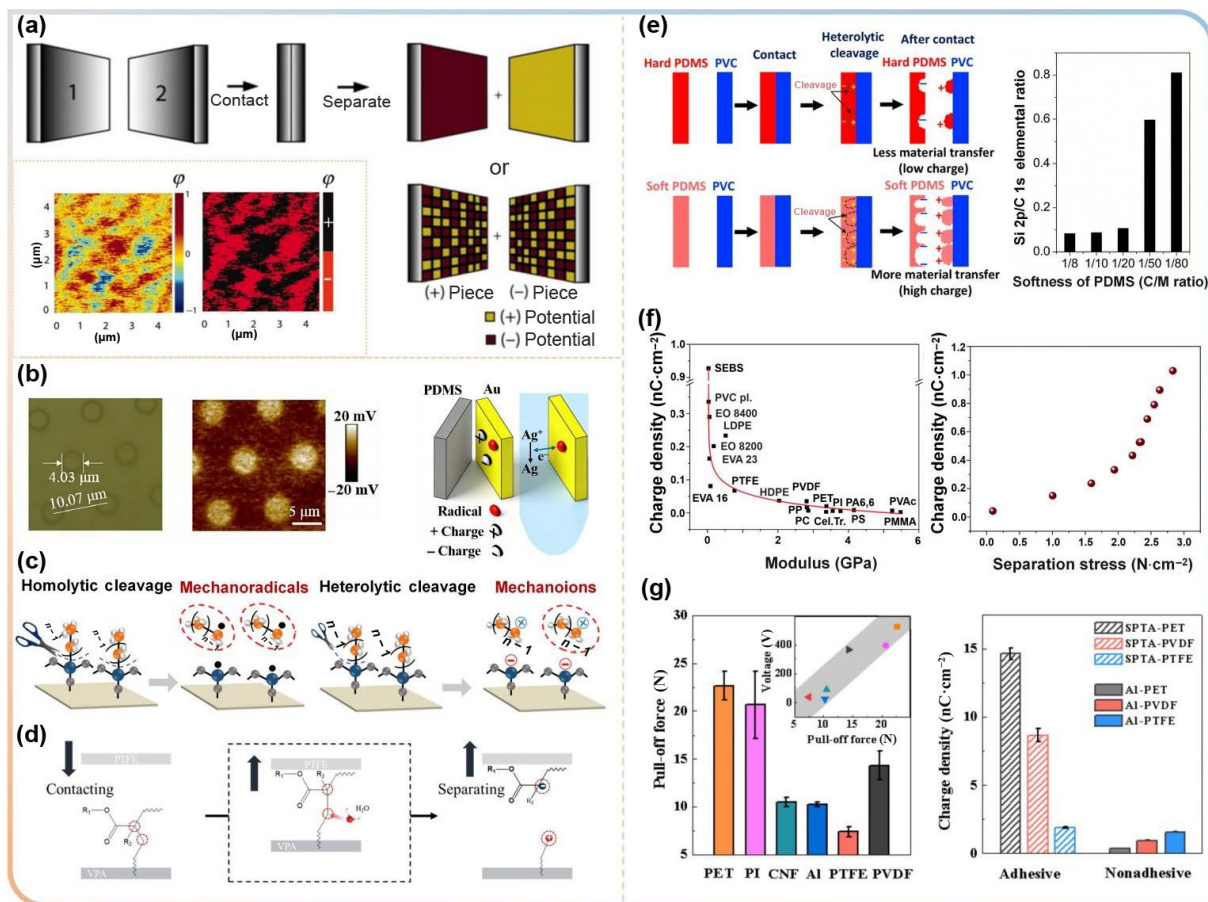


Figure 5 Mass transfer mechanism for contact electrification. (a) The mosaic of surface charge in contact electrification. Reproduced with permission from Ref. [73], © American Association for the Advancement of Science 2011. (b) Optical images of dot-patterned PDMS, contact potential difference (CPD) of Au after contact with the dot-patterned PDMS, and electrochemical reaction on the contacted Au. Reproduced with permission from Ref. [74], © American Chemical Society 2018. (c) Schematic diagrams of homolytic and heterolytic cleavage by contact electrification. Reproduced with permission from Ref. [78], © Fang, Y. et al. 2024. (d) The generation of macromolecular charges with opposite signs in contact electrification between PTFE and viscoelastic polymer adhesive. Reproduced with permission from Ref. [81], © The Royal Society of Chemistry 2024. (e) Scheme illustrating the material transfer on polymer materials with different mechanical properties. Reproduced with permission from Ref. [82], © American Chemical Society 2018. (f) Correlation between the modulus of polymer material and surface charge, and relationship between the charge and separation stress. Reproduced with permission from Ref. [83], © The Royal Society of Chemistry 2019. (g) Pull-off force of different triboelectric counterparts from an adhesive surface (inset shows the relation between pull-off force and output voltage), and comparison of surface charge density between the triboelectric pairs with and without adhesive interface. Reproduced with permission from Ref. [84], © Wiley-VCH GmbH 2023.

polymers (Fig. 5(g)), and the amount of transferred charge directly relates to the quantity of transferred material [82, 84]. Fu et al. utilized a viscoelastic polyacrylate adhesive to amplify the electrification effect and they proposed the covalent bond cleavage mechanism of polymer chains based on the observed fiber drawing phenomenon during contact electrification process [81]. A record-high charge density of $90.31 \text{ nC}\cdot\text{cm}^{-2}$ was achieved with polytetrafluoroethylene (PTFE) applied as the counterpart, and the corresponding device exhibited unique frequency-insensitive and high-performance characteristics.

However, the practical application of adhesive polymers in TENGs faces several challenges, such as surface contamination, viscosity degradation, and high interfacial separation forces. Furthermore, several fundamental questions remain unresolved: (1) the underlying mechanism of material transfer in modulating surface charge, (2) the relative contributions of different bond cleavages to surface charge, and (3) the selective migration mechanism of polar charged material. These unresolved issues pose significant challenges to the fundamental understanding of contact electrification, which require further investigation.

2.2 Charge dissipation pathways

In contact electrification, charge dissipation plays a crucial role in charge generation [36, 38, 88–90]. Generally, transferred charges will undergo inevitable decay due to charge dissipation, and materials with poor charge storage capability experience a rapid decline in charge density. Therefore, the charge dissipation process greatly influences the steady-state electrostatic charges on material surface. Typically, charge dissipation can be ascribed to the following aspects.

2.2.1 Neutralization by atmospheric ions

Charged ions can be produced by cosmic rays and radioactive substances, and exist in the atmosphere with a concentration ranging from hundreds to thousands of pairs per cubic centimeter at the ground [91, 92]. After contact electrification, when a charged material is exposed to air, atmospheric ions with opposite polarity are attracted to and neutralize the surface charges via electrostatic interaction, as shown in Fig. 6(a). Considering the low concentration of atmospheric ions under normal conditions, the derived charge dissipation is relatively slow and may take several days [93]. However, the charge dissipation rate can be suppressed or accelerated by decreasing or increasing the atmospheric ion concentration, respectively.

2.2.2 Air/dielectric breakdown

During contact electrification, materials will be positively or negatively charged through charge transfer. The accumulated electrostatic charges on the material surface will build an electric field, which may exceed the breakdown strength of air and initiate the ionization of gaseous molecules. As depicted in Fig. 6(b), the ionization process produces positively and negatively charged species in the atmosphere, which are attracted to and deposit onto the material surface with opposite polarity, neutralizing the original charges and resulting in a significant reduction in net surface charge [94, 95]. In contrast to air breakdown, dielectric breakdown refers to the failure of the insulating triboelectric materials. When the induced electric field is sufficiently high, the triboelectric material will be electrically broken down with an instantaneous conductive behavior, leading to a rapid dissipation of electrostatic charge. Since

the breakdown strength of most insulating triboelectric materials is much higher than that of air, air breakdown typically occurs before dielectric breakdown.

According to Gauss's law, the shape and size of the charged material significantly influence the resulting electric field, thereby affecting the dissipation of surface charge [9]. Additionally, as shown in Fig. 6(c), different gas molecules exhibit different dielectric breakdown strengths; charge dissipation via air breakdown can be inhibited by performing contact electrification in gas composition with high breakdown strength. Based on Paschen law, gas pressure (p) also plays a significant role in its dielectric breakdown strength (Fig. 6(d)). An appropriate gas pressure contributes to higher effective energy output with reduced charge dissipation [96]. Studies have indicated that surface charge density of triboelectric material is limited to $240\text{--}250 \text{ }\mu\text{C}\cdot\text{m}^{-2}$ in atmospheric environments, but can reach up to $660 \text{ }\mu\text{C}\cdot\text{m}^{-2}$ in a vacuum environment (Fig. 6(e)) [97].

Apart from material and atmospheric factors, rational structure design and circuit management in TENGs can effectively suppress air breakdown, for instance, charge pumping TENGs and charge excitation TENGs [35]. In 2018, Xu et al. developed an integrated self-charge pumping TENG consisting of a main TENG and a pump TENG. A floating layer in the main TENG structure was designed to store triboelectric charges unidirectionally pumped from the pump TENG, thereby inhibiting air breakdown. This elaborate design enabled a surface charge density of $1020 \text{ }\mu\text{C}\cdot\text{m}^{-2}$, four times the typical air breakdown limit [98]. Similarly, the use of Zener diodes and external capacitors in the circuit of charge excitation TENGs has proven effective in suppressing air breakdown and enhancing surface charge density [99, 100]. In 2024, Wang and co-workers prepared a novel triboelectric polymer of poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene) (P(VDF-TrFE-CFE)) with high dielectric permittivity and thin thickness. When incorporated into a charge excitation TENG, air breakdown was effectively suppressed, resulting in a record-breaking charge density of $8.6 \text{ mC}\cdot\text{m}^{-2}$ at that time (Fig. 6(f)) [101].

2.2.3 Charge diffusion

Charge diffusion primarily arises from surface conduction and bulk conduction [102]. Due to the concentration gradient of surface charge, charged species (e.g., electrons) can laterally migrate across the material surface toward regions of low potential. On the other hand, charged species can also drift vertically into the bulk material under the built-in electric field [35]. Materials with high electrical conductivity typically exhibit rapid charge diffusion, whereas charges on insulating material surfaces dissipate more slowly via surface and bulk conduction. However, the surface conductivity of insulating materials can increase significantly when water molecules from the atmosphere adsorb onto the material surface. Since water possesses relatively high electrical conductivity compared to insulators, it facilitates the movement of ionic charges [103]. Consequently, higher ambient humidity leads to greater adsorption of water molecules, resulting in increased surface conductivity and accelerated charge diffusion [104]. Thus, both humidity and material hydrophilicity play vital roles in charge dissipation.

It can be seen from Fig. 6(g) that a nanoscale triboelectrification experiment conducted by Zhou et al. using atomic force microscopy (AFM) and scanning Kelvin probe microscopy (SKPM) revealed that the charged area becomes larger over time after triboelectrification, and the peak voltage contrast becomes smaller,

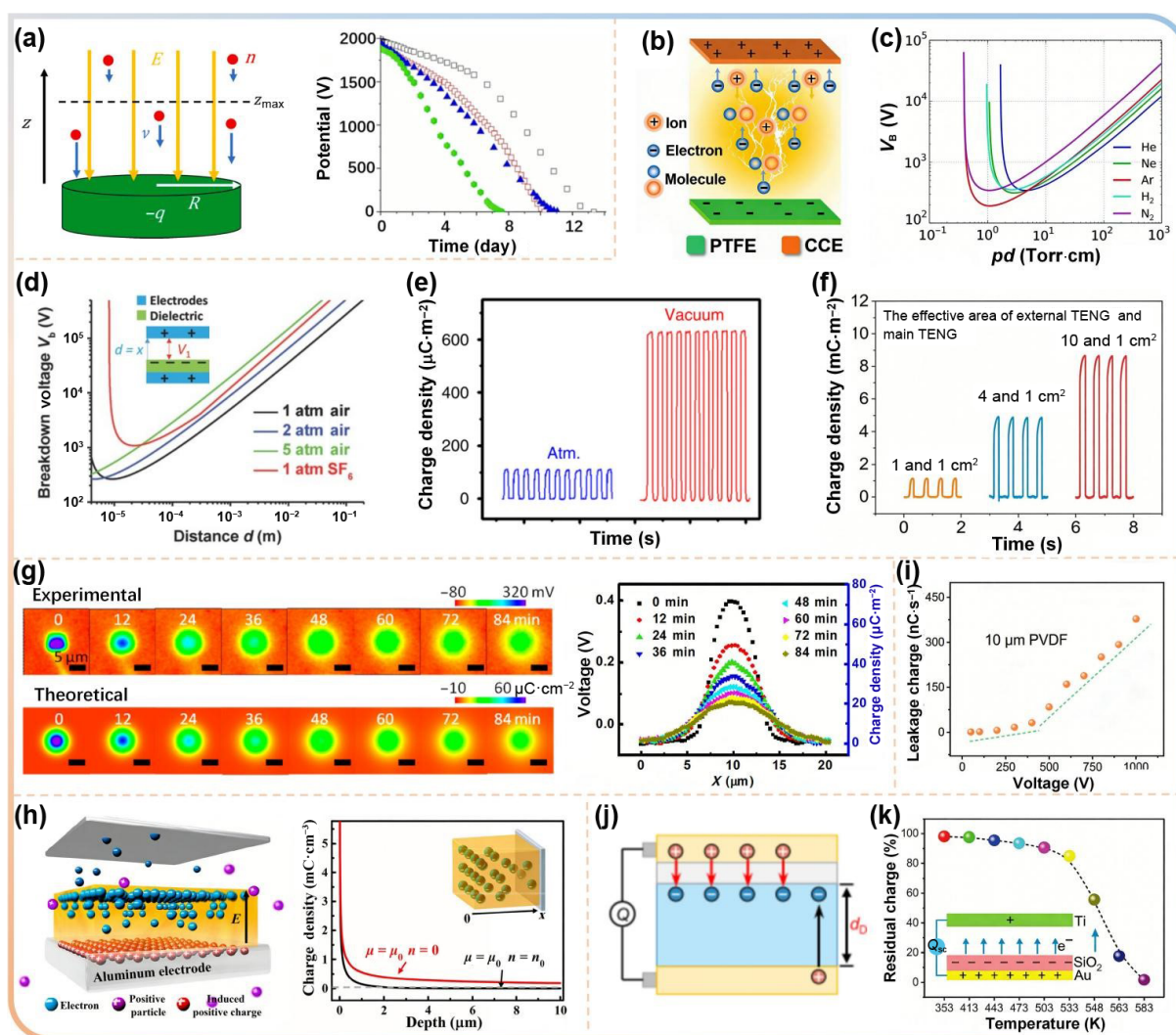


Figure 6 Charge dissipation for contact electrification. (a) Scheme illustrating the neutralization of a charged surface by atmospheric ions, and the time dependence of the surface potential on the levitating sample in a Class 10,000 clean room (open symbols) and a Class 1000 clean room (closed symbols). Reproduced with permission from Ref. [93], © Elsevier B.V. 2021. (b) Schematic diagram of avalanche breakdown between two electrification materials. Reproduced with permission from Ref. [95], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2020. (c) Paschen's curves for different gases: breakdown voltage against the product of p and gap distance (d). Reproduced with permission from Ref. [9], © The Royal Society of Chemistry 2022. (d) Paschen's curves for different gas pressures. Reproduced with permission from Ref. [96], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2017. (e) Charge density of a Cu-PTFE TENG in atmosphere and high vacuum ($p = 10^{-6}$ Torr). Reproduced with permission from Ref. [97], © Wang, J. et al. 2017. (f) Charge density of external charge excitation TENGs with an external TENG of different sizes and 1 cm^2 main TENG. Reproduced with permission from Ref. [101], © The Royal Society of Chemistry 2024. (g) Surface potential distribution as a function of time after triboelectrification, and the cross-section data of the series of images. Reproduced with permission from Ref. [105], © American Chemical Society 2013. (h) Schematic of the transport process of triboelectric electrons in the negative friction layer of a TENG, and the theoretical triboelectric charge distribution in the friction layer (μ_0 and intrinsic carrier density (n_0)). Reproduced with permission from Ref. [36], © American Chemical Society 2016. (i) Leakage charge per second of the TENG with a $10\text{ }\mu\text{m}$ PVDF dielectric under an increasing bias voltage. Reproduced with permission from Ref. [106], © Wiley-VCH GmbH 2023. (j) Schematic diagram of field emission. Reproduced with permission from Ref. [107], © Liu, D. et al. 2025. (k) The percentage of residual charges of the TENG at different temperatures. Reproduced with permission from Ref. [53], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2018.

which indicates the diffusion of surface charges to adjacent areas [105]. Furthermore, vertical charge diffusion or drift (i.e., buck conduction) can be non-negligible in thin material (e.g., triboelectric layer in TENGs). The internal electric field established between the surface charges and the induced opposite charges on the electrode drives the surface charges to drift into deeper regions (Fig. 6(h)), even reaching the back electrode and combining with induced opposite charges, leading to a leakage current across the material. In 2023, Wang's group reported for the first time the phenomenon of dielectric charge leakage that limits the maximum output of TENGs prior to air breakdown [106]. As displayed

in Fig. 6(i), they emphasized the critical influence of charge leakage on surface charge density and TENG performance. By employing a dual dielectric layer of PVDF-polyimide (PI), they simultaneously suppressed charge decay from both air breakdown and dielectric charge leakage, achieving an output charge density of $2.2\text{ mC}\cdot\text{m}^{-2}$. Hence, charge diffusion of the triboelectric materials from charge leakage should be carefully considered in the design of TENGs.

2.2.4 Field/thermionic emission

When two contacting materials are charged with opposite polarities, a strong electric field develops during their separation,

particularly at the initial point of detachment. Under this high electric field, transferred electrons can be stimulated and emitted back toward the original (positively charged) material surface, thereby reducing the net surface charge [107]. This process is referred to as field emission, as illustrated in Fig. 6(j). Separately, thermionic emission occurs when a charged material is subjected to elevated temperatures. Thermal excitation enables electrons to gain sufficient energy to escape from the charged surface [53, 108], as shown in Fig. 6(k). Recently, Liu et al. demonstrated that the field emission arising from contact electrification occurs prior to dielectric breakdown, and constitutes a major factor limiting surface charge density and TENG performance. By effectively suppressing the field emission effect, they achieved an ultrahigh charge density of $2.816 \text{ mC}\cdot\text{m}^{-2}$ in contact electrification [107].

2.3 Approaches for enhancing charge storage capability

Charge storage is intrinsically associated with charge dissipation.

Improving a material's charge storage capability can significantly mitigate charge dissipation, thereby promoting a high surface charge density [109, 110]. From the perspective of triboelectric materials, enhancing their ability to retain charges represents an efficient and feasible approach to increasing charge density and improving TENG performance [111–113]. Current strategies to boost charge storage capacity or inhibit charge decay primarily focus on dielectric modulation, the introduction of functional layers, and the regulation of charge traps.

2.3.1 Dielectric modulation

Dielectric properties are critical for triboelectric materials and exert a significant influence on surface charge density [114–117]. As shown in Fig. 7(a), the typical contact–separation TENGs can be simplified down to the equivalent capacitance model, in which the transferred charge quantity is positively correlated with the effective permittivity of the materials [118]. In addition, higher permittivity

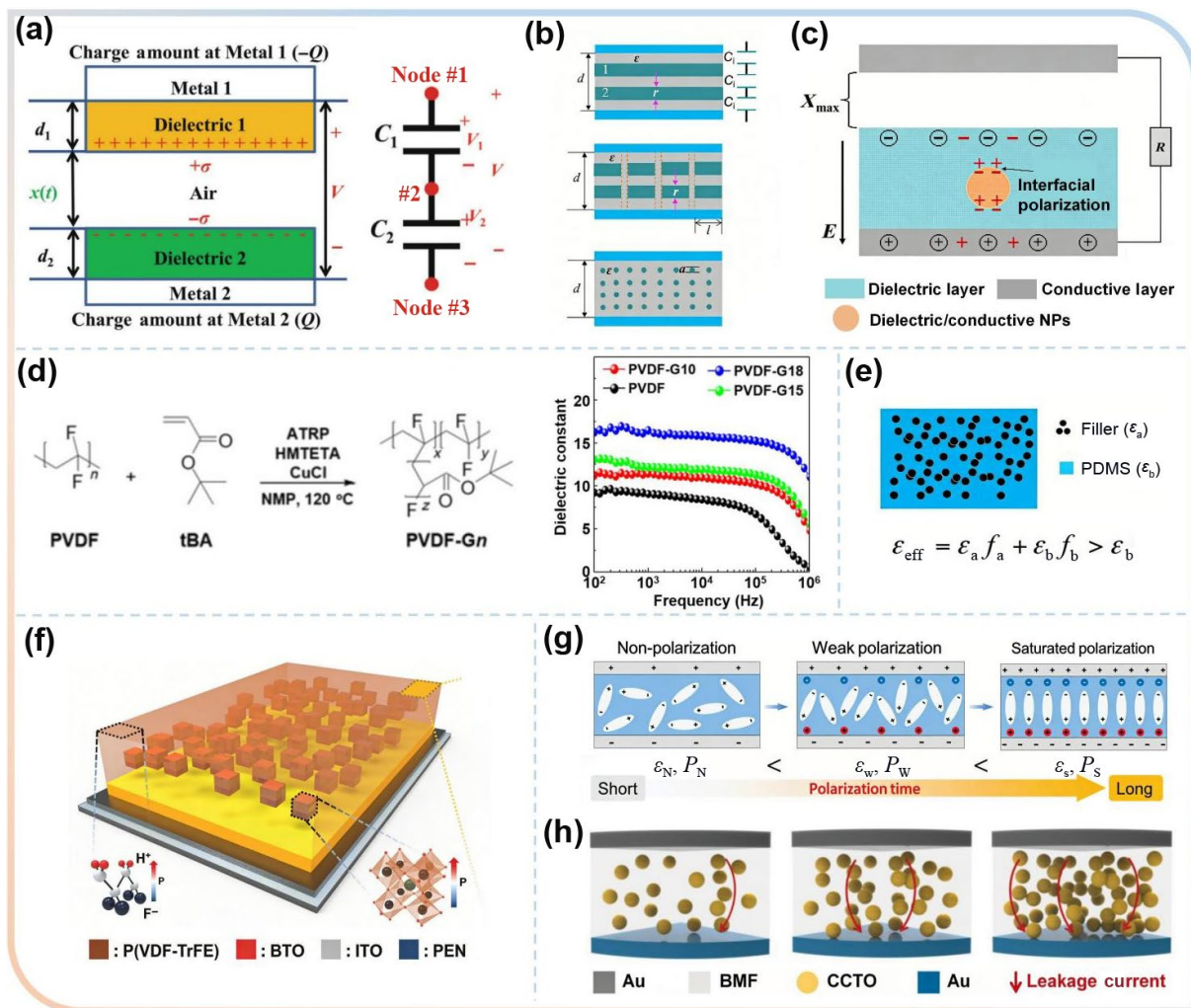


Figure 7 Dielectric modulation for enhancing charge storage capability. (a) Capacitor theoretical mode and working mechanism of contact–separation mode TENGs. Reproduced with permission from Ref. [118], © Elsevier Ltd. 2014. (b) Schematic diagram of the capacitor structure with different shapes and sizes of fillers in polymer. Reproduced with permission from Ref. [116], © Tsinghua University Press and Springer-Verlag Berlin Heidelberg 2016. (c) Schematic diagram of internal interface polarization in TENG dielectric layer doped with dielectric/conductive nanoparticles. Reproduced with permission from Ref. [125], © Elsevier Ltd. 2023. (d) Synthesis of graft copolymers and their corresponding dielectric constant. Reproduced with permission from Ref. [126], © Lee, J. W. et al. 2017. (e) Dielectric nanocomposites fabricated via filler addition. Reproduced with permission from Ref. [122], © American Chemical Society 2015. (f) Schematic description of a ferroelectric composite-based TENG. Reproduced with permission from Ref. [127], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2016. (g) Schematic diagram of self-polarization process. Reproduced with permission from Ref. [128], © Wiley-VCH GmbH 2022. (h) Schematic illustrations of leakage current generation in triboelectric nanocomposite. Reproduced with permission from Ref. [129], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2020.

always corresponds to stronger capacitive characteristics, enabling the material to store more charges while suppressing charge diffusion. In triboelectric composite materials, the added fillers can be regarded as numerous micro-capacitors that contribute to the whole capacitance of the triboelectric layer (Fig. 7(b)). Furthermore, fillers with high permittivity contribute to enhanced polarization of triboelectric materials under electric field (Fig. 7(c)), which also benefits the reduction of charge diffusion and the mitigation of air breakdown [119]. Previous studies have confirmed that materials with higher permittivity can support more surface charge, thereby exhibiting stronger triboelectric effects and higher output performance in TENGs [118, 120–124].

Current strategies for enhancing the permittivity of polymer-based triboelectric layers include synthesizing intrinsically high-permittivity polymers (Fig. 7(d)) and fabricating composites with high-permittivity inorganic fillers (Fig. 7(e)) [38, 122, 126]. Chemical synthesis routes are complex, and the improvement of permittivity is limited. In contrast, high permittivity composite materials engineered through dielectric blending combine the merits of polymers and inorganic fillers, and have been widely employed to enhance the electrification process [129, 130], as illustrated in Fig. 7(f). In 2022, Wu et al. prepared a high permittivity composite layer made of lead zirconate titanate powder doped into PVDF (PZT-PVDF), and adopted it as the triboelectric material in a charge excitation TENG [128]. The charge excitation strategy enabled the composite film to undergo self-polarization during device operation (Fig. 7(g)), which further increased the relative permittivity of the composite film and effectively raised the output charge density to a high level of $3.53 \text{ mC}\cdot\text{m}^{-2}$.

However, it should be noted that the poor compatibility between inorganic filler and organic polymer in the composites may lead to filler aggregation and interface defects. In addition, the mismatch of their permittivity will result in an uneven distribution of inner electric field [131]. These factors cause dielectric loss in the composite and a significant increase in leakage current at phase interfaces (Fig. 7(h)), ultimately reducing the surface charge density and limiting the output performance of TENGs [129, 131, 132]. Therefore, when constructing high permittivity triboelectric materials, the heterogeneous interface should be carefully designed and optimized (e.g., chemical modification of fillers, grafting polymers on fillers, and utilization of core-shell structured fillers) to effectively suppress charge leakage [132].

2.3.2 Introduction of functional layer

Generally, charge generation, dissipation, and storage always occur on/in the same material. However, it is difficult to find a material that fulfills all the required properties simultaneously, such as high charge yield, low charge dissipation rate, and high charge storage capacity. To address this challenge, numerous studies have introduced additional functional layers onto/into triboelectric materials, aiming to combine the advantages of different materials and enhance the efficiency of each charge-related process, maximally [102, 133, 134]. Based on this strategy, the introduced functional layers can be categorized into charge transport layers (Figs. 8(a)–8(e)) and charge block layers (Figs. 8(a) and 8(f)), with the ultimate goal of increasing the amount of electrostatic charge stored in the triboelectric material.

The charge transport layer is introduced to facilitate charge migration from the surface to the bulk. Therefore, conductive materials with high carrier mobility (μ ; e.g., PS + carbon nanotubes

(CNTs) [36] and PVDF + CNTs [140]) are always adopted as charge transport layers and sandwiched within the triboelectric material as an intermediate layer to prevent charge leakage. Compared to monolayer triboelectric material, the incorporation of a transport layer can significantly enhance the storage depth and capacity of triboelectric charges, thereby increasing the bulk charge density [109, 133, 141]. For instance, as shown in Fig. 8(b), Li et al. prepared a multilayered fiber-based triboelectric material incorporating a charge transport layer of PS + carbon black (CB) [135]. The introduced conductive transport layer effectively improved the transfer rate and storage depth of triboelectric charges during the electrification process. Lai et al. built the internal-space-charge zones through embedding ravines and gullies in criss-crossed gold layers in the near-surface of the triboelectric layer (Fig. 8(c)) [136]. Acting as passageways, the gold layers facilitate the triboelectric charges drifting to the internal space of the triboelectric material. Moreover, the charge transport layer can be constructed in either positive or negative triboelectric layer, or both, greatly promoting the transport of triboelectric charge into deep region and enhancing the triboelectric charge density [137, 138], as shown in Figs. 8(d) and 8(e). Significantly, the migration of charges to a deep region can suppress air breakdown and mitigate the charge repulsion effect (hindering the entrance of new charges) caused by the accumulation of surface charges [36].

On the other hand, the charge block layer is utilized to inhibit charge drift/leakage toward the back electrode under the built-in electric field, thereby preventing their combination with opposite induced charges on the electrode [133, 134, 142]. Unlike the charge transport layer, the charge block layer can be mounted inside or below the triboelectric material. Materials with a wide band gap, low carrier mobility, or high permittivity are always adopted as charge block layers, such as BN, TiO_x , PS, and PDMS [35, 139]. For example, Park et al. added a layer of high-permittivity TiO_x between the PDMS triboelectric layer and the bottom electrode (Fig. 8(f)) [139]. The electron blocking effect of TiO_x could significantly improve the surface charge density from 15 to $30 \mu\text{C}\cdot\text{m}^{-2}$. Cui et al. found that adding a PS dielectric layer as a charge block layer to PVDF increased its triboelectric charge density by 7 times [36]. Furthermore, when a PS + CNTs charge transport layer was sandwiched between PVDF and PS (Fig. 8(a)), the triboelectric charge density increased by 11.2 times, demonstrating the effectiveness of combining both charge block and transport layers in enhancing triboelectric charge storage.

2.3.3 Regulation of charge traps

Charge traps refer to localized energy states within semiconductor or insulating materials that are capable of capturing and storing mobile charges [143]. Essentially, charge traps originate from physical defects (e.g., lattice vacancies, interstitial atoms, dislocations, grain boundaries, and amorphous free volume) or chemical defects (e.g., impurity atom/molecular, residual polar groups, cross-linking points, and functional groups) in materials, and their energy levels are situated within the band gap [144, 145]. In the energy band structure (Figs. 9(a)–9(c)), the energy levels of defects near the Fermi level are termed deep traps, which facilitate stable charge retention. In contrast, the energy levels of defects distributed at the edges of the conduction band or valence band are termed shallow traps. Charges captured by shallow trap sites can be easily excited and escape, leading to a rapid charge decay [143, 146, 147]. Therefore, both the trap energy/depth and trap

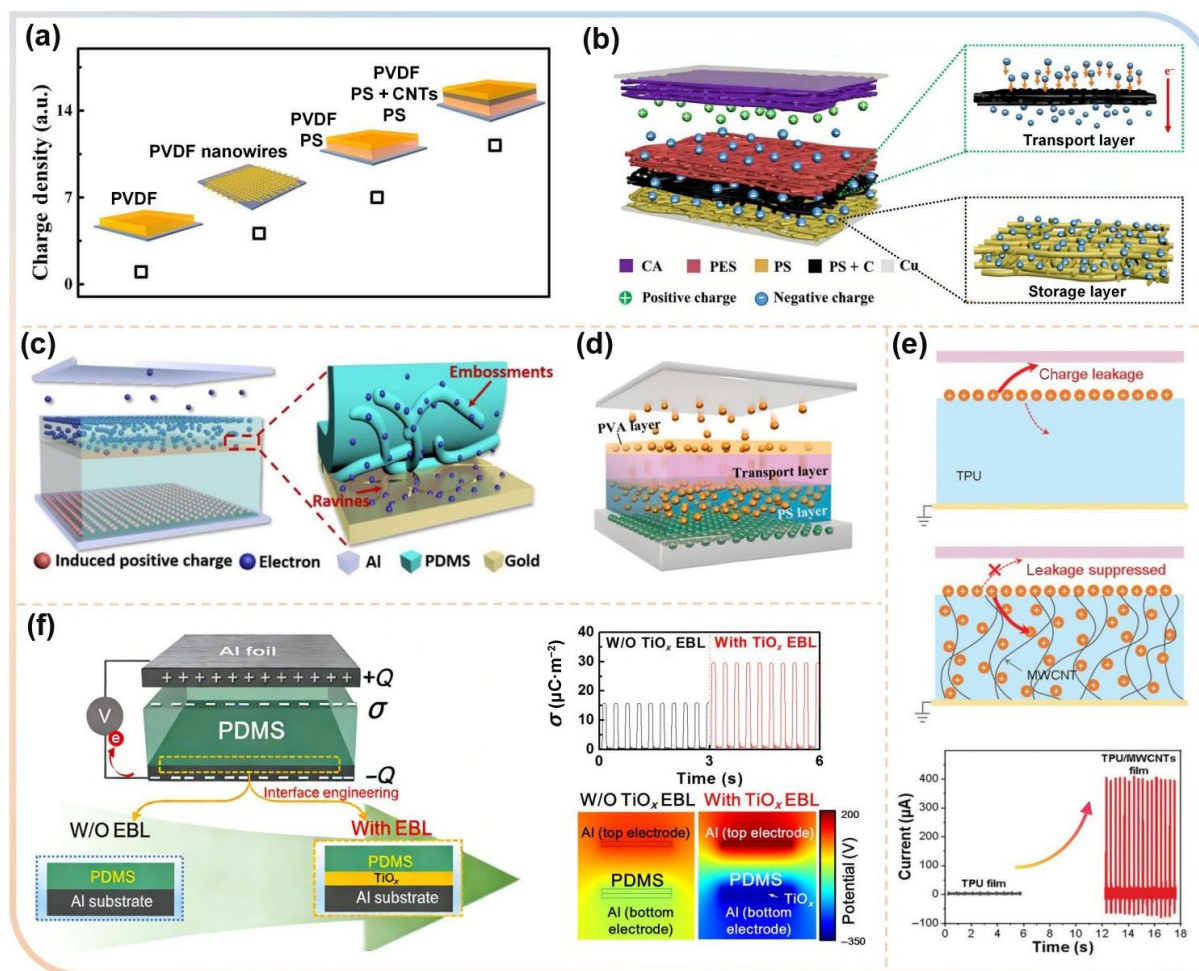


Figure 8 Introduction of functional layer for enhancing charge storage capability. (a) Improvement effects of different composite friction layer structures. Reproduced with permission from Ref. [36], © American Chemical Society 2016. (b) Illustration of the function layer in the three-layer structured TENG. Reproduced with permission from Ref. [135], © Elsevier Ltd. 2018. (c) Schematic diagram of electrons' drift in the TENG, and electrons' escape from PDMS to the gold. Reproduced with permission from Ref. [136], © American Chemical Society 2017. (d) Schematic of the charge transport process of poly(vinyl alcohol) (PVA)-PS-doped 0.7 wt.% CNTs (PSC)-PS positive friction layer of TENG. Reproduced with permission from Ref. [137], © American Chemical Society 2018. (e) Schematic diagrams of charge leakage and suppression of charge leakage via charge transport, and the comparison of triboelectric output current. Reproduced with permission from Ref. [138], © Wiley-VCH GmbH 2023. (f) Schematic illustration of the structure, charge density, and COMSOL Multiphysics simulation results of the TENGs with and without the TiO_x electron blocking layer (EBL). Reproduced with permission from Ref. [139], © Elsevier Ltd. 2018.

density determine a material's ability to capture and store charges. Materials with deeper traps and higher trap density are expected to exhibit enhanced charge storage capability [148–150].

In triboelectric materials, charge traps can capture transferred triboelectric charges and inhibit their diffusion, migration, and excitation, thereby improving the transmission efficiency and storage depth of triboelectric charges [134, 151, 152]. Moreover, deep charge traps can preserve triboelectric charges over extended periods, which is conducive to for TENG performance. In 2018, Kim et al. demonstrated the crucial role of charge traps in capturing and retaining triboelectric charges via inserting a PDMS layer between a PVDF triboelectric layer and an Al electrode (Fig. 9(d)) [153]. Compared with the shallow traps in PVDF, the deep traps in PDMS endowed the triboelectric device with higher charge density and output performance. Meanwhile, charge storage capacity was observed to increase with PDMS thickness. However, a thick PDMS layer can decrease the electrostatic induction effect and device capacitance, whereas a thin PDMS layer exhibits relatively low charge trap density, potentially leading to an easy combination

of triboelectric charges with induced charges under high electric fields. Hence, an optimal PDMS thickness for charge trapping is required, and the trap density, charge leakage, and electrostatic induction should be comprehensively considered.

Recently, composites with enhanced charge trapping capability have been extensively explored for constructing high-performance triboelectric materials and TENGs [154–157]. Nanoscale additives, in particular, can introduce abundant interfaces and charge trap sites into the polymer matrix due to their high specific surface area [158]. The energy level of charge traps is related to the difference between lowest unoccupied molecular orbital (LUMO)/highest occupied molecular orbital (HOMO) energy bands of the fillers and the polymer [159, 160], as shown in Fig. 9(e). Given the diversified additives and various physical/chemical modification methods, specific composites with tailored trap parameters can be designed and prepared (Fig. 9(f)) [144]. In 2024, Wang and co-workers prepared P(VDF-TrFE-CFE) composites with engineered trap density and energy levels by using high-polarity interfaces from barium titanate (BTO) nanoparticles and dense chain segment

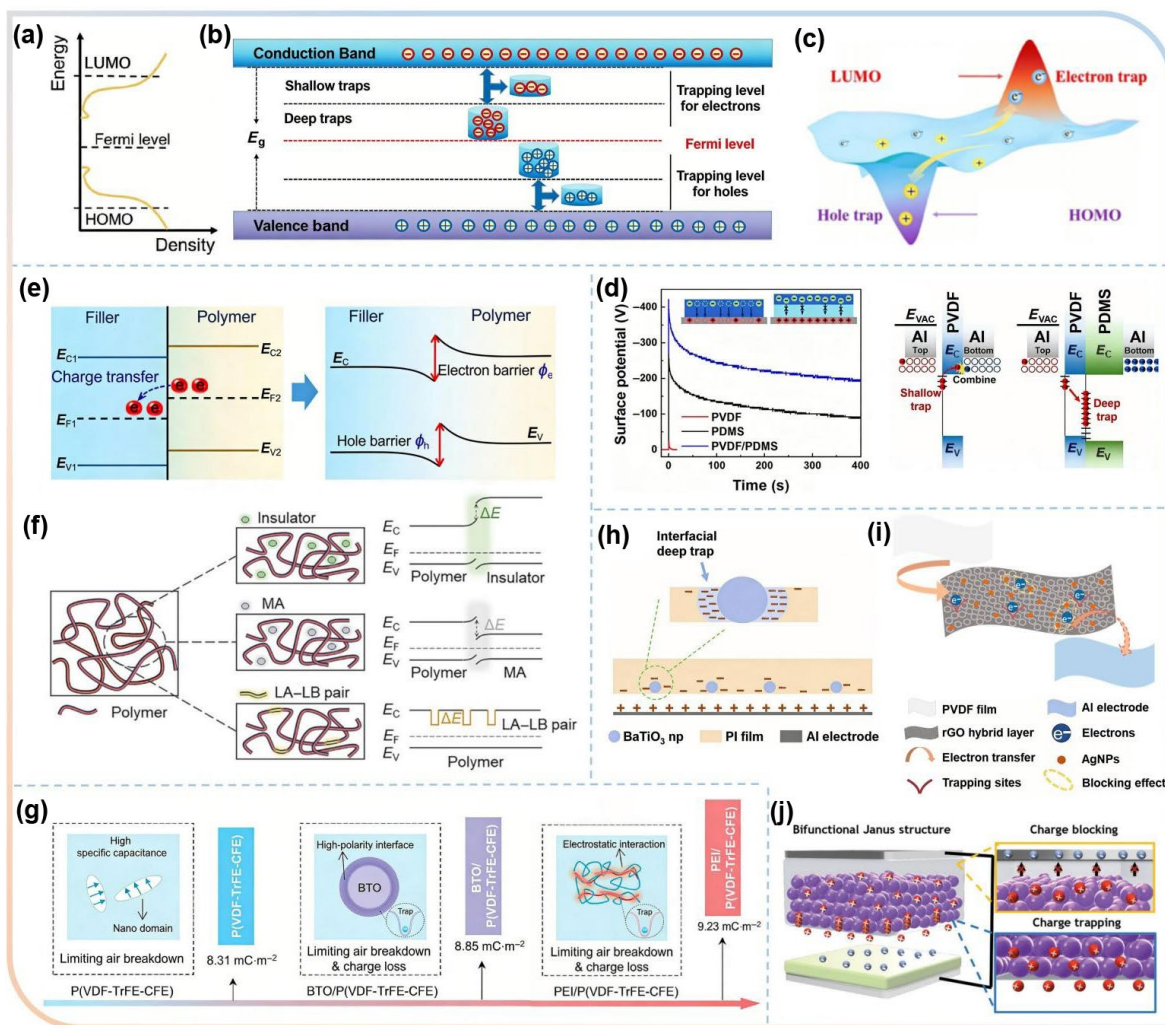


Figure 9 Regulation of charge traps for enhancing charge storage capability. (a) Distribution of trap states on the energy band. Reproduced with permission from Ref. [152], © Wiley-VCH GmbH 2024. (b) Schematic representation of the distribution of shallow and deep traps in a dielectric material. Reproduced with permission from Ref. [149], © Wiley-VCH GmbH 2024. (c) Schematic spatial distributions of electron trap (LUMO) and hole trap (HOMO). Reproduced with permission from Ref. [147], © The Royal Society of Chemistry 2023. (d) Temporal changes in the surface potential of the PDMS, PVDF, and PVDF/PDMS films, and the schematic charge trapping mechanism of the PVDF-based TENG and PVDF/PDMS-based TENG. Reproduced with permission from Ref. [153], © Elsevier Ltd. 2018. (e) Illustration of the interfacial charge transfer and the formation of charge trap between filler and polymer. Reproduced with permission from Ref. [159], © Elsevier Ltd. 2024. (f) Illustration of different charge trapping mechanisms in polymer-based composites. Reproduced with permission from Ref. [160], © Fan, L. et al. 2025. (g) Trap engineering via introducing high polarity interfaces by doping BTO nanoparticles and engineering the chain segment stacking behavior via electrostatic interaction with PEI interchain. Reproduced with permission from Ref. [119], © Wiley-VCH GmbH 2024. (h) The schematic of trapped charge in interface of nanoparticles and polymer. Reproduced with permission from Ref. [161], © Wiley-VCH GmbH 2021. (i) Schematic illustration of the charge-trapping-blocking mechanism. Reproduced with permission from Ref. [142], © Elsevier Ltd. 2020. (j) Illustration explaining the function of charge blocking and charge trapping layer resulting from the asymmetric structure of the fabricated triboelectric materials. Reproduced with permission from Ref. [134], © Yoo, H. et al. 2024.

stacking induced by electrostatic interaction with polyetherimide (PEI) to enhance charge retention capability (Fig. 9(g)) [119]. Compared to the pristine P(VDF-TrFE-CFE) film, both the 0.2 vol.% BTO and 0.2 vol.% PEI composite films showed increased trap energy and density for deep and shallow traps. In particular, the modified interfacial traps enabled an ultrahigh charge density of $9.23 \text{ mC}\cdot\text{m}^{-2}$ in an external charge excitation TENG based on the 0.2 vol.% PEI composite film.

In practice, the effects of dielectric modulation, functional layer incorporation, and charge trap regulation always coexist in composite materials. For instance, incorporating high-permittivity fillers into a polymer matrix not only enhances the composite's permittivity but also creates new charge traps at interfaces (Fig. 9(h)). Furthermore, the introduction of a functional layer,

especially one made of high-permittivity material, can significantly improve charge storage capacity through the synergistic effects of increased capacitance, facilitated charge transport/blocking, and enhanced charge trapping, as shown in Figs. 9(i) and 9(j).

3 Surface charge density and TENG performance

3.1 Role of surface charge density in TENGs

Governed by displacement current, the TENG performance is mainly characterized by output voltage, current, charge density, and instantaneous power density (Fig. 10(a)). As energy harvesters, TENG performance directly determines their application level and commercial potential. However, the relatively low output power

density remains a key technical challenge hindering the widespread practical application of TENGs [162]. It is widely recognized that TENG performance depends on multiple factors, including triboelectric materials, material structure, device architecture, circuit management, and operating conditions [163], as depicted in Fig. 10(b). From a fundamental perspective, the surface charge density of the triboelectric material is the core parameter determining TENG outputs, and pursuing higher charge density continues to be a primary goal for commercializing TENG technology [164, 165].

Considering the processes of charge generation and dissipation in TENGs, Wang et al. proposed that the maximum surface charge density ($\sigma_{\max}$) is constrained by contact electrification ($\sigma_{\text{contact electrification}}$), air breakdown ($\sigma_{\text{air breakdown}}$), and dielectric breakdown ($\sigma_{\text{dielectric breakdown}}$), and is ultimately limited by the lowest value among them [3]. This implies that both air breakdown and dielectric breakdown must be thoroughly considered when pursuing high charge density from contact electrification. Furthermore, due to the diversity of operational modes and mechanical conditions, a unified quantitative evaluation of TENG performance has been challenging. To address this, Zi et al. introduced a methodology for quantitatively assessing TENG performance from both structural and material perspectives [167]. Since the output signals of TENGs are periodic and time-dependent, the output energy per cycle can be represented by the plot of built-up voltage vs. transferred charge (Fig. 10(c)). The potential maximum output energy per cycle (E_m) is given by Eq. (1) [167]

$$E_m = \frac{Q_{\max}}{2} (V_{\max} + V'_{\max}) \quad (1)$$

here, $Q_{\max}$ denotes the maximum transferred charge; $V_{\max}$ is the maximum open circuit voltage; and $V'_{\max}$ is maximum achievable absolute voltage at $Q_{\max}$. All these three parameters are directly proportional to the surface charge density (σ). Consequently, the output energy has a quadratic relationship with σ , and the figure of merit (FOM) for the material is σ^2 from a material perspective. In addition, the FOM for the structure (FOM_s) is derived from the maximum FOM_s extracted from finite element simulations and serves as a standard criterion for evaluating the structure, calculated using Eq. (2) [167]

$$\text{FOM}_s = \frac{2\epsilon_0}{\sigma^2} \cdot \frac{E_m}{Ax_{\max}} \quad (2)$$

where $x_{\max}$ is the maximum displacement of the triboelectric pair, ϵ_0 is the vacuum dielectric constant ($8.85 \times 10^{-12} \text{ F}\cdot\text{m}^{-1}$); and A is the contact area. From the perspective of structure, different working modes of TENGs can be calculated by finite element simulation and evaluated by FOM_s (Fig. 10(d)). The FOM for performance (FOM_p) serves as a universal standard for evaluating TENG performance, which is calculated by the product of the FOM for material and structure, as shown in Eq. (3) [167]

$$\text{FOM}_p = \text{FOM}_s \cdot \sigma^2 = 2\epsilon_0 \cdot \frac{E_m}{Ax_{\max}} \quad (3)$$

As seen from the above equations, E_m is a critical factor influencing

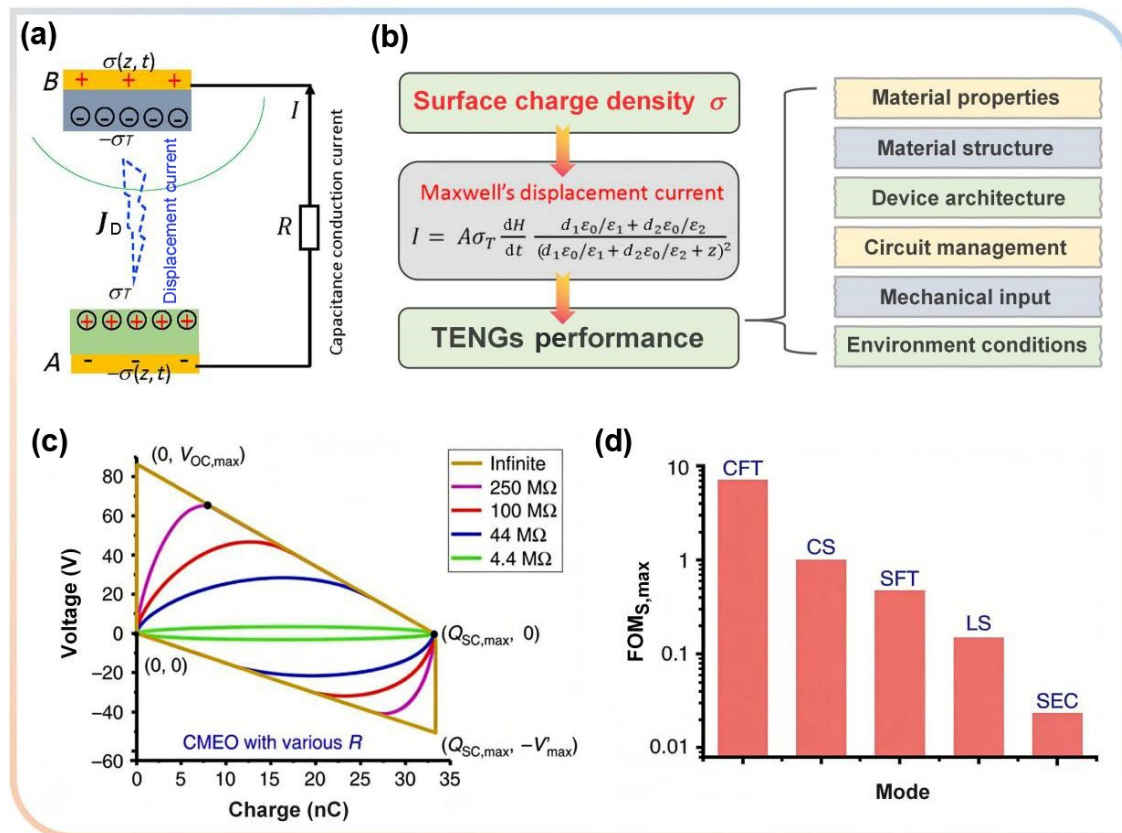


Figure 10 Surface charge density and TENG performance. (a) Displacement current in the contact-separation mode TENGs. Reproduced with permission from Ref. [166], © Elsevier Ltd. 2019. (b) Surface charge density and other aspects that influence TENG performance. (c) The cycles for maximized energy output with various load resistances. ((c) and (d)) Reproduced with permission from Ref. [167], © Macmillan Publishers Limited 2015. (d) The maximum structural FOM of different TENG structures extracted from finite element method (FEM) simulations.

FOM_p, and surface charge density plays a dominant role in determining TENG performance.

3.2 Strategies to enhance surface charge density

Surface charge density in triboelectric materials is influenced by various factors, including electronegativity, surface roughness, capacitance of the triboelectric materials, etc. [168]. To achieve high-performance TENGs, researchers have continuously explored methods for fabricating materials with high surface charge density. Strategies to enhance the material's surface charge density include: selecting appropriate materials, chemical or physical modification, leveraging ferroelectric polarization, coupling piezoelectric charges, optimizing capacitance and charge traps, constructing heterogeneous structures, suppressing air/dielectric breakdown, adopting charge injection/compensation/excitation techniques, etc. [168–172]. In essence, these approaches aim to engineer surface charge by boosting charge generation, suppressing charge dissipation, enhancing charge storage capability, or their synergistic effect.

Generally, a greater difference in electronegativity or triboelectric series between two materials leads to stronger charge transfer capability and more charge generation (Fig. 11(a)). Through rational chemical modification, the electronegativity of a triboelectric material can be tuned (Figs. 11(b) and 11(c)), thus increasing its triboelectric effect with its counterpart, and boosting charge generation. Meanwhile, patterned triboelectric materials through etching, template printing, nanoimprinting, and electrospinning techniques can increase the surface roughness and effective contact area (Fig. 11(d)), thereby promoting charge generation and surface charge density [163]. However, materials modified chemically or physically may suffer from poor mechanical stability and degraded device output over time. In addition, incorporating ferroelectric or piezoelectric materials into the triboelectric layer can remarkably increase charge generation and enhance the TENGs' output [173, 174]. Examples include using polarized ferroelectric PVDF-TrFE film as triboelectric material to induce greater charge transfer (Figs. 11(e) and 11(f)) [127, 175], or adding piezoelectric barium titanate (BaTiO₃) nanoparticles in a PDMS matrix to couple piezoelectric charges with triboelectric charges (Fig. 11(g)) [174, 176]. As discussed in Section 2.3, enhancing charge storage capability through capacitance optimization, charge trap engineering, and the construction of multi-level functional layers can effectively inhibit charge dissipation (Fig. 11(h)), thereby increasing surface charge density and TENG output [177]. Charge dissipation can also be mitigated by controlling ambient humidity and suppressing air or dielectric breakdown through adjustments of gaseous environment, device configuration, and circuit design.

To further boost surface charge density and TENG performance, strategies involving charge injection, compensation, and excitation have been developed [98, 100, 178–182]. Charge injection involves pre-loading the triboelectric material (particularly electrets) with charges from an external source, such as corona polarization, prior to contact electrification (Fig. 11(i)). The injected charges provide extra charge generation, and endow the triboelectric material with a high surface charge density, contributing to an enhanced TENG output. Charge compensation indicates supplying additional charges to the material for suppressing surface charge dissipation. In 2023, Yang et al. proposed a compensation method that suppresses charge escape on triboelectric polymer by inducing

radical ion transfer [180]. As shown in Fig. 11(j), they fabricated an ionized-PTFE layer rich in radical ions, and paired it with a corona-polarized fluorinated ethylene propylene (FEP) film in a TENG. The results demonstrated that the charge-escaping phenomenon of FEP can be well compensated by radical ion transfer during contact electrification, and charge densities of 525 and 1237 $\mu\text{C}\cdot\text{m}^{-2}$ are respectively realized in contact-separation and sliding mode TENGs. Charge excitation represents an innovative strategy that shifts the site of charge accumulation from the material surface to the interior of the dielectric layer and the electrode. In this case, the ultimate charge density limit is no longer determined by air breakdown strength, but by the intrinsic breakdown strength of the solid triboelectric layer, which is usually much higher than that of air. Through a charge excitation circuit, the stored charges that are generated by the TENG itself (self-charge excitation) or by an external device (external charge excitation) are pumped unidirectionally and continuously into the TENG (Fig. 11(k)). This cyclic amplification process during contact electrification enables exponential accumulation and storage of triboelectric charges, resulting in a remarkable enhancement of TENG performance [98, 100, 178, 181, 183].

3.3 Strategies to improve TENG performance

Though TENG performance is primarily governed by the surface charge density of triboelectric materials, it is also influenced by electrostatic induction, device configuration, external circuit management, operating conditions, etc. [16, 163]. As previously discussed, increasing the surface charge density of triboelectric materials can significantly enhance TENGs' output performance. It should be noted that the surface charge is ultimately converted into electrical output through the induction of free charges on the electrode. Therefore, TENGs' output performance is closely related to electrostatic induction and the free charge generation, which is always overlooked in the design of triboelectric materials and TENGs. The electrostatic induction effect depends not only on the electrode material (carrier concentration, carrier mobility), but also on the triboelectric material (thickness, permittivity) [125, 129, 153], as demonstrated in Fig. 12(a). Hence, when designing high-performance TENGs, electrostatic induction should be considered along with charge transfer and charge dissipation in the overall device architecture.

Substantial efforts have been devoted to optimizing device structure to improve TENG performance [189], as shown in Fig. 12(b). For example, the use of soft materials (e.g., PDMS) or elastic supporting structures (e.g., springs and sponges) allows the triboelectric material to undergo sufficient deformation and achieve intimate contact even under low pressure, thereby facilitating charge generation. Such structural designs can also reduce mechanical impact and wear during contact-separation cycles, thereby extending the device's operational lifespan [39]. Furthermore, connecting multiple independent TENG units in parallel or series in a synchronized working manner can effectively enhance the overall output. Parallel connection increases the short-circuit current, whereas series connection enhances the open-circuit voltage. This represents one of the most direct and effective structural strategies for output multiplication. For example, TENGs can be designed into a sandwich structure, in which triboelectric layer and electrode are alternately stacked. Otherwise, in the rotating disc type TENG, multiple fan-shaped units are alternately arranged on the disc, and it operates continuously during rotation

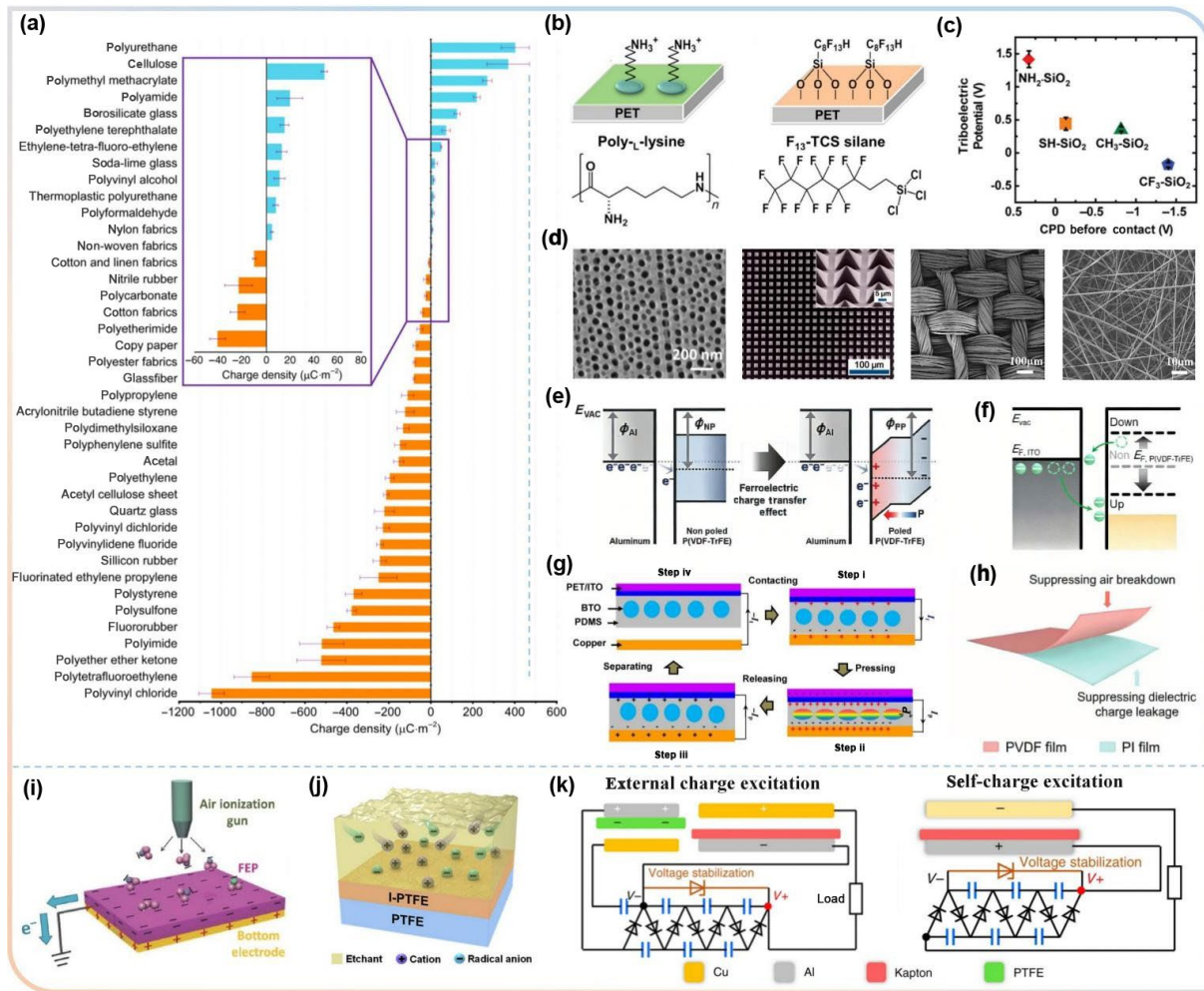


Figure 11 Strategies for increasing surface charge density of triboelectric materials. (a) Triboelectric charge density of various materials in vacuum conditions. Reproduced with permission from Ref. [184], © Liu, D. et al. 2022. (b) Polyethylene terephthalate (PET) surface is functionalized with poly-L-lysine and trichloro(1H,1H,2H,2H-perfluorooctyl) silane (TCS). Reproduced with permission from Ref. [185], © American Chemical Society 2015. (c) Triboelectric potentials of the various surfaces as a function of the CPD before contact. Reproduced with permission from Ref. [172], © American Chemical Society 2016. (d) Different surface structures for triboelectric materials. Reproduced with permission from Ref. [186], © The Royal Society of Chemistry and the Centre National de la Recherche Scientifique 2022. Reproduced with permission from Ref. [187], © American Chemical Society 2012. Reproduced with permission from Ref. [188], © American Chemical Society 2016. (e) Charge transfer between Al and P(VDF-TrFE) with and without ferroelectric polarization. Reproduced with permission from Ref. [127], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2016. (f) Schematic illustration of polarized dipole-shifted work function of P(VDF-TrFE). Reproduced with permission from Ref. [175], © Elsevier Ltd. 2022. (g) Surface charge density enhanced by the combined effects of piezoelectricity and triboelectricity. Reproduced with permission from Ref. [174], © American Chemical Society 2016. (h) Demonstration of the dual dielectric layer for suppressing charge decay. Reproduced with permission from Ref. [106], © Wiley-VCH GmbH 2023. (i) Charge injection via corona discharging of the air. Reproduced with permission from Ref. [182], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2014. (j) Schematic diagram of the structure of ionized-PTFE. Reproduced with permission from Ref. [180], © Elsevier Inc. 2023. (k) Structure of external charge excitation TENG and self-charge excitation TENG. Reproduced with permission from Ref. [100], © Liu, W. L. et al. 2019.

with an enhanced output. In the case of charge pump and charge excitation TENGs, revolutionary designs incorporate an auxiliary unit (e.g., a pump TENG, Zener diode, or external capacitor) for charge pumping or excitation, enabling pre-injection of charges into the main unit to achieve ultrahigh charge storage capacity and output performance. As a compromise, the auxiliary unit will increase the system volume, cost, and power consumption, posing a trade-off relationship between output performance and system complexity. This trade-off balance can be scenario-dependent. In the high-energy-demand large-scale application scenarios, maximizing output power and energy density is the core demand, and the system complexity is an acceptable compromise. In terms of miniaturized wearable/medical self-powered devices, they pursue ultra-thin, small volume and low power consumption. The

performance improvement brought by complex auxiliary circuits is redundant, and the extra circuit overhead may become the primary limiting factor.

The inherent high voltage, low current, and pulsed output characteristics of TENGs make it challenging to directly power most electronic devices. Circuit management plays a key role in enhancing the practical output performance (particularly the available energy and power) of TENGs, and improving the efficiency of energy transfer from the “source” to the “load” [196], as shown in Fig. 12(c). Basic measures include using rectifiers to convert alternating current (AC) output to direct current (DC), and capacitors or batteries to store pulsed electrical energy [197]. The combined use of rectifiers and storage elements ensures a stable power supply to the load during intermittent pulse intervals.

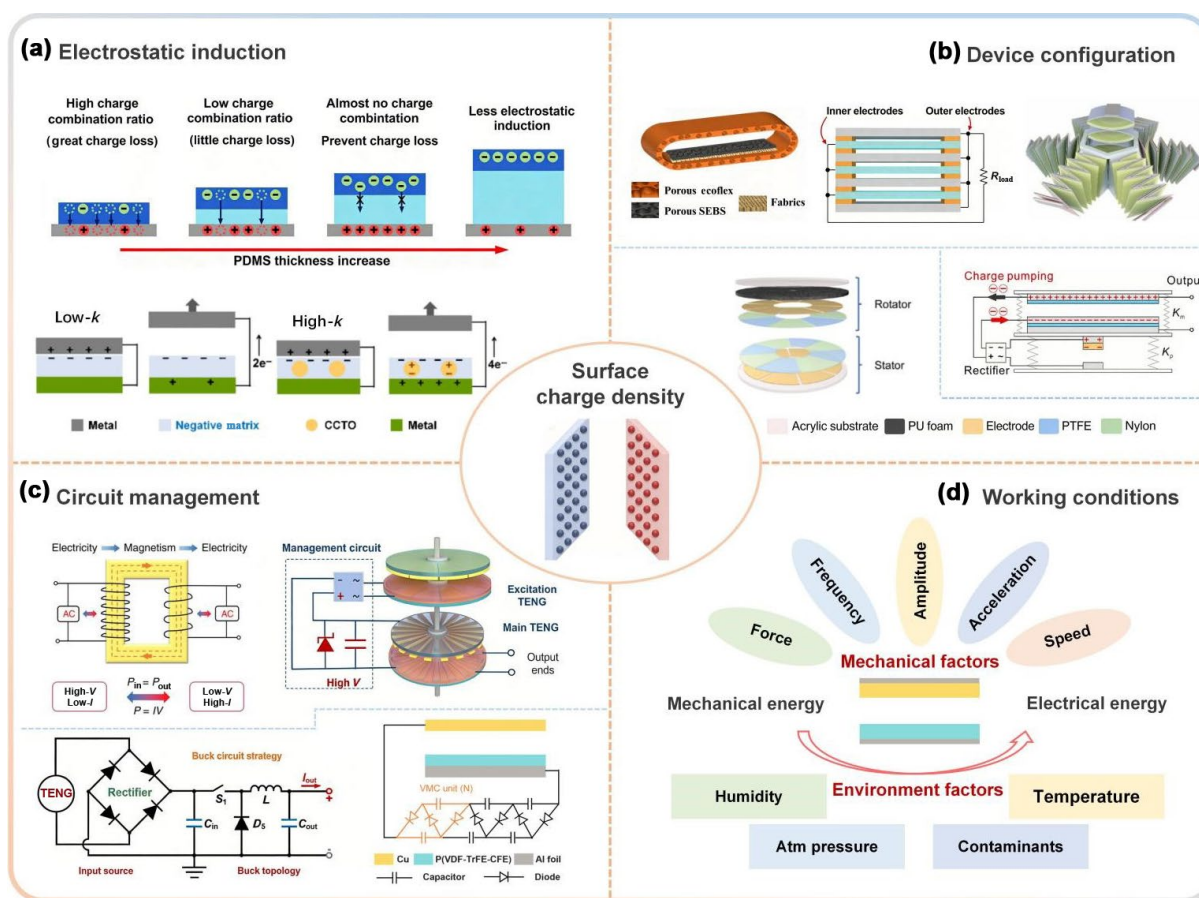


Figure 12 Strategies for enhancing TENG performance. (a) Schematic illustration of the electrostatic potential induction according to the thickness and dielectric constant of the triboelectric layer. Reproduced with permission from Ref. [129], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2020. Reproduced with permission from Ref. [153], © Elsevier Ltd. 2018. (b) Diverse structures of the TENG. Reproduced with permission from Ref. [98], © Elsevier Ltd. 2018. Reproduced with permission from Ref. [190], © Elsevier B.V. 2024. Reproduced with permission from Ref. [191], © Elsevier Ltd. 2014. Reproduced with permission from Ref. [192], © Elsevier Ltd. 2021. Reproduced with permission from Ref. [193], © Wiley-VCH GmbH 2025. (c) Different circuits adopted in TENGs. Reproduced with permission from Ref. [101], © The Royal Society of Chemistry 2024. Reproduced with permission from Ref. [181], © The Royal Society of Chemistry 2025. Reproduced with permission from Ref. [194], © Liu, W. L. et al. 2020. Reproduced with permission from Ref. [195], © The Royal Society of Chemistry 2025. (d) Working conditions, including mechanical and environmental factors, that influence TENG performance.

Moreover, as a power source, the high voltage and low current output of TENGs require appropriate conversion to match load requirements. Transformers can step down the rectified high voltage from TENGs to levels suitable for electronic devices (e.g., 3.3 or 5 V), significantly improving energy transfer efficiency [39]. According to the theory of maximum output power, output power is maximized when the internal resistance of the power source is equal to that of the load. Generally, TENGs exhibit high internal resistance (megohm level), whereas conventional electronic devices have low impedance (below kilohms). This leads to a severe impedance mismatch, and most of the power is consumed on the internal resistance [198]. To address this, an inductor combined with a high-speed switch can be incorporated into the circuit [101, 195, 199, 200]. The switch closes when the TENG displacement reaches its maximum (i.e., the maximum charge quantity), enabling instantaneous energy transfer from the TENG to the inductor. When the switch opens, the energy stored in the inductor is released to the load or a storage capacitor. Through this switching action, the circuit presents a virtual high impedance to the TENG, thereby achieving excellent impedance matching and increasing the output power by several or even tens of times. In addition, an adaptive switch can automatically control its on/off

states at the optimal moment by detecting the voltage or current signals of the TENG, allowing the TENG to adapt to different working frequencies and amplitudes [201]. Circuit management serves as an effective energy optimization strategy, capable of improving TENG output performance by one to two orders of magnitude and accelerating the practical application of TENGs in powering electronic devices.

Working conditions have a crucial and decisive impact on the output performance of TENGs, as shown in Fig. 12(d). As mechanical energy harvesters, the input mechanical excitation serves as the direct energy source and is a core factor influencing the electrical output. Generally, output current and instantaneous power are positively correlated with mechanical frequency [202]. Before the triboelectric pairs achieve full contact, charge generation and TENG output enhance with the increase of mechanical force or amplitude until saturation is reached. On the other hand, the contact speed and acceleration influence charge transfer and induction. High-speed contact-separation enables charge transfer and induction to be completed in an extremely short time; meanwhile, the dissipated charge could also be reduced, thus benefiting higher instantaneous current pulses [124]. Environmental factors, such as humidity and temperature, also

affect TENG performance. High humidity increases the charge dissipation rate, while elevated temperatures may cause material aging and electron thermal excitation [203–205]. Therefore, it is essential to first clarify the operating conditions of TENGs (e.g., frequency, amplitude, and humidity) and then design the materials, structure, circuits, and energy harvesting mode accordingly. Such an approach facilitates efficient mechanical energy utilization and optimized TENG output performance.

4 Applications

Due to their simple structure, scalable dimensions, and self-powered characteristics, TENGs can be applied in diverse scenarios where periodic mechanical energy exists, such as in wind, sound waves, ocean waves, mechanical vibration, and human movement [15, 206]. Up to now, research on TENGs' practical applications has progressed rapidly, and the TENGs have demonstrated their unique advantages in areas, including flexible wearable devices, biomedical systems, electrochemical setups, wireless sensing and monitoring networks, etc., which have been extensively summarized in earlier reviews [27–30]. Here, the TENG applications are briefly

introduced and classified into the following domains: power supply, self-powered sensors, high voltage sources, and blue energy (Fig. 13).

With the rapid advancement of nanotechnology and microelectronics, electronic devices have become increasingly compact, intelligent, and integrated. Conventional batteries, however, face challenges, such as large size, heavy weight, limited lifespan, high maintenance demands, and environmental concerns, making them less suitable for powering large numbers of small-scale, distributed, and mobile electronics [220, 221]. TENGs offer a promising alternative by enabling continuous and stable power generation without external sources, potentially overcoming limitations related to long-term energy supply and maintenance costs [222, 223]. Apart from driving intelligent electronics, the converted nano-micro energy can be efficiently utilized in powering biomedical or electrochemical systems [224–227], as depicted in Fig. 13(a).

Beyond energy harvesting, TENGs can function as self-powered sensors by translating input stimuli or interfacial changes into analyzable electrical signals. Their high sensitivity to external stimuli enables applications in active sensing of pressure, temperature,

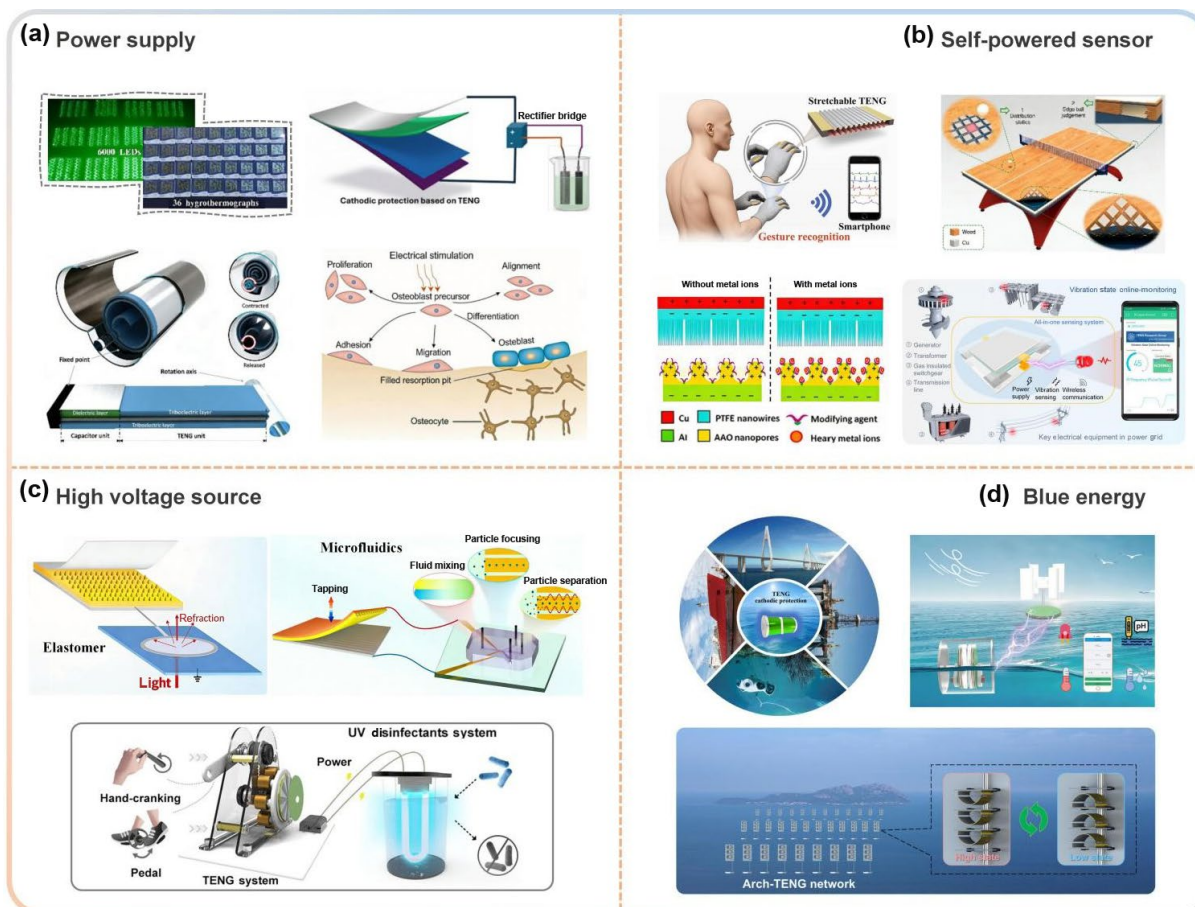


Figure 13 Diverse applications of TENGs. (a) TENGs acting as power supplies. Reproduced with permission from Ref. [90], © The Royal Society of Chemistry 2026. Reproduced with permission from Ref. [207], © Elsevier Ltd. 2021. Reproduced with permission from Ref. [208], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2018. Reproduced with permission from Ref. [209], © The Royal Society of Chemistry 2026. (b) TENGs acting as self-powered sensors. Reproduced with permission from Ref. [210], © Xu, Q. Q. et al. 2026. Reproduced with permission from Ref. [211], © Luo, J. J. et al. 2019. Reproduced with permission from Ref. [212], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2016. Reproduced with permission from Ref. [213], © Wiley-VCH GmbH 2023. (c) TENGs acting as high voltage sources. Reproduced with permission from Ref. [214], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2016. Reproduced with permission from Ref. [215], © Elsevier Ltd. 2021. Reproduced with permission from Ref. [216], © American Chemical Society 2026. (d) TENGs used in blue energy. Reproduced with permission from Ref. [217], © Wiley-VCH GmbH 2026. Reproduced with permission from Ref. [218], © Tsinghua University Press 2023. Reproduced with permission from Ref. [219], © Wiley-VCH GmbH 2026.

humidity, motion, acoustics, chemical signals, etc. [202, 212, 228–231], as shown in Fig. 13(b). This sensing technology originates from the output signals of TENG without external power source, exhibiting a unique advantage over traditional sensors. Self-powered sensing based on TENGs holds broad potential in environmental monitoring, sports science, healthcare, industrial manufacturing, and intelligent security systems [28, 232, 233], thereby promoting the rapid development of the Internet of Things, biomedicine, and artificial intelligence.

Unlike traditional generators that aim for high output current and power, the typical features of TENGs are high voltage, low current, and high impedance. These properties make them inherently suitable for applications requiring high voltage at ultralow power consumption. According to this point, researchers have made numerous efforts and successfully applied TENGs in areas, such as microfluidics, electrostatic spinning, ferroelectric poling, plasma excitation, air purification, and medical electrical stimulation (Fig. 13(c)), where high voltage sources are essential for driving or controlling electric fields [234, 235].

Ocean wave energy represents a vast and largely untapped resource, characterized by low frequency, high amplitude, and strong randomness. Traditional electromagnetic generators that are based on Faraday's law of electromagnetic induction typically operate efficiently under high-frequency and regular mechanical motion. TENGs provide a viable and efficient means of harvesting this "blue energy" from ocean waves, a concept first proposed by Wang [236, 237]. To date, TENGs-based blue energy harvesting has been widely explored and exhibits great potential in applications, such as powering marine buoys and sensors for monitoring water temperature/salinity/pH, providing cathodic protection to reduce corrosion in offshore structures, and supplying supplemental energy to coastal and island facilities (Fig. 13(d)) [238–241].

5 Conclusions

As an emerging technology for converting dispersed mechanical energy into electrical energy, TENGs based on contact electrification and electrostatic induction have demonstrated significant potential in nano/micro energy harvesting and self-powered sensing, owing to their broad range of material choices, simple structure, and high cost-effectiveness. The fundamental process of contact electrification involves interfacial charge transfer, primarily explained by electron transfer, ion transfer, and mass transfer mechanisms. These mechanisms are not mutually exclusive but rather operate synergistically, influenced by the physicochemical properties of the contacting materials and the operating environment. During contact electrification, the steady state of surface charges is determined by both charge generation and charge dissipation. The latter occurs through multiple pathways, including atmospheric ion neutralization, air/dielectric breakdown, charge diffusion, and field/thermionic emission, all of which can severely limit the surface charge density. An effective strategy to suppress charge dissipation is to enhance the charge storage capacity of triboelectric materials via dielectric modulation, the incorporation of functional interlayers, and the engineering of charge traps. Such charge engineering approaches contribute to achieving high surface charge density, a key parameter directly determining TENG output performance. Furthermore, through optimizing device architecture, implementing efficient circuit management, and tailoring operational conditions, the actual output power and energy utilization efficiency of TENGs can be

substantially improved. Building on these advances, TENGs have now expanded into a range of important applications, including power supplies, self-powered sensors, high-voltage sources, and blue energy, demonstrating their unique and promising role in the development of next-generation energy and sensing systems.

6 Perspectives

Triboelectric energy harvesting technology has been extensively studied and advanced, yet several challenges remain to be addressed for its further development. Future research on TENGs should focus specifically on the following aspects:

(1) Fundamental mechanisms

Research on fundamental mechanisms is essential for guiding the targeted design of new materials, device architectures, and applications of TENGs, which still requires in-depth investigation. As longstanding key scientific challenges in this field, mature microscale *in-situ* characterization techniques for interfacial charge transfer are absent, and the investigation of surface charge lacks quantitative evaluation criterion for electron/ion/mass transfer contribution. In the future, multi-field coupled *in-situ* detection platform combining KPFM, AFM and optical photoelectric testing, and quantitative thermionic emission experimental system to distinguish the respective contribution of electron/ion/mass transfer should be developed to obtain direct and conclusive evidence for a more comprehensive understanding of contact electrification.

(2) Advanced triboelectric materials

High surface charge density is required for high-performance triboelectric materials, in which charge generation and charge dissipation should be optimized, corporately. Additionally, material properties, such as durability, weather resistance, and mechanical robustness, must be considered to ensure long-term operational stability. To mitigate charge saturation in monopolar materials, both positive and negative triboelectric materials should be strategically optimized to maximize the output charge density in a triboelectric pair.

(3) TENG's design and manufacture

TENGs with diverse structures, dimensions, functions, and output power levels are required for different application scenarios. Enhancing TENGs' electro-mechanical conversion efficiency and their sensitivity to micro-environmental variation are key engineering issues that require further exploration. Meanwhile, their environmental adaptability and stability, especially in extreme environments, should be considered, as harsh environments can significantly degrade TENG performance. Besides, feasible, scalable, and economic manufacturing routes should be established to meet commercial demands and promote the rapid development of the electronics industry.

(4) Circuit management

High-performance TENG systems require synergistic progress in materials, devices, and circuits. Achieving the electric output on demand (within the maximum output limit) and maximizing the energy transfer efficiency via circuit management are crucial for the regulation and utilization of the converted electrical energy. Therefore, efficient circuit management is crucial for tailoring electrical output to specific requirements and maximizing energy transfer efficiency. Additionally, developing flexible, stretchable, and miniaturized circuit management systems is of great importance for seamless integration with TENGs in next-generation intelligent electronics.

(5) Commercial applications

Although TENGs have demonstrated considerable potential across various fields, their large-scale engineering implementation and integration within multi-energy systems remain to be fully validated. Future efforts should emphasize the competitive advantages of TENGs over existing technologies to achieve differentiated competition in diverse application scenarios. In addition, more efforts should be concentrated on industrial transformation and commercialization of TENGs, thereby promoting their rapid development in the sustainable energy era.

Data availability

Not applicable.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

K. M. S.: Conceptualization, investigation, data curation, visualization, funding acquisition, writing manuscript. B. C.: Investigation. P. K. J.: Supervision. X. Y. H.: Formal analysis, funding acquisition, project administration, supervision. All the authors have approved the final manuscript.

Use of AI statement

None.

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