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Review

Flexible self-powered electronics: Materials design, structure engineering, and multifunctional integration

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PROGRESS AND POTENTIAL Flexible self-powered electronics have demonstrated significant academic and practical value in a wide range of applications, including wearable electronics, personalized healthcare, environmental monitoring, human-machine interaction, and the Internet of Things. Implemented in energy-harvesting devices such as solar cells, triboelectric nanogenerators (TENGs), piezoelectric nanogenerators (PENGs), thermoelectric generators (TEGs), biofuel cells (BFCs), moisture-induced electric generators (MIEGs), and magnetoelastic generators (MEGs), these systems have attracted considerable attention due to their unique capability to harvest ambient and biomechanical energy, eliminate rigid battery dependence, enable energy autonomy, and adapt to soft, deformable, and skin-conformable surfaces, making them ideal candidates for next-generation applications in smart textiles, implantable medical devices, extreme environment exploration, intelligent transportation, and distributed sensing networks. Despite the notable progress in intrinsic flexible materials design for conductors, semiconductors, and dielectrics, bionic and artificial structural engineering, and multifunctional system integration, further research is needed for elucidating the synergistic mechanisms of conductor-semiconductor-dielectric multi-material systems, resolving the inherent trade-off between mechanical flexibility and energy output, developing scalable and low-cost manufacturing processes, enhancing long-term operational stability in complex and extreme environments, and optimizing the compatibility of multi-module integrated systems. In the longer term, the convergence of multifunctionality, miniaturization, biocompatibility, and sustainability in flexible self-powered electronics is poised to reshape industries ranging from personalized healthcare and wearable technology to smart cities, aerospace engineering, and marine exploration. Their ability to seamlessly merge ambient energy harvesting, multimodal sensing, signal processing, data transmission, and actuation in a single platform not only holds promise for immediate impact in battery-free wearable systems but also lays the foundation for adaptive, energy-autonomous, and environmentally responsive intelligent electronic systems. As research continues to evolve, this field is expected to contribute meaningfully to the creation of sustainable and intelligent societies through interdisciplinary innovation in materials chemistry, structural mechanics, device physics, and artificial intelligence-empowered systems engineering.

SUMMARY

The rapid expansion of the Internet of Things (IoT) has driven explosive growth in the global wearable electronics market, which was valued at ~ $70–$80 billion in 2023 and is projected to reach $138.5 billion by 2029. Wearable electronics integrate intelligent components into textiles or onto the human body, enabling seamless human-digital interactions. Nevertheless, their reliance on rigid, short-lifespan batteries severely restricts adaptability and sustainability. Self-powered technologies, which have emerged as a pivotal solution, are capable of converting ambient energy and human biomechanical energy into electricity, reducing battery dependence while facilitating device miniaturization and integration. Despite these advances, two critical challenges hinder the practical application of self-powered wearables: the inherent trade-off between device

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mechanical flexibility and self-powered generator energy output and insufficient stability in complex usage environments. This review focuses on the development of flexible manufacturing (inherent flexibility of materials, structural optimization), multifunctionalization, and integration, systematically summarizing design solutions to address the aforementioned bottlenecks: (1) intrinsic flexible materials design (for conductors, semiconductors, dielectrics) and structural engineering (bionic structures and artificial structures) for reconciling flexibility and performance and (2) multifunctionalization and integration for addressing the challenges of real-world complex applications. Finally, a forward-looking perspective on future development directions is provided, aligning with the goal of advancing energy-autonomous wearables for personalized healthcare, environmental monitoring, and human-computer interaction.

INTRODUCTION

The rapid convergence of artificial intelligence (AI), the Internet of Things (IoT), and personalized applications has propelled wearable electronics into a cornerstone of next-generation smart technologies.[1,2] Wearables achieve seamless human digital interaction by integrating intelligent components into various wearable fabrics, wristbands, and even skin patches, greatly promoting personalized applications, such as human-computer interaction, human applications, environmental monitoring, etc.[3] The global wearable electronics market was valued at ~$70–$80 billion in 2023 and is projected to reach $138.5 billion by 2029, and this explosive growth highlights the urgent need for sustainable power supply solutions in the field.[4] Traditional wearable devices primarily rely on rigid batteries for power,[5,6] which not only increases the weight and size of the device but also compromises the flexibility of the wearable electronics.[7,8]

To address this limitation, self-powered technologies have emerged as a transformative solution, leveraging ambient energy (solar energy and humidity gradients) and human biomechanical energy (body heat, joint motion, and biomass) to eliminate battery dependence.[9,10] These systems encompass solar cells, moisture-induced electric generators (MIEGs), thermoelectric generators (TEGs), triboelectric nanogenerators (TENGs), piezoelectric nanogenerators (PENGs), biofuel cells (BFCs), and magnetoelastic generators (MEGs). Collectively, these technologies not only can reduce the size of the equipment but also ensure long-term stability.[11–16]

Conductor materials, semiconductor materials, and dielectric materials are important components of self-powered wearables, exhibiting unique advantages in improving energy conversion efficiency and enhancing mechanical flexibility and adaptability to complex environments.[17,18] Nevertheless, current research mostly focuses on single materials or single functions (e.g., only achieving self-healing), lacking the collaborative design of "conductor-semiconductor-dielectric" multi-materials to simultaneously improve flexibility and energy density. Moreover, the compatibility after function integration (such as the collaborative regulation of self-healing and high-temperature resistance) has not yet formed a systematic solution, which becomes a core bottleneck restricting the marketization of self-powered wearable devices.

The rapid advancements in flexible materials have enabled significant improvements in the stretchability, durability, etc., of self-powered wearables while balancing their output performance.[19] There are two principal strategies for enhancing flexibility: one approach involves directly synthesizing intrinsic flexible materials (e.g., gel materials and polymers) or preparing composite materials on flexible substrates.[20] Another strategy is the structural design of materials, which allows previously inflexible materials to absorb external stress and strain through structural optimization (bionic and artificial structures), thereby preventing material failure and improving durability.[21] Additionally, self-powered wearable devices with single functionalities are no longer sufficient to meet the diverse needs across different environments. The development of multifunctional components through rational functional design and their integration into one unified system has emerged as a key research focus. For instance, the frequent triboelectric power generation of TENGs leads to material wear. Incorporating self-healing capabilities can enhance their mechanical strength and prolong their service life.[22] Electronics with functional designs such as self-cleaning, high-temperature resistance, and ice resistance can maintain stable performance in harsh environments.[23,24] These features make them highly promising for applications in outdoor exploration, aerospace, deep-sea exploration, and polar scientific research.[25]

In this review, we summarize the optimization strategies for self-powered wearable electronics. Improving device flexibility encompasses two primary approaches: intrinsic material design and architectural reconfiguration. The development of inherently flexible materials, such as conductor, semi-conductor, and dielectric materials, significantly enhances the mechanical compliance of self-powered devices, thereby improving comfort and long-term durability. Structural design, such as bionic and artificial structures, enables exceptional elasticity and stretchability in otherwise inflexible materials. These structures simultaneously optimize both mechanical properties and functional performance in wearable systems. Additionally, we summarize the innovative cases of multifunctionalization and integration, which meet the specific demands of complex application scenarios, to help readers capture the design principles and evolution trends in this field.

Ultimately, this review aims to provide novel insights and theoretical guidance for the design of multifunctional wearable devices based on self-powered technologies, fostering further development and application in the flexible, multifunctional and integrated design of self-powered wearable devices.

MECHANISMS AND FLEXIBLE STRATEGY FOR SELF-POWERED WEARABLES

The principles of self-powered technologies are closely related to their application scenarios. Figure 1 illustrates the

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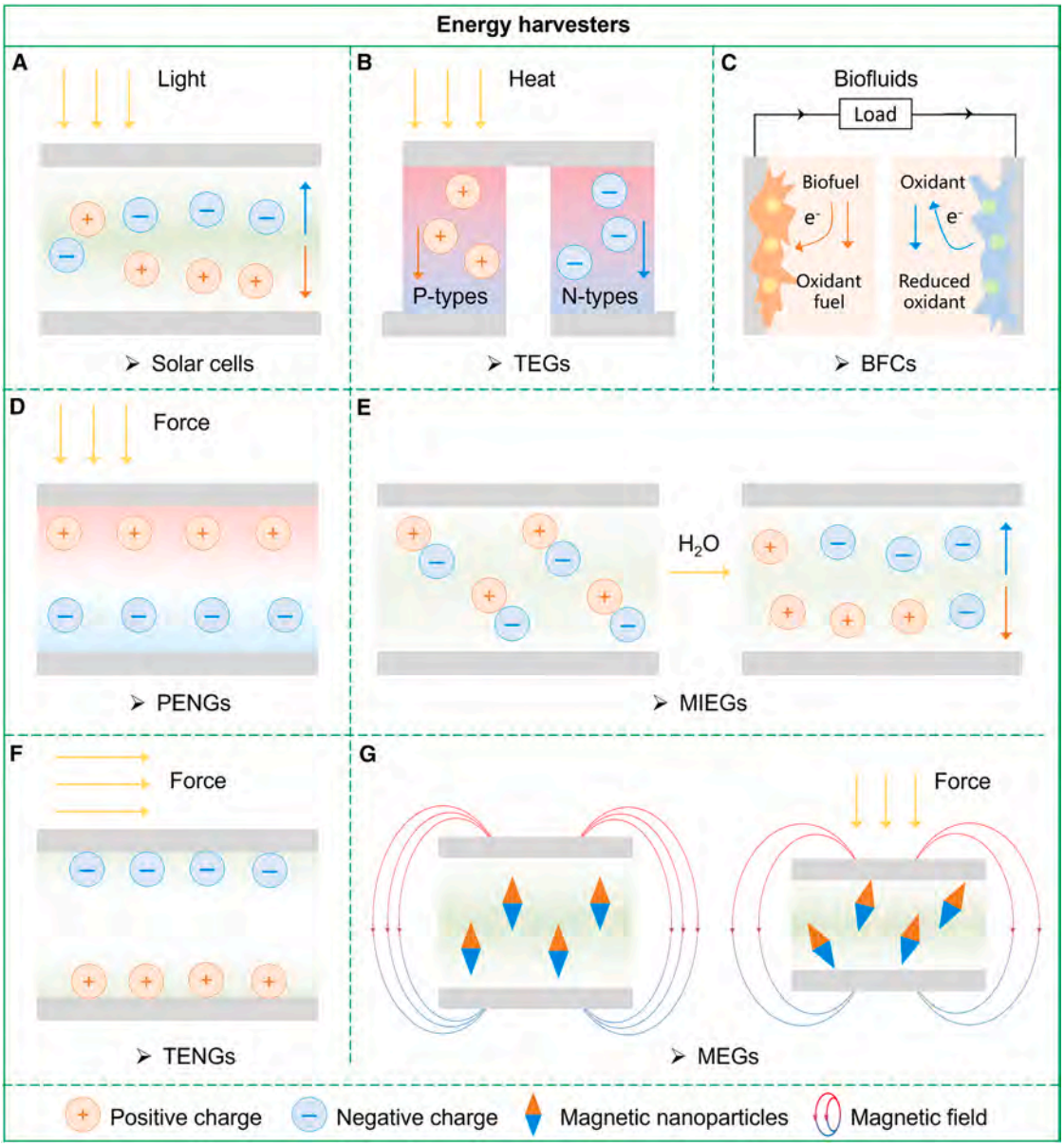

Figure 1. Different types of energy harvesters

(A) Solar cell.
(B) Thermoelectric generators (TEGs).
(C) Biofuel cells (BFCs).
(D) Piezoelectric generators (PENGs).
(E) Moisture-induced electric generators (MIEGs).
(F) Triboelectric nanogenerators (TENGs).
(G) Magnetoelastic generators (MEGs).

mechanisms of different self-powered technologies: (1) Collecting energy from the environment: solar cells, converting photon energy into electricity via the photovoltaic effect, which is currently one of the most mature technologies in the market; thermoelectric generators (TEGs), utilizing temperature difference to drive the directional movement of charge carriers via Seebeck effect to capture human and environmental temperatures for power generation, which has a unique advantage in the field of low-quality thermal power generation; MIEGs, harvesting electricity via the charge separation and ion migration effect driven by humidity gradients or moisture adsorption-desorption processes, which exhibits outstanding potential for energy harvesting in humid ambient environments and low-power microdevice power supply. (2) Collecting energy from the

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human body: PENGs, generating electricity via the piezoelectric polarization effect induced by mechanical pressure during human activities, which is widely applicable to wearable and implantable electronics; TENGs, generating electricity via the contact electrification (triboelectrification) effect produced by frictional contact-separation during human motions, which features high output voltage and simple structural design; BFCs, converting biochemical energy into electricity through enzymatic or microbial redox reactions, which achieves *in situ* energy harvesting by utilizing endogenous substances in the human body; MEGs, transforming mechanical deformation into magnetic field variation via the magnetoelastic coupling effect and realizing the conversion of mechanical energy to electrical energy through electromagnetic induction, which has excellent compatibility with human body mechanical movement characteristics.

The key breakthrough of self-powered wearable electronics lies in the balance between flexibility and output, as well as the multifunctionality and integration of devices, which are the necessary paths for self-powered wearable devices to move toward commercialization.[4] In the following text, we discuss material design strategies for self-powered wearables, including flexible design for different materials (conductors, semiconductors, and dielectrics), structural design (e.g., artificial structures and biomimetic structures), and multifunctional (self-healing, self-cleaning, heatproof, etc.) and integrated design (e.g., intelligent perception and output management, information collection and data transmission, human-computer interaction system, and therapy and monitoring).

FLEXIBLE MATERIALS DESIGN

For self-powered wearables, the conductive, semiconductive, and dielectric materials play complementary roles that collectively determine device performance. Table 1 summarizes the roles of conductors, semiconductors, and dielectrics in different energy harvesters. The conductive layer provides efficient charge collection and transport, the semiconductor layer governs charge generation and carrier modulation, and the dielectric layer controls electric field distribution and charge storage. These functions are strongly coupled through interfacial energy alignment, electrostatic interactions, and mechanical compatibility. In addition, self-powered wearables may face performance degradation due to strain during long-term use. Consequently, it is necessary to consider collaborative design from all layers to optimize device efficiency and long-term stability, which highlights the crucial importance of coordinating materials and interface engineering.

Conductors

Flexible conductors serve as foundational components in self-powered electronic devices, primarily for fabricating flexible electrodes, flexible substrates, and flexible sensors—key building blocks that determine device conformability and operational reliability. These materials can be categorized into three major classes, each with distinct physicochemical properties tailored to specific wearable scenarios: (1) metal-based conductors (e.g., metal nanoparticles, metal nanowires, ultrathin metal films, and liquid metals [LMs]),[26,27] which offer ultrahigh electrical conductivity and good thermal stability; (2) carbon-based materials (e.g., graphene, carbon nanotubes [CNTs], and carbon cloth [CC]),[28,29] characterized by light weight, excellent mechanical flexibility, and tunable electronic properties; and (3) conducting polymer materials (e.g., conductive polymer films and ion-conductive hydrogels),[30,31] notable for their intrinsic flexibility and biocompatibility. For conductor materials, frequent deformation during practical use can damage the material structure, severely affecting the service life of the entire integrated system. Self-healing structures with high dynamic stability can be designed to effectively restore mechanical and electrical properties. Sun et al. constructed a self-healing conductor with high dynamic stability based on electromechanical coupling effects, where the force-electric coupling arising from hydrogen bonds and coordination bonds between the structure and conductive components significantly enhances electrical stability under dynamic conditions. This enables resistance changes below 0.7 ohms at 500% strain and allows stable, precise monitoring of human health status even under simulated hand tremors caused by Parkinson's disease.[32] Wang et al. employed spin-coating technology combined with metal stencils to deposit LM onto elastic microfiber fabrics, forming high-resolution conductive patterns. During initial stretching, the natural oxide layer on the LM micromesh surface grows, preventing full rebound and transforming the smooth surface into a wrinkled structure. This microstructural change shifts the deformation mechanism of the LM coating from stretching-relaxation to folding-unfolding, significantly suppressing resistance variation. During stretching to an extreme strain of 300%, the resistance change rate of the LM micromesh remained only 11%.[33] Collectively, these flexible conductors exhibit high electrical conductivity, robust stretchability, and superior bendability—coupled with facile processability via techniques like electrospinning or screen printing. These attributes not only enable the optimization of energy collection efficiency and signal transmission stability in wearable self-powered devices but also facilitate large-scale commercial fabrication.

Nanoparticles have advantages in specific surface area, excellent biocompatibility, and high chemical reactivity, and in flexible manufacturing, they can be easily combined with flexible substrates. For instance, gold nanoparticles can enhance the biocompatibility and conductivity of electrodes and provide abundant active sites to promote electrochemical reactions in myoglobin detection (Figure 2A), thereby significantly optimizing the detection sensitivity and signal stability of sensors.[34] Highly conductive host electrodes can be fabricated via a small-molecule-linker-bridged Au nanoparticle-multiwalled CNT nanocomposite assembly, which effectively enhances electron transfer between the host electrode and the oxidase layer in BFCs.[46] This multi-ply fiber electrode system exhibits unprecedented high-power output (about 10.4 mW cm^{-2}) and excellent operational stability. Quasi-one-dimensional nanowires exhibit excellent electrical conductivity and can readily assemble into unique percolated networks enabling the formation of continuous long-range conductive pathways, which endows them with remarkable advantages in efficient electron transport—an essential property for optimizing energy conversion and signal transmission in self-powered wearable systems. Besides, their

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Table 1. Different energy harvesters and the roles of dielectrics, semiconductors, and conductors

Device Type	Mechanism	Dielectrics	Semiconductors	Conductors
Solar cells	photovoltaic effect	role: anti-reflection coatings, passivation, encapsulation advantages: high refractive index tuning, low surface recombination, mechanical/chemical stability	role: light absorption, photogeneration, charge separation (p-n junction) advantages: tunable band gap, high absorption coefficient, high carrier mobility/lifetime for efficient exciton dissociation	role: current collection and transport (electrodes, busbars, back contacts) advantages: low resistivity, high conductivity reduces series resistance, transparent conductors enable light transmission
TEGs	Seebeck effect	role: thermal/electrical insulation between legs advantages: low-κ ceramics, high-temperature stability, prevents electrical shunting	role: p-type and n-type legs for Seebeck effect advantages: high Seebeck coefficient, low thermal conductivity via phonon scattering	role: interconnects, electrodes for hot/cold side advantages: high electrical conductivity, minimizes contact resistance
BFCs	bioelectrocatalytic effect	role: proton exchange membrane, encapsulation advantages: high ionic conductivity, selective permeability, prevents shortcut currents, mechanical robustness	role: redox mediation, enzyme immobilization advantages: tunable Fermi level, high catalytic activity, stability in biofluids	role: current collectors, biocatalyst supports. advantages: high surface area, excellent conductivity, biocompatibility
PENGs	piezoelectric effect	role: piezoelectric matrix (often overlaps with semiconductors) advantages: high electromechanical coupling, flexibility in polymers (PVDF), dipole alignment for electromechanical coupling enhancement	role: piezoelectric active layer advantages: high piezoelectric coefficient, wide band gap for insulation, nanostructuring enhances sensitivity	role: electrodes for charge collection advantages: high conductivity, flexible conductors for wearable devices, low contact resistance
MIEGs	hydroelectric effect	role: hydrophilic matrix for moisture gradient, ion-selective layers advantages: high water uptake, nanoporous structure sustains ion flow, mechanical flexibility	role: hygroscopic sites for water gradient, limited direct role advantages: functionalized semiconductors create ion channels, gradient doping drives streaming potential	role: ion/electron transport pathways, asymmetric electrodes advantages: high ionic conductivity, chemical stability in humid environment, large surface area for ion adsorption
TENGs	triboelectric effect	role: triboelectric layers for charge generation/separation. advantages: extreme electron affinity difference, high surface charge density, micro/nanostructuring boosts contact area, flexibility and durability	role: limited, occasionally doped layers for charge trapping advantages: semiconducting polymers enhance surface charge density, interface states improve output	role: triboelectric electrodes and back contacts advantages: high conductivity. induces electrostatic charges, conductive fabrics for wearables
MEGs	magnetostrictive effect	role: the matrix for accommodating micromagnets advantages: high flexibility, porosity, low mechanical hysteresis, low Young's modulus	role: magnetostrictive material[a] advantages: conversion of mechanical strain into magnetic energy variation	role: magnetic source in magnetomechanical coupling layer, conductive wire in magnetic induction layer advantages: high deformability, excellent conductivity, biocompatibility

[a]Semiconductors are not a necessary component of MEGs. Magnetostrictive materials are the core power-generating component of MEGs.

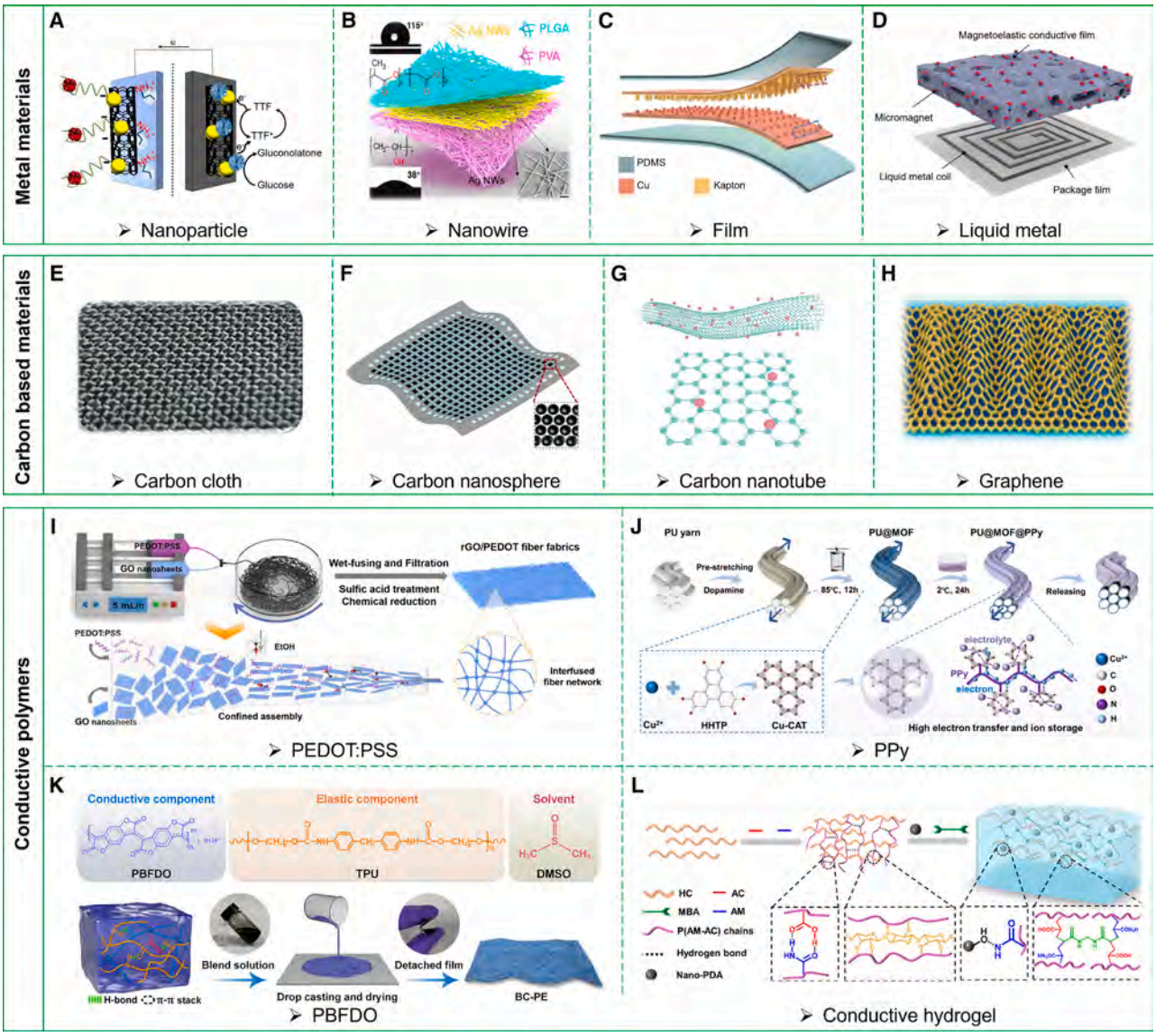

Figure 2. Flexible conductor material for self-powered wearable applications

(A) Schematic illustration of the self-powered sensor device consists of a biocathode with gold nanoparticle and carbon nanotubes for detecting myoglobin.[34]

(B) Schematic illustration of the Ag nanowire sandwich structure of the all-nanofiber TENG-based e-skin.[35]

(C) Schematic diagram of TENGs with Kapton thin film and nanostructured Cu thin film for cardiovascular disease diagnosis.[36]

(D) Structure of the proposed bimodal self-powered flexible sensor consists of a magnetoelastic conductive film and a liquid metal coil with package film.[37]

(E) Carbon cloth used as substrate for flexible wearable supercapacitors.[38]

(F) Sensing film featuring ordered spiky carbon nanospheres embedded in polydimethylsiloxane (PDMS) matrix.[39]

(G) Schematic diagram of oxidase immobilization on multiwalled carbon nanotube (MWCNT).[40]

(H) Wrinkled graphene film directly patterned on PDMS for TENGs.[41]

(I) Schematic illustrations of phase inversion-based microfluidic-fiber-spinning assembly of graphene oxide (rGO)/polythiophene: polystyrene sulfonate (PEDOT) fiber fabrics.[42]

(J) Illustration of the process of fabricating polyurethane (PU)@metal-organic frameworks (MOF)@polypyrrole (PPy) yarn electrodes.[43]

(K) Schematic demonstration of the fabrication of the bicontinuous polymer electrode, along with the photographs of the thermoplastic polyurethane (TPU)/poly(benzodifurandione) (PBFDO) blend solution and the detached blend film.[44]

(L) A nanoporous-polydopamine-reinforced hemicellulose-based hydrogel applied for human motion monitoring.[45]

outstanding mechanical flexibility (capable of withstanding repeated bending and stretching), moderate Young's modulus, and high transparence make them particularly suitable for wearable applications that simultaneously demand structural compliance, mechanical robustness, and optical transparency. For instance, in an electronic skin based on TENGs, Ag nanowires

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are introduced as conductive layer between top polylactic-co-glycolic acid and bottom polyvinyl alcohol to construct a three-dimensional micro-nano porous layered structure that provides a large specific surface area for efficient contact electrification (the maximum peak power density achieving 130 mW m^{-2}) and sensitive pressure response (the voltage response pressure sensitivity achieving 0.011 kPa^{-1}) and helps maintain the thermal and moisture balance of the skin's surface microenvironment, ensuring long-term wearing comfort (Figure 2B).[35] Metal thin films are also widely used in self-powered devices, which have excellent conductivity and can effectively transmit electrical energy and signals while minimizing energy loss. They also exhibit extraordinary flexibility and stretchability, capable of long-term stable operation under mechanical deformation. For instance, thanks to the flexible nanostructured film increasing the actual contact area of the friction layer, the tip discharge effect of the nanoelectrode promotes charge transfer and the resulting TENGs for cardiovascular disease diagnosis exhibits excellent performance (Figure 2C).[36]

LMs have represented their attractive potential in self-powered wearable electronics due to their superior deformability, electrical and thermal conductivity, and biocompatibility. The liquid nature of LMs endows them with strain insensitivity, allowing stable component connections even under severe deformation, and makes them suitable for various fabrication methods.[30,31] A stretchable LM core-shell fiber with high conductivity for self-powered sensing can be stretched up to 1,170%, with an extremely high conductivity of 4.35×10^4 S m^{-1} and a resistance change as low as 4% under 200% strain.[47] By combining different packaging materials, LMs can also perceive various environmental information (such as pressure and bending) to enhance the information perception and the ability to perform meticulous tasks of flexible devices (Figure 2D).[37] When integrated with polymers via physical or chemical interactions, the resulting composites can be endowed with various functionalities. For example, LM electrodes with extremely high adhesion strength (8.9 MPa) can be prepared by introducing adhesive polymers based on uracil ketone,[48] which can be connected to normal or injured skin to monitor health status and accelerate wound healing. The enhanced adhesion is attributed to the "pinning" effect of LMs on hydrogen bonds formed between the substrate and the polymer composites, which strengthens the interface. Besides, LMs are often used in the magnetic induction layer of MEGs. Based on coils patterned by LMs, Xu et al. developed a programmable magnetoelastic sensor array with an optimal signal-to-noise ratio of 34 dB and a rapid response time of 0.2 s, which enables real-time wireless control of a household lamp and a Bluetooth music speaker, even under high-humidity conditions such as heavy perspiration.[49]

Carbon-based materials (CC, carbon nanosphere, CNT, and graphene) are regarded as promising materials for flexible self-powered wearable devices due to their lightweight, good structural flexibility, excellent conductivity and electrochemical stability, and significant specific surface area.[50] Depending on the specific application, they can serve as both a conductive substrate and an active component.[51] CC has extremely high flexibility and bendability, which can maintain stable electrical properties under various complex deformations. Besides, CC can be integrated with other flexible materials (such as polymer films and metal foils) to construct flexible layers with more complex functions, which can further improve the performance and reliability of the device (Figure 2E).[38] Carbon nanospheres offer uniform morphology, tunable surface chemistry, and mechanical robustness, with the additional advantage of excellent dispersibility. It is worth mentioning that Wu et al.[39] prepared a monodisperse carbon nanosphere array on polydimethylsiloxane (PDMS), forming a flexible carbon-based material similar to CC (Figure 2F). The strain sensor based on this achieves a sensitivity of up to 70,000, providing a new approach for drawing strain fields in applications such as flexible electronics, soft robotics, and biomechanics.

CNTs feature a very high specific surface area, providing abundant active sites for reactions and enhancing interactions with electrolytes or other materials. Additionally, they possess excellent mechanical properties, including extremely high strength and elasticity.[52] These characteristics enable CNTs to more effectively collect, store, or convert energy in self-powered wearable devices.[53] For example, CNTs can form a 3D hierarchical porous membrane, which promotes rapid mass transfer, efficient electron conduction, and stable enzyme loading.[54] The resulting BFCs can be further encapsulated by a hydrogel layer to maintain the integrity and activity of enzymes and thus exhibited high flexibility, excellent performance, and long-term stability in self-powered wearable devices (Figure 2G).[40] In MEGs, the effective manipulation of voltage output by encapsulating multi-walled CNTs and LM together using PDMS in magnetic induction layer has been demonstrated.[55] With a power density of 0.23 mV cm^{-2}, these optimized MEGs can charge a commercial capacitor at a rate of 0.63 mV s^{-1}. Other carbon-based materials, such as graphene, have the characteristics of flexibility, high energy density, biocompatibility, and stability, providing strong support for the development of self-powered wearable devices.[56] By combining with flexible substrates, graphene can also achieve flexible patterning (Figure 2H),[41] which can be stretched to 100% strain without significantly reducing the power output of the device.

Conductive polymer materials have good conductivity and flexibility and are more cost-effective compared with noble metals and nanocarbon materials. Common conductive polymers include polyaniline, polypyrrole, and polythiophene:polystyrene sulfonate (PEDOT: PSS).[57] Besides, recently, a highly conductive n-type polymer, poly(benzodifurandione)was successfully synthesized by Tang et al.[58] The application of this novel flexible conductive polymer has been explored and has yielded encouraging outcomes in enhancing flexibility, electrical stability, and overall device efficiency.[44,59] Figures 2I–2K illustrates various ways in which conductive polymers are utilized in the fabrication of flexible devices, such as spinning, coating, and blending.[42–44] In particular, spinning conductive polymers into fibers or blending them with elastomers can effectively enhance the mechanical properties of the resulting materials. For instance, a highly stretchable composite film was obtained by blending PEDOT:PSS with natural rubber latex, showing the enhanced power factor compared with neat PEDOT:PSS (from 13.7 to 20 $\mu W \cdot cm^{-1} \cdot K^{-2}$).[31] Hydrogel is another ideal matrix for

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conductive polymers due to its excellent mechanical properties, biocompatibility, and multifunctional potential. For example, through synergistic dual-crosslinking, Lan et al.[60] prepared polyacrylamide integrated with PEDOT interpenetrating network-based hydrogel electrode and presented an innovative molecular bridging method using PEDOT to establish a highly effective connection between hydrogel electrode and adjacent frictional piezoresistive sensing layer. The resulting piezoresistive sensor and TENG exhibited an enhanced sensitivity of 27.8 kPa^{-1} and an output power density of 3.1 mW m^{-2}. In addition to cross-linking with the hydrogel network, some conductive particles or fibers can also be directly added to the hydrogel to improve the conductivity of the hydrogel. For instance, nano-polydopamine-reinforced hemicellulose-based hydrogels with typical multistage pore structures were prepared, showing potential as drug patches capable of facilitating transdermal introduction of electrically stimulated drug ions (Figure 2L).[45] The aforementioned hydrogels rely mainly on electronic conduction pathways; hydrogel polymer electrolytes (HPEs) can provide good ionic conduction, and by modifying HPEs differently, specific materials that meet the needs of self-powered wearable devices can be obtained.[50–52]

The application of flexible conductor materials in wearable self-powered devices still faces some challenges, mainly including energy supply and conversion efficiency, mechanical stability, integration difficulty, and manufacturing cost. For instance, metals may have stability problems during long-term use, such as the oxidation or chemical reaction with surrounding materials, which may affect their electrical conductivity. LM needs to be encapsulated in flexible substrates, posing a challenge to packaging technology. The intrinsic chemical inertness of carbon materials has long hindered the formation of stable and commercial interfacial connections. Conductive polymers also face issues such as limited conductivity and environmental instability. When designing new conductor materials, it is also important to consider the biocompatibility, implantability, wet adhesion, ductility, and flexibility of the materials. Blindly pursuing the superposition of energy conversion effects will increase the number of materials used and the complexity of the structure, which is not beneficial for the miniaturization of devices.

Table 2 summarizes the characteristics, processing methods, roles, performance, and flexibility of conductor material types for self-powered wearables.

Semiconductors

Semiconductor materials have significant advantages in self-powered devices due to their tunable band gaps, high efficiency in energy conversion, and low electrical losses.[67] Typical semiconductor materials include inorganic semiconductors (elemental semiconductors, oxide semiconductors, chalcogenides semiconductors, etc.), organic semiconductors (small molecules and polymers), and organic-inorganic hybrid semiconductors (hybrid perovskites, metal-organic frameworks [MOFs], etc.).[68,69] Choosing the appropriate semiconductor material based on specific application requirements, such as high thermal conductivity, high optical transparency, and environmental resistance, is crucial for ensuring optimal device performance and reliability.[70] In addition, emerging two-dimensional (2D) semiconductor materials (transition metal chalcogenides, black phosphorus [BP], etc.) present substantial advantages due to their high specific surface area, superior electron mobility, tunable electronic properties, and robust stability.[71,72] These characteristics render them promising for the development of low-power and long-lifetime self-powered wearable devices.

Inorganic semiconductors are commonly believed to possess high performance but to be brittle at room temperature. Size-induced flexibility can be achieved when they are fabricated into micro-nanostructures. By combining micro-nanostructured inorganic semiconductors with flexible substrates or directly preparing flexible films, it is possible to reconcile the performance and flexibility of self-powered wearable electronic products. For instance, Te nanowire fillers can effectively enhance the Seebeck coefficient of PEDOT:PSS. The resulting composite fibers exhibited both high power factors and good flexibility, showing potential for flexible thermoelectric-based power generation (Figure 3A).[73] Growing ZnO nanowire arrays on GaN films gave rise to flexible semiconductor heterojunctions (Figure 3B).[74] The self-powered photodetectors based on them showed excellent photodetection performance without obvious decrease after thousands of bending cycles. Besides, some inorganic semiconductors can exhibit outstanding properties through the introduction of dopant-induced energy levels. Notably, several self-powered sensors integrating ZnS:Cu with flexible matrix (PDMS) have been reported (Figure 3C),[75] which realized a dual-mode sensing. Furthermore, it is necessary to consider the stress tolerance and durability of semiconductor materials in practical use, the molecular/crystalline structure of semiconductors determines their conformational adaptability and carrier transport stability under strain. This necessitates balancing the relationship between conjugated rigidity and flexibility while suppressing band structure distortion. Kang et al. achieved high-density integration on large-area molecularly tailored elastic substrates using LM interconnects and dual-island metal oxide transistors. This significantly enhanced the strain resilience and electrical performance of devices, demonstrating exceptional mechanical stability with less than 20% performance degradation under 50% strain and multiple stretching cycles.[84] Lu et al. proposed a unique interleaved layer structure arising from Te and Bi/Sb atomic exchange near the van der Waals gap. After over 1,000 repeated bends at a 4 mm bending radius, the film conductivity decreased by only 9%.[85]

Organic semiconductors constitute a large family that can generally be classified into organic small-molecule semiconductors and organic polymer semiconductors.[86] Traditionally, the performance of small-molecule semiconductors depends heavily on crystallinity and ordering, which, while conferring high charge-carrier mobility, also limits their intrinsic mechanical flexibility. Therefore, they are often incorporated as fillers or films.[87,88] Figure 3D shows a new small-molecule acceptor, which can be evenly dispersed in the polymer. This short-range order ensured high electron mobility and excellent flexibility.[76] Organic polymer semiconductors, on the contrary, owing to their inherent flexibility, tunable electrical properties, and good biocompatibility, are assuming an increasingly important role in wearable devices. Their main applications are organic light-emitting diodes (OLEDs), organic TEGs, organic electrochemical

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Table 2. Comparison of various parameters of conductor material types and corresponding examples

Material type	Representative material	Characteristics	Processing methods	Roles	Performance	Flexibility	Reference
Metal-based	Au NPs	high specific surface area chemical stability biocompatibility	chemical reduction method solvent dispersion	forming heterojunction with Te in flexible TEGs	power factor 74.7 $\mu Wm^{-1} K^{-2}$	>150 bending cycles	Chen et al.[61]
	Ag NWs	mechanical flexibility optical transparency solution processable	spin coating embedded in matrix dip coating	functional sensing layer in hybrid generators for smart sensing	V_{OC} = 22.4 V I_{SC} = 7.04 μA	>2,000 bending cycles	Wen et al.[62]
	Ag film	high electrical conductivity precise thickness tunability	physical vapor deposition chemical vapor deposition	working electrode in self-powered medical masks	V_{OC} = 1.0 V	>1,500 bending cycles	Liu et al.[63]
	liquid metals	conformability fluidity felf-healing	inkjet printing microchannel injection digital embroidery	magnetic induction layer in MEGs	V_{OC} = 5 V I_{SC} = 0.7 μA power density 0.23 mV cm^{-2}	competent for various bending deformations	Ock et al.[55]
Carbon-based	carbon cloth	mechanical flexibility porosity and lightweight processability	surface modification laser patterning	tribo-charge reservoirs and stretchable conductors in TENGs	V_{OC} = 288 V I_{SC} = 1.23 μA	competent for various bending deformations	Peng et al.[64]
	CNTs	high strength and toughness easy surficial functionalization	screen printing vacuum filtration spray coating	conductive component in composite electrodes loading enzymes	power density 1.98 mW cm^{-2}	competent for various bending deformations	Wang et al.[40]
	graphene	two-dimensional conductivity high specific surface area	screen printing vacuum filtration spray coating	electrode in TENGs for self-powered wearable acoustic and vibration detector	V_{OC} = 80 V I_{SC} = 0.76μA	>50 bending cycles	Kovalska et al.[65]
Conductive polymer	PBFDO	high electrical conductivity excellent stability solution processability	spin coating drop casting wet spinning	n-type thermoelectric material in flexible TEGs	V = 4.3 mV	>1,000 bending cycles	Zhang et al.[59]
	PPy	pseudocapacitance non-toxicity affordability	screen printing spray coating	conducting coating in pressure sensor for self-powered sensing textiles	power density 211.22 W kg^{-1}	competent for various bending deformations	Peng et al.[43]
	PEDOT: PSS	tunable electrical conductivity thermoelectric properties water processability	screen printing spray coating	active component in all-solid-state supercapacitor for self-powered wearable device	energy density 22.7 μWh cm^{-2}	>5000 bending cycles	Zhu et al.[42]
	HPEs	excellent stretchability biocompatibility ionic conductivity	chemical crosslinking physical crosslinking	flexible moist-electric generator for respiration-monitoring masks	V_{OC} = 0.81 eV current density 480 μA cm^{-2}	>10,800 s under different deformation states	Zhang et al.[66]

V_{OC}, open-circuit voltage; I_{SC}, short-circuit current.

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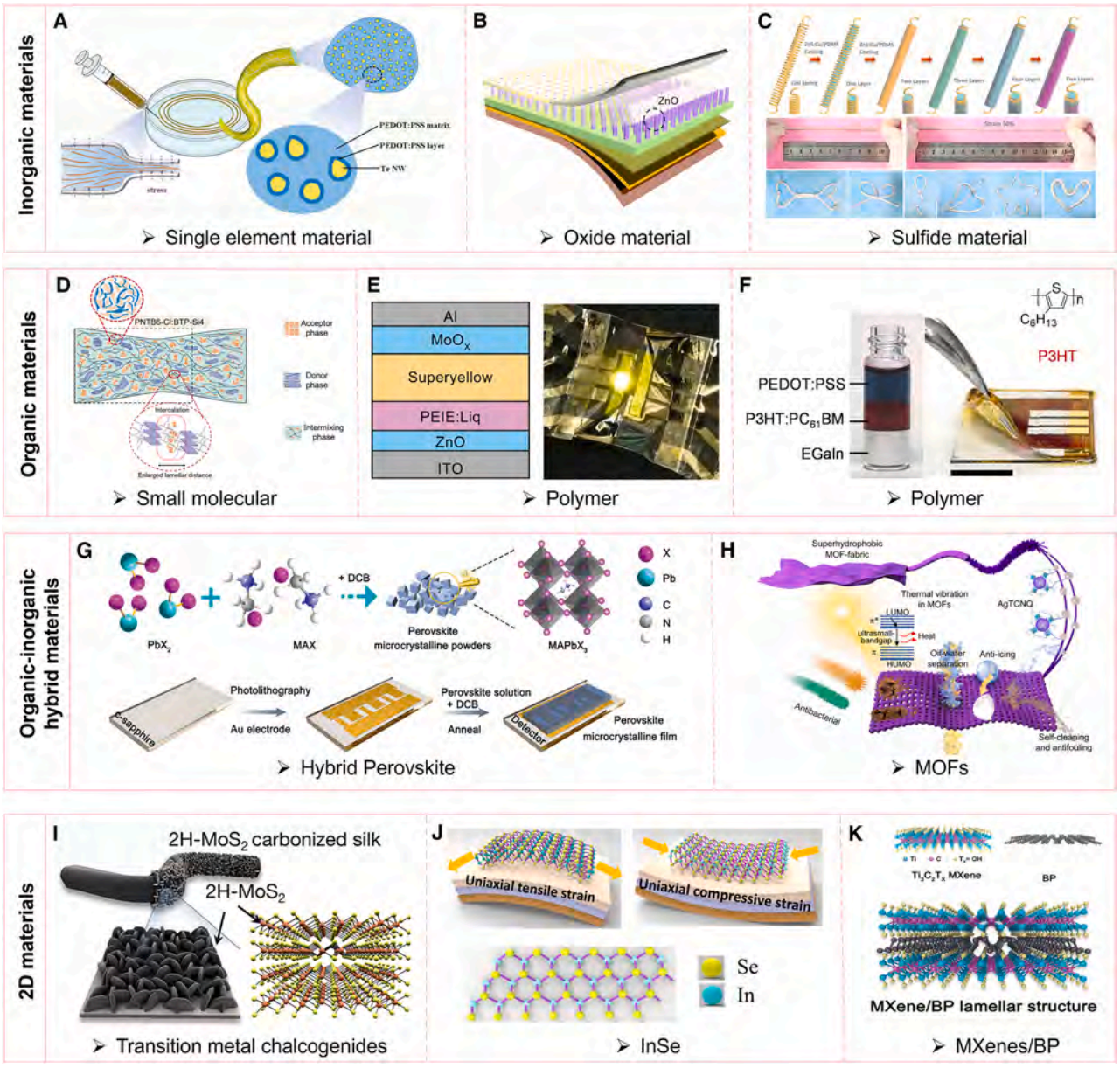

Figure 3. Flexible semiconductor material for self-powered wearable applications

(A) Illustration of the wet-spinning process of the PEDOT:PSS/PEDOT:PSS layer-coated Te nanowire (NW) composite fibers.[73]

(B) Device structure of the self-powered flexible UV photodetector composed of GaN thin film and ZnO nanowire.[74]

(C) Fabrication of the TENGs based on ZnS:Cu/PDMS.[75]

(D) Schematic illustration of the morphology of PNTB6-Cl:BTP-Si4 blend, the long-range ordering (large acceptor domains) is suppressed, while retaining sufficient short-range order to ensure efficient electron transport, resulting in excellent photovoltaic performance and considerable stretchability.[76]

(E) Schematic diagram of cross-sectional view of the stack present in polymer light-emitting diode (PLED) and its photograph during operation.[77]

(F) Photographs of solutions and delamination process of the ultrathin organic optoelectronic devices from glass substrates.[78]

(G) Schematic of the $MAPbX_3$ (X = Cl, Br, I) perovskite microcrystal.[79]

(H) Conceptual design and multifunctional flexible features of the MOF fabric.[80]

(I) Schematic illustration of the structure of 2H-MoS_2 carbonized silk and METs based on MoS_2.[81]

(J) Illustration showing the application of uniaxial strain to the flexible substrate based on InSe.[82]

(K) Schematic illustration of the MXene/BP-based flexible self-powered smart sensor system.[83]

transistors, and so on. For example, an ultraflexible self-powered organic optical system for photoplethysmogram monitoring has been developed by combining air-operation-stable OLEDs, organic solar cells, and organic photodetectors (Figure 3E).[77] These ultraflexible OLEDs retained 70% of the initial luminance even after 11.3 h of operation under air. Another advantage of organic semiconductors is their low processing cost, as they can be deposited into films via solution methods rather than vacuum technology. In particular, solution processing enables large-scale fabrication of ultrathin wearable electronics with integrated functions. Recently, a trilayer device, applicable to organic photovoltaics, photodetectors, and light-emitting diodes, with comparable performance and improved stability compared to complex reference devices with evaporated electrodes, has been realized by all-solution processing (Figure 3F).[78] In BFC research, carbon-based enzyme-like organic semiconductors with highly conjugated structures and high electron mobility are also worthy of attention, as they can mimic enzymatic functions while offering excellent biocompatibility, strong robustness under harsh conditions, and versatile chemical tunability.[89] Besides, stress strain optimization for organic semiconductors can be suppressed through interface design, enabling interfacial reconstruction. He et al. proposed a nanoconfinement-induced polarization strategy, successfully fabricating a series of organic conjugated polymer single-crystal films exhibiting ultra-high-energy order (minimum Urbach energy of only 25 meV) and near-ideal-state spatially confined current transport.[90]

Organic-inorganic hybrid semiconductor materials (such as hybrid perovskites and MOFs) are widely used in fields such as the Internet of Things, human health monitoring, and medical testing.[91–93] For instance, in the field of microwave detection, perovskite microcrystals (Figure 3G) can precisely adjust their microwave absorption characteristics by modifying their polar groups, exhibiting excellent electromagnetic response to multiple bands of microwave, visible light, and X-rays.[79] Besides, perovskite can also be used in other self-powered generators such as TENGs[94] and PENGs.[95] For example, perovskite can be used as the positive friction layer material for TENGs. By changing the composition, the binding energy of the perovskite film can be reduced, making it easier for electrons to escape, thereby increasing the triboelectric output with an open-circuit voltage of 245 V and a short-circuit current of 24 μA.[96] MOFs represent a highly tunable class of materials. Through rational design and modulation, MOFs can exhibit semiconducting properties. Band gap-engineered nanostructured MOFs have been reported to integrate with smart textiles, which exhibited the ability of photothermal deicing and antimicrobial therapy benefiting from the excellent photon-to-thermal conversion due to the ultrasmall band gap (Figure 3H).[80] The development of MOFs has also stimulated key applications in wearable devices.[97] Conductive 1D MOFs with narrow band gap can be used as active layers for supercapacitors and optoelectronic devices. They can be integrated onto flexible substrates such as polyethylene terephthalate (PET) to enhance flexibility while maintaining device electrical performance.[98] Such synergistic design of multiple materials ensures that the device does not undergo significant degradation.

Aside from conventional semiconductor materials, two-dimensional semiconductors are increasingly employed in self-powered wearable electronics due to their distinctive electrical and optical properties such as exceptionally high carrier mobility, which enhances charge transport and improves the energy conversion efficiency of self-powered devices. Wearable MIEGs based on MoS_2 nanosheets can form heterogeneous electric double layer through phase engineering, further enhancing the electrical performance, specifically by introducing a phase gradient between 2H semiconducting MoS_2 in carbonized fibers and 1T metallic MoS_2 in cotton fibers (Figure 3I).[81] The MIEGs based on MoS_2 obtained a peak output power density of 36.12 W/cm^2, three orders of magnitude higher than the current standard. In addition, 2D materials possess a very large strain limit that outperforms bulk semiconductors. Two-dimensional InSe with low Young's modulus can, therefore, exhibit considerable flexibility. A tunable band gap and a large piezoresistive effect of 2D InSe are achieved through strain engineering, which can be used as flexible strain sensors to detect human motion (Figure 3J).[82] InSe is also considered to have great potential in developing high-performance photoelectric conversion devices due to broad spectral response; a self-powered opto-sensor based on InSe flakes has been demonstrated as a promising component for artificial visual systems.[99] The tunable layered architecture of two-dimensional materials also provides a distinctive avenue for tailoring and optimizing material properties. For instance, the insertion of BP into the interlayers of MXene forms a periodic staggered layered structure (Figure 3K),[83] which not only creates small gaps at the interfaces of MXene flakes to improve deformability but also accelerates ion diffusion, enhancing the sensitivity of MXene/BP composite films.

Semiconductors with their distinctive electronic properties, superior charge transport, etc., offer significant advantages for wearable self-powered electronics. However, the application of semiconductor materials in self-powered wearable devices still faces some challenges. For instance, direct growth of high-quality inorganic semiconductors in a scalable way on flexible metal foils or polymer films remains highly challenging, as current techniques typically rely on high-temperature processes (chemical vapor deposition, physical vapor deposition, and so on) and lack sufficient process maturity, while the weak and poorly controlled bonding between inorganic semiconductors and metallic substrates further complicates integration. As for solution-processable organic semiconductors, which offer attractive prospects for large-scale manufacturing, achieving performance comparable to inorganic semiconductors remains fundamentally challenging due to intrinsic limitations in charge transport, structural order, doping controllability, and long-term stability. These challenges highlight a fundamental trade-off between process compatibility and electronic performance in flexible semiconductor technologies.

Table 3 summarizes the characteristics, processing methods, roles, performance, and flexibility of semiconductor material types for self-powered wearables.

Dielectrics

Flexible dielectric materials are essential for self-powered wearable electronics; they can serve as insulation layers or support structures to protect circuits, act as flexible substrates to

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Table 3. Comparison of various parameters of semiconductor material types and corresponding examples

Material type	Representative material	Characteristics	Processing method	Roles	Performance	Flexibility	Reference
Inorganic semiconductors	Te NWs	P-type narrow band gap high Seebeck coefficient	chemical vapor deposition solution-phase approach thermal deposition	fillers in PEDOT:PSS thermoelectric fibers for flexible TEGs	power factor 385.4 $\mu W\ m^{-1}\ K^{-2}$	>200 bending cycles	Jia et al.[73]
	ZnO	wide band gap piezoelectricity optical transparency	chemical vapor deposition hydrothermal method molecular beam epitaxy	typical piezoelectric semiconductor in piezoelectric device	output voltage 0.48 V Output current 74.7 nA	competent for various bending deformations	Deng et al.[100]
	doped ZnS	wide band gap mechanoluminescent piezoelectricity	sol-gel method co-precipitation method solid-state reaction method	mechanoluminescent fillers in friction layer of wearable TENGs for dual-mode human motion monitoring	output power 0.9 Wm^{-2}	competent for various bending deformations	Luo et al.[75]; Zhang et al.[101]
Organic semiconductors	BTP-Si4	non-fullerene acceptor high miscibility	solvent dispersion	acceptor in stretchable organic solar cell	V_{OC} = 0.90 V PCE = 16%	>1,000 bending cycles	Peng et al.[76]
	P3HT	solution processability affordability	spin coating dip coating spray coating	donor and matrix in photosensitive layer of ultra-flexible photodetector	responsivity 100 mA W^{-1}	>20,000 bending cycles	Yan et al.[102]
	PBDTTT-OFT	donor polymer thermal stability mechanical compliance	spin coating dip coating spray coating	active layer components in organic photodiodes for underwater vital sign monitoring	detectivity 6.2×10^{11} Jones	conformable to fingertip	Du et al.[103]
Organic-inorganic hybrid semiconductors	MA_2SnBr_6	tunable band gap good light absorption high carrier mobility	solution approach	functional fillers in piezo/triboelectric self-powered wearable dual functional sensors	peak voltage 59.94 V output current 55.53 μA	competent for various bending deformations	Tiwari et al.[104]
	DDA-Cu	controllable preparation good air stability high conductivity	solution reaction	the active layer of photosynaptic device	ΔPSC = 5.0 nA	competent for various bending deformations	Shang et al.[98]

(*Continued on next page*)

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Table 3. *Continued*

Material type	Representative material	Characteristics	Processing method	Roles	Performance	Flexibility	Reference
2D semiconductors	MoS_2	medium band gap excellent optical performance environmental stability	mechanical exfoliation liquid-phase exfoliation vapor deposition	semiconductor of friction layer in tribovoltaic nanogenerator	power density 39.15 mW m^{-2}	competent for various bending deformations	Fan et al.[105]
	InSe	considerable flexibility ultrahigh mobility tunable band gap	mechanical exfoliation liquid-phase exfoliation vapor deposition	functional sensing layer in flexible strain sensor for human motion detection	electron mobility 383 $cm^2 V^{-1}$	>2,000 bending cycles	Kang et al.[82]
	black phosphorus	remarkable surface area excellent carrier mobility rapid ion diffusion properties	mechanical exfoliation liquid-phase exfoliation vapor deposition	component in 2D hybrid materials for wearable wristband	power density 2.22 mW cm^{-2}	competent for various bending deformations	Lu et al.[83]

V_{OC}, open-circuit voltage; PCE, power conversion efficiency; ΔPSC, postsynaptic current change.

integrate components, and affect the energy storage efficiency of capacitors through their polarization characteristics.[106] Common dielectric materials include polymers (polymethylmethacrylate [PMMA], polyvinylidene difluoride [PVDF], PDMS, PET, etc.),[107,108] glass,[109] and paper-based materials.[110] These materials can effectively isolate charges and prevent current loss and interference, thereby improving the efficiency of energy conversion.[111,112] Flexible dielectric materials need to consider the adverse effects of long-term strain during service; the key to mitigating strain effects lies in achieving stress dissipation while maintaining dielectric properties. This requires dynamic structural designs that dissipate strain energy and suppress mechanical damage, while preserving the dielectric material's stable dipole orientation, charge trapping capability, and insulating characteristics. Concurrently, these materials must align with the energy conversion demands of self-powered mechanisms (piezoelectricity and triboelectricity). Microstructures serve as strain transmission carriers. By incorporating stress-buffering units (island phases, porous structures, encapsulated nanofillers), they can prevent dielectric pathway failure while maintaining functionality.

Polymer dielectrics combine mechanical flexibility with outstanding insulating behavior and dielectric tunability and in certain systems, also exhibit good piezoelectric properties. These combined merits enable efficient charge storage and retention, compliance, and integration in conformable systems, thereby underpinning their extensive applications in self-powered wearable electronics. For example, polymer dielectrics can serve as triboelectric layers in wearable TENGs, generating and storing charges that are subsequently harvested through integration with electrodes. Bui et al. demonstrated the preparation of a sponge-like PMMA-GO/copper mesh hybrid (GO [graphene oxide]) via a scalable one-step dip-coating method, with *in situ* GO decoration induced by solution-phase separation (Figure 4A).[113] This advanced electret-electrode hybrid simultaneously improved surface charge transfer, charge trapping, mechanical robustness, and breathability of TENGs, achieving high output performance (14.5 W m^{-2}) with excellent durability over 21,000 cycles. By adding conductive agents such as CNTs, polymer dielectrics can be further processed into flexible and stretchable electrodes. Figure 4B demonstrates a PDMS-based compliant electrode coated on an acrylic ester film to develop a dielectric elastomer actuator (DEA), which can be used for physical rehabilitation and treatment of patients with oculomotor nerve palsy.[114] Besides, polymer dielectrics are also widely employed as flexible substrates and encapsulation materials. For example, in a MEGs-based self-powered electrical stimulating platform programming fibroblasts into neurons, PDMS can be utilized to render it tissue compliant and biocompatible.[120]

Inorganic dielectrics, such as Al_2O_3, $BaTiO_3$, h-BN, and glass fiber, also play an important role in the field of self-powered wearable electronics owing to their superior intrinsic properties. Compared with organic counterparts, inorganic dielectrics exhibit higher dielectric constants and greater mechanical strength, as well as remarkable thermal and chemical robustness. These merits enable inorganic dielectrics to serve effectively as encapsulation layers—preventing current leakage and mitigating the degradation of organic components, or as

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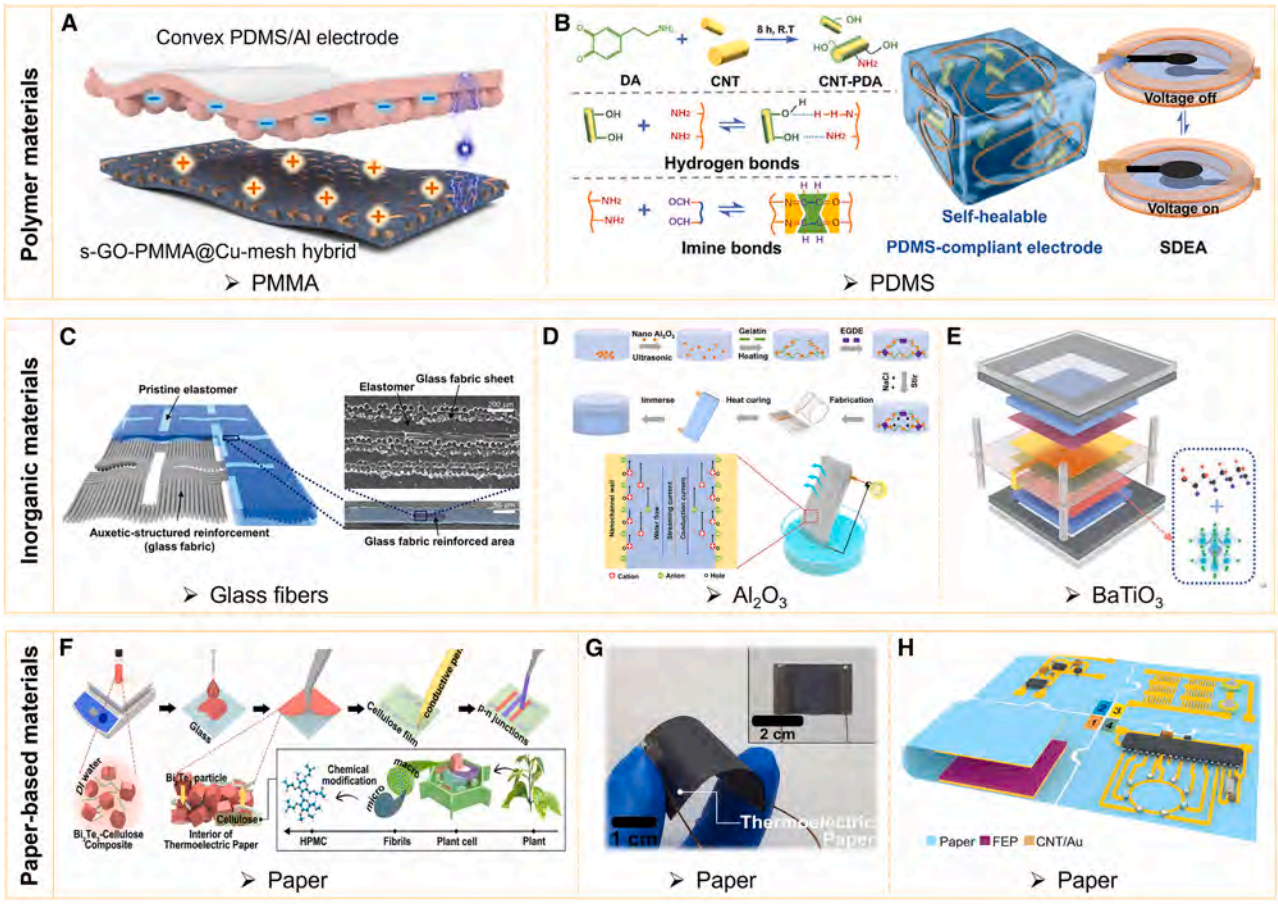

Figure 4. Flexible dielectric material for self-powered wearable applications

(A) 3D schematic representation of a morphologically antagonistic TENGs structure composed of the s-PMMA-GO/Cu-mesh hybrid and convex patterned PDMS (c-PDMS).[113]

(B) The preparation process of self-healable PDMS-compliant electrodes and construction of self-healable DEA.[114]

(C) Structures of the skin-like stretchable substrate composed of the auxetic-structured reinforced domain (glass fabric) and pristine elastomer domain.[115]

(D) Schematic diagram of S-ENG preparation process and working process.[116]

(E) 3D structural schematic of dielectrically polarized TENGs (the inset shows the structural molecular models of the composite film PVDF and BTO).[117]

(F and G) Schematic illustrations of the fabrication process for resorbable f-TEH based on TE paper (DI, deionized; HPMC, hydroxypropyl methyl cellulose).[118]

(H) Schematic illustration of the sustainable functional paper modules.[119]

reinforcement—imparting enhanced mechanical strength to soft materials. For example, carefully designed periodic stacks of Al_2O_3/ZnO nanostructured layers deposited by atomic layer deposition (ALD) can be employed as protective coatings in a self-powered smart clothing system based on polymer solar cells, endowing this textile with outstanding washability and long-term operational stability; auxetic-structured glass fiber fabric can be applied to polymer composites, achieving not only enhanced robustness but also a negative Poisson's ratio (Figure 4C).[115,121] In fact, both materials (Al_2O_3 and glass fiber) can also serve as functional parts: Al_2O_3 acts as hydrophilic surface in hydrovoltaic energy harvesters (Figure 4D), whereas glass fiber fabric functions as the positive triboelectric layer in TENGs.[116,122,123] Some inorganic dielectrics such as $BaTiO_3$ particles are also widely used due to their excellent piezoelectric properties. Flexible piezoelectric generators can be realized by incorporating these piezoelectric particles into polymer matrix.[124,125] More interestingly, integrating $BaTiO_3$ particles with ferroelectricity into TENGs has been reported to result in enhanced triboelectric charge density and tribo-piezoelectric synergistic generators.[126,127] Figure 4E shows a 3D structural schematic of TENGs, in which an ultrafast self-polarization effect is found by the introduction of $BaTiO_3$.[117] Apart from aforementioned dielectrics, two-dimensional h-BN has also attracted considerable attention in self-powered wearable electronics. It can form strong van der Waals interactions with graphene without relying on chemical bonds, making it an ideal interface buffer layer between inert graphene electrodes and functional layers.[128]

Paper-based materials have the characteristics of good flexibility, foldability, sustainability, biodegradability, lightweight, and low cost. The distinctive three-dimensional hierarchical structure of paper enables the substrates to host a wide range of active materials, opening up numerous opportunities for advanced

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electronics development.[129–131] Recently, paper-based wearable electronics have attracted considerable attention, particularly in areas demanding high foldability and conformability.[132–134] For instance, paper can be used as a substrate for electronic products.[135] Park et al.[118] developed a kirigami TE paper with excellent flexibility by forming an inorganic particle network layer below the cellulose matrix layer, which can be freely cut or folded into various shapes (such as birds, butterflies, boats, and clouds) (Figures 4F and 4G). The prepared p-type and n-type TE papers exhibited power factor values of 3.11 and 1.16 $\mu W/(m \cdot K^2)$, respectively, at 298 K. Beyond a single module, researchers have also developed multifunctional systems integrating multiple modules on one paper. Sun et al.[119] proposed a modular paper-based self-powered system that includes power management circuits, energy storage, and functional components, which can directly complete energy collection, storage, and utilization on the paper system and effectively improve energy transmission/conversion efficiency (Figure 4H). Besides, paper-based materials offer excellent compatibility with laser processing,[136] enabling precise structural patterning,[137] *in situ* carbonization,[138] and circuit design.[139]

In general, polymer dielectric materials often render self-powered wearable devices good flexibility, stretchability, biocompatibility, and comfortable wearing experiences. The simple and mature manufacturing processes mean that they will not be an obstacle to large-scale production. However, these polymer materials may experience swelling, brittleness, aging, and other phenomena during long-term operation due to exposure to biofluids and sunlight, which can affect the stability and reliability of equipment. In contrast, encapsulation strategies based on inorganic dielectric materials (such as ALD) generally provide superior barrier performance and long-term stability; however, their relatively complex fabrication processes and higher associated costs continue to pose challenges for large-scale manufacturing. As for paper-based materials, manufacturing electronic products on paper substrates requires solving problems such as large surface roughness, porosity, and chemical impurities, which will increase manufacturing costs. Therefore, the trade-offs between different dielectric materials need to be carefully considered according to specific requirements.

Table 4 summarizes the characteristics, processing methods, roles, performance, and flexibility of dielectric material types for self-powered wearables.

FLEXIBLE STRUCTURE ENGINEERING

Structural design, namely, conferring specific structural geometry and topology to materials, is increasingly recognized for highlighting their unique advantages in flexible systems and integrated devices. Structural design provides a universal strategy to enhance flexibility and stretchability across materials, regardless of their intrinsic mechanical properties. Moreover, rational structural design can ensure stable electrical performance during deformation, enable specific sensing functionalities, and even improve device output performance. In the following, the applications of representative structural designs in self-powered wearable devices are reviewed from the perspectives of bionic structures and artificial structures.

Bionic structures

The concept of bionics is not new. In ancient Greek mythology, Daedalus and Icarus crafted wings from feathers and wax to imitate the flight of birds—a remarkable early attempt at bionics that reflected humanity's desire to learn from nature. Later, Aristotle asserted that ''the forms of natural things can inspire human creations,'' laying the philosophical foundation for biomimetic thought. Bionics provides profound inspiration for the design of flexible structures. By studying the adaptive, deformable, and resilient features found in natural organisms (such as the bending of leaves, the contraction of muscles, or the flexibility of fish fins), engineers can develop materials and systems that combine strength with compliance. This biomimetic approach transforms rigid mechanical concepts into dynamic, responsive designs, driving innovations in wearable technology. This section summarizes the applications of bionic structures in flexible electronics.

The spider web, renowned for its remarkable combination of strength, flexibility, and adhesion, offers profound inspiration for bionic design. Drawing on this natural architecture, a web-droplet-like electronic skin was developed, integrating a breathable network structure with adhesive and conductive components (Figure 5A).[146] This biomimetic strategy endows the device with excellent flexibility, adhesion, and breathability, highlighting the potential of spider-web-inspired designs in wearable electronics. Inspired by fish lateral line (Figure 5B),[147] Ma et al. employed latex-balloon-encapsulated air channels to replicate lateral line tubes, spiral silver-plated nylon yarn to imitate sensory nerves, and porous silicone rubber and nylon fluff to imitate hair cells, and it achieved a maximum output voltage of 54.74 V and a maximum output current of 186.43 nA while withstanding tensile strains of over 140%. To meet the protection demands for flexible electronics working in complex environments, a novel electronic armor (E-armor), inspired by snake skin, is proposed. The soft-hinge strategy in this E-armor mimics the rigid-soft coupling structure of snake skin, where rigid scales connected by soft tissues inspire a modular design that integrates protection, flexibility, and sensing capabilities (Figure 5C).[148] Sun and colleagues introduced core-shell structured Galinstan microdroplets into a soft self-healing polyurea to obtain a synthetic structure similar to that of vascular smooth muscles, surpassing the trade-off between soft self-healing and high fracture toughness and resulting in an increased crack-resistant strain and fracture toughness of 12.2 and 34.9 times without sacrificing softness (Figure 5D).[149] Leaves and veins also stand as classical examples of the flexible structures found in nature. By neutral-axis management and introduction of reinforcing fibers, electronic film devices can emulate such natural architectures, exhibiting remarkable resistance to folding and stretching (Figure 5E).[150]

In fact, the intricate role of natural structures in living organisms extends far beyond providing flexibility. They can efficiently mediate interactions with external stimuli, such as stress, light, heat, or humidity, and facilitate internal biochemical or electrical signaling. Many bionic structural designs have been demonstrated to enhance the performance of energy harvesters, storage devices, and sensors while maintaining flexibility. For example, some microstructures in plants and human body have been exploited in the design of wearable devices.

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Table 4. Comparison of various parameters of dielectric material types and corresponding examples

Material type	Representative material	Characteristics	Processing method	Application example	Performance	Flexibility	Reference
Polymer materials	PMMA	optical transparency good weathering tribo-positive	Solution casting Electrospinning Hot pressing Spin coating	Protect layer for ZnO in wearable PENGs	V_{OC} = 3.5 V Mean power output 20 nW cm^{-2}	Competent for various bending deformations	García-Casas et al.[140]
	PDMS	flexible and stretchable breathability hydrophobicity	Casting Hot embossing Spin coating	Elastic matrix forming self-healing electrodes in ocular-therapy actuators	Output voltage 275 V	Competent for various bending deformations	Xing et al.[114]
	PVDF	good mechanical strength thermal and chemical tolerance piezoelectricity	Solution casting Electrospinning Hot pressing Spin coating	core of piezoelectric-thermoelectric-coupled nanofiber for multifunctional electronic skin	V_{OC} = 25 V	>1,000 bending cycles	Li et al.[141]
	ultraviolet-curable oligomers	3D printable rapid prototyping good adhesion	photocrosslinking	substrate in stretchable TEGs for health monitoring	[ower outputs 0.40 mWcm^{-2}	>380 compression cycles	Zadan et al.[142]
Inorganic materials	Al_2O_3	good densification optical transparency	low-temperature ALD ultrasonic dispersion surface functionalization	encapsulation barrier in polymer solar cells for washable textile	V_{OC} = 0.77 V PCE = 7.26%	>1,000 bending cycles	Jeong et al.[121]
	$BaTiO_3$	high dielectric constant ferroelectricity lead free	ultrasonic dispersion surface functionalization	piezoelectric nanofillers on glass fiber fabric for wearable sensing	V_{OC} = 90 V I_{SC} = 1.5 μA	>3.000 cycles bending	Zhou et al.[143]
	glass fiber	high mechanical strength thermal and chemical tolerance polymer affinity	plain weave knitting nonwoven	positive triboelectric layer in all-textile TENGs for textile electronics	V_{OC} = 261 V I_{SC} = 1.5 μA	competent for various bending deformations	Zheng et al.[123]
	h-BN	van der Waals materials high-temperature stability high thermal conductivity	physical vapor deposition chemical vapor deposition	substrate for ZnO array growth in PENGs	V_{OC} = 5 V I_{SC} = 18 μA power density 169 mW cm^{-2}	competent for various bending deformations	Liu et al.[144]
Paper-based materials	paper	high flexibility sustainability affordability	laser cutting physical cutting	substrate in thermoelectric paper	power density 4 μW cm^{-2}	>3,000 bending cycles	Rana et al.[118]
	paper			substrate in wearable integration module	V_{OC} = 4.76 V PCE = 10.6%	>200 bending cycles	Lomeri et al.[145]

V_{OC}, open-circuit voltage; I_{SC}, short-circuit current; PCE, power conversion efficiency.

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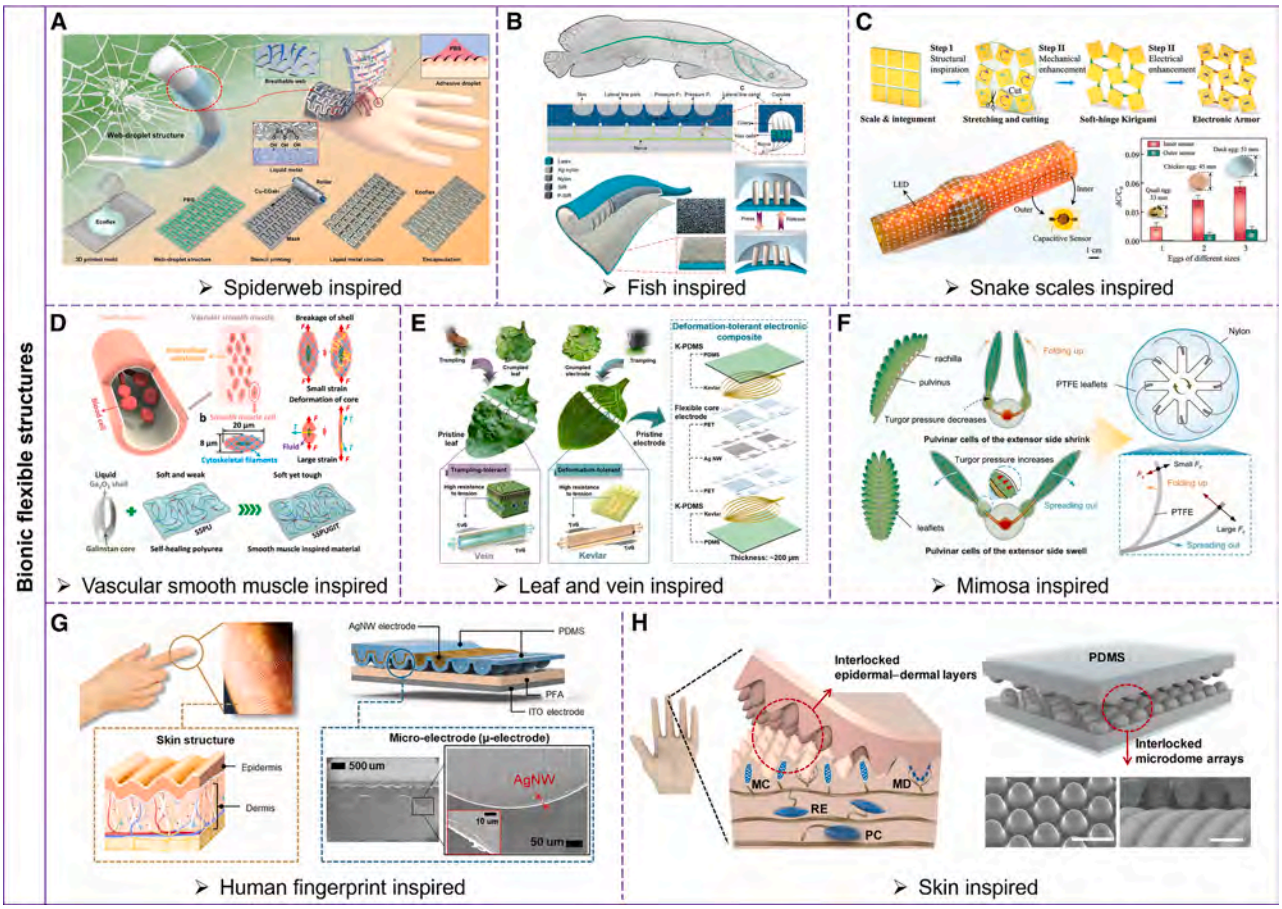

Figure 5. Realization of improved flexibility and performance through bionic structures

(A) Liquid-metal-based highly adhesive, stretchable, and breathable spider-web-inspired electronic skin.[146]

(B) Schematic of the structure of fish lateral line system TENGs.[147]

(C) Evolution and functional demonstration of the snake scales-inspired soft hinge Kiri-MM E-armor.[148]

(D) Schematic fabrication process of composite inspired by multimodal toughening mechanism of vascular smooth muscle cell.[149]

(E) The deformation-tolerant electronic composite inspired by the leaf and vein structure.[150]

(F) The working principle of *Mimosa*-inspired adaptive TENGs.[151]

(G) Schematic structure of a human fingerprint-inspired sensitive stress sensor.[152]

(H) Schematic structure of stress-direction-sensitive stretchable electronic skins inspired by the interlocked microstructures found in the epidermal and dermal ridges in human skin.[153]

Mimosa-inspired adaptive TENGs were reported to autonomously switch modes with varying wind speeds. This capability arises from a rational structural design that enables regulation of the contact state between the friction layers through centrifugal force (Figure 5F).[151] The skin at the tip of the finger is composed of conformally formed epidermis and dermis layers along the wavy patterns in the fingerprint. Inspired by the fingerprint structure, novel μ-TENGs were designed, composed of microstructured dielectric material and conformally formed μ-electrodes along the 3D geometries of microstructures to form an asymmetric geometry with a bottom flat electrode (Figure 5G).[152] Such a structure maximizes its capacitance variation through the increased pressure-induced parallel intersecting area variation between the paired electrodes, which maximizes triboelectric generation and promotes pressure sensitivity. Similarly, the interlocked microstructures found in epidermal and dermal ridges in human skin have shown application in stress-direction-sensitive stretchable electronic skins (Figure 5H).[153]

Artificial structures

Over thousands of years, humans have developed a range of unique structural configurations through long-term practice and engineering innovation. These artificial architectures provide excellent mechanical adaptability and stability, offering effective strategies for constructing flexible and stretchable electronic devices.

Wavy structures, helical structures, and kirigami/origami structures have long appeared on the historical stage. These structures release or absorb deformation caused by external forces through geometric deformation, rather than relying on tensile or compressive strain within the material, generally enabling large deformations and have been demonstrated to

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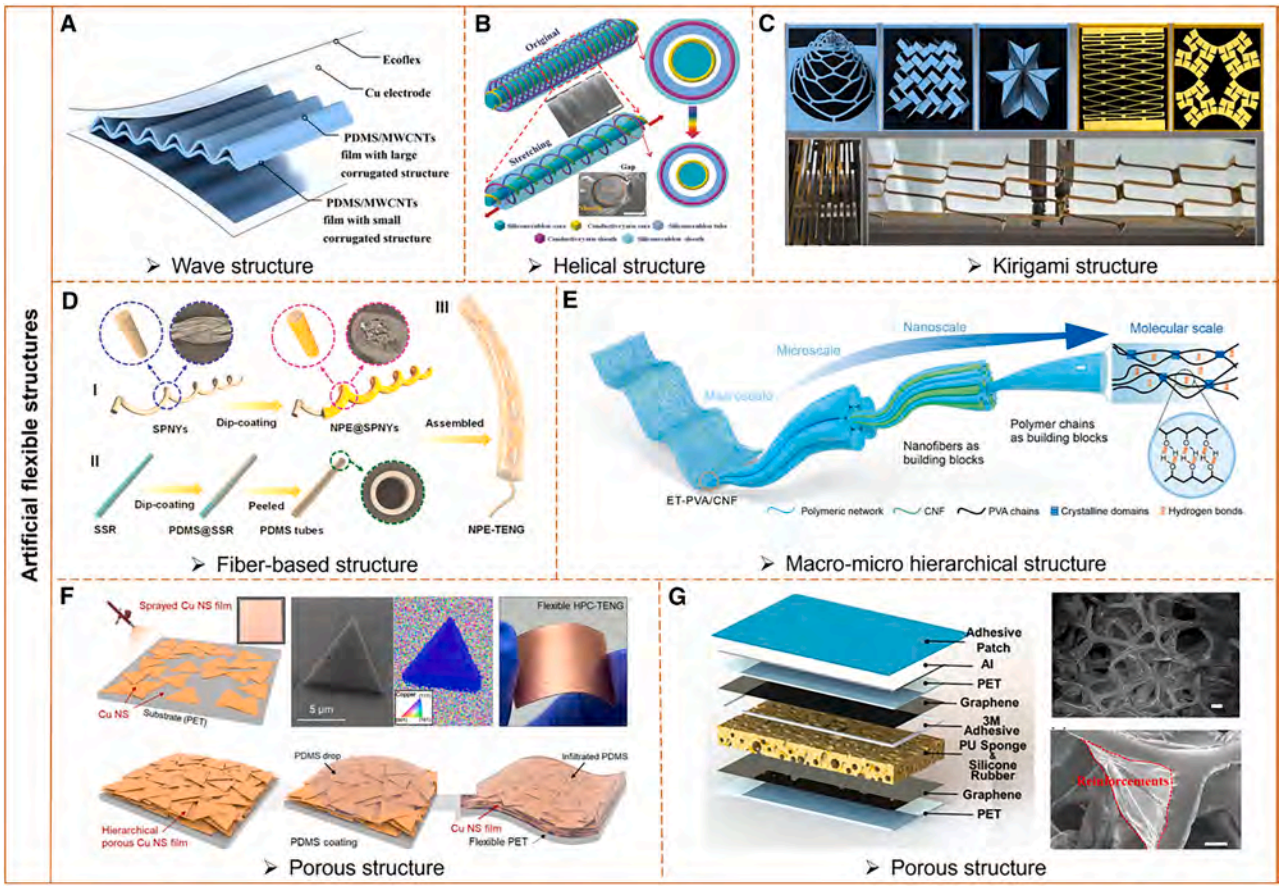

Figure 6. Realization of improved flexibility and performance through artificial structures

(A–C) Three classic deformable structures. (A) Wavy structure.[154] (B) Helical structure.[155] (C) Kirigami structure.[156]

(D) Fiber-based structural design. Fiber-shaped one-dimensional wearable electronics.[157]

(E) Flexibility facilitated by macro-micro hierarchical structure.[158]

(F) Porous structural design. Schematic preparation process of porous Cu film based on 2D nanosheets.[159,160]

(G) Schematic illustrations of flexible triboelectric patch, and scanning electron microscopy image of silicone rubber reinforcements in porous PU sponge.[161]

considerably improve the flexibility of wearable devices (Figures 6A–6C).[154–156] However, the introduction of geometric features such as curvature, folds, and cuts inevitably leads to localized stress concentrations, which can accelerate mechanical fatigue and pose challenges to structural stability and long-term reliability under repeated deformation.

One-dimensional fiber structures can exhibit unexpected resistance to both deformation (high strength) and fracture (high toughness) and significantly promote the development of self-powered wearable devices. For example, when a number of aligned CNTs are assembled into a fiber structure, excellent mechanical properties can be achieved. However, these fiber-based devices often face challenges of low power output and poor sensing capability, which have been the focus of extensive research efforts. As an instance, novel polycation-modified carbon dot (PCD)-tailored PCD/polyvinyl alcohol nanocomposite polymer electrolytes (NPEs) were prepared and applied as triboelectric materials on fiber coatings (Figure 6D).[157] Fiber-shaped TENG based on NPEs delivered a high power density of 265.8 μW/m. In addition, developing fiber-shaped wearable systems though a rational design and effective integration of multifunctional components into one single fiber remains a great challenge. Pan et al. proved the possibility for an all-in-one stretchable coaxial-fiber sensing system simultaneously integrating strain detection and power supporting supercapacitor, which can be applied for the next-generation wearables.[162] Besides, the concept of hierarchical structures is very suitable for fiber-based design (Figure 6E).[158] On one hand, the materials that form the fibers can contain a variety of interactions and the fibers themselves can be designed to flexible structures such as spring; on the other hand, the fibers can be further twisted into yarn and woven into fabrics. All these hierarchical structural designs work synergistically to enhance the flexibility of the final products.[163,164]

Porous structures offer a huge deformation space to eliminate the stress concentration and thus endow materials with high flexibility. Their lightweight nature, breathability, high specific surface area, and many other advantages—together with flexibility—make them widely used in self-powered wearable devices. However, simple porous structures often fail to meet the

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practical needs of wearable devices due to instability of pore architectures and their insufficient mechanical strength, which has inspired the proposal of various porous structure design strategies. For example, in addition to using foaming agents and template methods, porous structures can be effectively formed by stacking nanoscale discrete units (nanofibers, nanosheets, etc.), the most common example being electrospun porous films. Recently, the self-assembly of 2D Cu nanosheets during solution processing was utilized to form a highly interconnected hierarchical porous film with abundant internal voids (Figure 6F).[159] This porous structure significantly enhances charge generation during mechanical cycles. Multifunctional TENGs based on this Cu film demonstrated remarkable performance enhancement and excellent flexibility. To tune the mechanical properties of the porous polyurethane (PU) sponge, Lei et al. exploited the self-assembly of silicone rubber, where the adsorbed silicone rubber on frameworks reinforces the sponge structure. Figure 6G illustrates the flexible triboelectric patch based on this porous-reinforcement microstructure.[161]

In summary, various materials design strategies offer versatile routes to enhance flexibility, stretchability, and performance in self-powered wearable devices. Importantly, structural engineering can expand the design space of materials, enabling functionalities that are difficult to realize through materials optimization alone. Therefore, the interaction between the structure and material design spanning conductor-semiconductor-dielectric creates a cocktail effect, in which their synergistic coupling can transcend the conventional trade-off between electrical performance and mechanical compliance, opening new opportunities for next-generation wearable energy systems. However, they may involve intricate implementations that increase device volume or complicate large-scale fabrication. Meanwhile, compared with simple continuous structures, more complex designs often introduce localized stress concentrations, which can undermine the stability of wearable devices and limit their long-term operational lifetime under repeated deformation. Future efforts should, therefore, aim to establish simplified structural frameworks through material-structure co-optimization. Furthermore, the integration of data-driven design methodologies with emerging fabrication technologies, such as additive manufacturing and laser processing, is anticipated to accelerate the development of structurally efficient, miniaturized, and application-oriented self-powered wearable systems.

Table 5 summarizes the comparison of various flexible structures applied for flexible wearables.

MULTIFUNCTIONALIZATION AND INTEGRATION

Through rational materials and structural design, the electrical and mechanical properties of self-powered wearable devices can be synergistically optimized, enabling an optimal balance between energy output and mechanical compliance.[166,167] However, achieving such a balance represents only one step toward real-world deployment. The other, equally critical step lies in multifunctionality and integrated system design. As more advanced and complex application scenarios continue to emerge, accompanied by an increasing emphasis on practical usability, the multifunctionalization and integration of wearable electronics are becoming an indispensable direction for translating self-powered wearable devices from laboratory demonstrations to market-ready technologies.

Multifunctionality can enable devices to meet different needs. For instance, self-healing and self-cleaning capabilities can help restore the mechanical and electrical properties of materials during long-term operation. Endowing devices intended for extreme conditions with environmental resilience such as resistance to heat, cold, moisture, or chemical exposure is crucial to maintaining stable operation. Other desirable features such as breathability, transparency, and biocompatibility are crucial for enhancing wearer comfort, which are becoming a key consideration in the design of self-powered wearable devices. In addition to multifunctionality, integration of diverse components into a compact and coherent system is equally important. Achieving seamless integration allows multiple functions—such as energy harvesting, sensing, and actuation—to operate synergistically within a single wearable platform, enhancing overall device performance and user experience.

Multifunctionalization

Wearable devices are often exposed to mechanical stress, dirt, moisture, sweat, and microbial contamination during prolonged use. Beyond mechanical flexibility, functionalities such as self-healing, self-cleaning, and antimicrobial functions are critical for maintaining long-term service: self-healing enables recovery from mechanical damage, while self-cleaning and antimicrobial functions provide resistance to physical and microbial contamination under real-world conditions. The self-healing properties of materials can usually be achieved through dynamic covalent bonds, non-covalent interactions such as hydrogen bonding or metal-ligand coordination, and physical processes. Introducing self-healing materials into critical regions can endow the device with self-healing capability. For example, a CNTs-doped disulfide crosslinked PU was employed as the encapsulation material for LM electrodes. The dynamic exchange of disulfide bonds endowed the PU with intrinsic self-healing capability, while the incorporation of CNTs enhanced its thermal conductivity, resulting in a self-healing and modularized flexible TEG with improved heat transfer across thermoelectric legs (Figure 7A).[168] Self-cleaning designs can be implemented by the introduction of superhydrophobic surfaces or photocatalytic effects. For instance, Figure 7B shows the superhydrophobicity of the 3D-printed magnetic device obtained by spraying the surface-modified silica nanoparticle solution.[169] This self-cleaning flexible device holds promise for converting raindrop impact into electromechanical energy. Similarly, TiO_2 and ZnO nanoparticles were incorporated as functional materials into the fluoride-co-hexafluoropropylene (PVDF-HFP) matrix, which served as the friction and encapsulation layers.[178] TENGs based on it were reported to exhibit excellent properties, such as the acid and alkali resistance, photocatalytic self-cleaning, and UV shielding. Likewise, antimicrobial capability can be introduced by integrating antimicrobial components such as Ag nanoparticles or bio-based agents like epsilon polylysine (ϵ-PL).[179] A soft conductive composite based on LM and phase-separation method was reported to exhibit excellent antimicrobial properties through the incorporation of ϵ-PL.[170] As shown in Figure 7C, porous

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Table 5. Comparison of various flexible structures applied for flexible wearables

Structure	Example	Category	Characteristics	Reference
Spider web	spider web-inspired electronic skin	deformation-oriented nature-inspired structure	flexibility stretchability breathability	Guo et al.[146]
Fish lateral line	fish-inspired TENGs	deformation-oriented nature-inspired structure	flexibility stretchability	Ma et al.[147]
Vascular smooth muscle	smooth muscle-inspired capacitive strain sensors	deformation-oriented nature-inspired structure	stretchability softness yet toughness	Sun et al.[149]
Leaf and vein	*Plantago*-inspired electronic composite	deformation-oriented nature-inspired structure	flexibility foldability stretchability	Hong et al.[150]
Mimosa	*Mimosa*-inspired TENGs	function-oriented nature-inspired structure	adaptive generation	Liao et al.[151]
Human fingerprint	fingerprint-inspired TENGs	function-oriented nature-inspired structure	high-pressure sensitivity	Lee and Park[152]
Human skin	skin-inspired piezoresistive arrays	function-oriented nature-inspired structure	multidirectional sensing flexibility stretchability	Park et al.[153]
Wave	wavy piezoresistive sensor	artificial structures	compressive robustness	Li et al.[154]
Helix	yarn-based spring-like TENG	artificial structures	flexibility stretchability high sensitivity	Dong et al.[155]
Paper cuts	kirigami-structured smart textiles	artificial structures	stretchability	Wang et al.[165]
Fiber	fiber-shaped TENGs	artificial structures	flexibility stretchability	Li et al.[157]
Porous structure	porous TENGs	artificial structures	enhanced charge generation flexibility foldability	Kim et al.[159]

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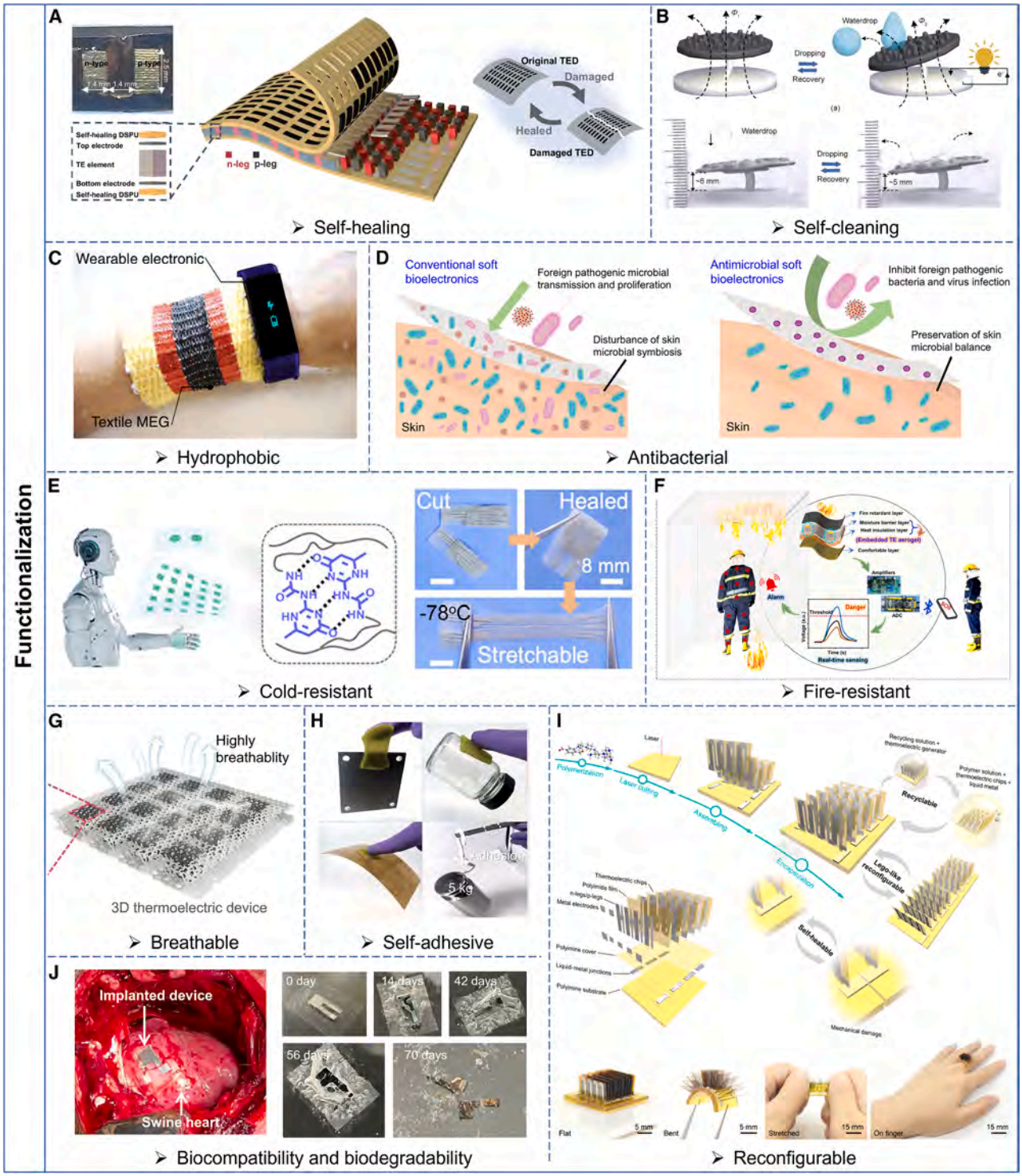

Figure 7. Multifunctional devices can adapt to different application scenarios

(A) Conceptual illustration of a self-healing TEG with EGaIn electrodes and self-healing heat conductors.[168]

(B) Schematic illustration of the mechanoelectrical conversion capacity of the 3D-printed magnetic device during waterdrop dripping.[169]

(C) Schematic of antimicrobial agents, conductive components, antimicrobial property, and porous structure of composites.[170]

(D) Schematic showing the aerogel-based self-powered wearable fire warning system that provides high-temperature warning to firefighters.[171]

(E) Schematic illustration of polar robot equipped with stretchable and self-healable e-skins at ultralow temperature.[172]

(F) Schematic of the textile MEG mixed with wool fibers driving a wearable biosensor system.[173]

(legend continued on next page)

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structure demonstrated robust encapsulation of the LM even under mechanical pressure. The combination of these unique attributes made it a promising candidate for skin-interfaced bioelectronic applications.

In specific scenarios such as high-temperature, polar, and underwater environments, self-powered wearable devices are inevitably exposed to extreme environments, which challenges the stable operation of devices, including normal energy output and the completion of functions such as data acquisition, data transmission, analysis, and monitoring.[180] Traditional approaches that rely on external barrier layers unavoidably increase the overall thickness of the device and may compromise the wearing comfort. Therefore, the development of new functional materials with intrinsic environmental resistance has become an urgent priority. By exploiting the inherent thermal insulation and flame-retardant characteristics of aerogels, Chen et al.[171] designed a lightweight, elastic thermoelectric composite capable of stable operation under high temperatures. The self-powered wearable system designed based on the thermoelectric aerogels can realize wide-range temperature detection, high-temperature alarm, gesture recognition, and other functions and can provide firefighters with self-powered high-temperature fire early warning capability (Figure 7D). Yang et al.[172] designed a PDMS-based supramolecular elastomer with multi-strength dynamic H-bonds (UPy units), achieving high stretchability and self-healing at −78°C (Figure 7E). The ultralow glass transition temperature of PDMS ensures chain mobility, while reversible UPy cross-links enable rapid recovery and excellent mechanical resilience in extreme cold. The composite is a promising candidate for robotic e-skins designed to function in harsh polar environments. For underwater applications, self-powered wearable devices based on MEGs are attaching more and more interest because magnetic fields can pass through water with negligible intensity loss (Figure 7F).[173] By exploiting MEGs and one-dimensional convolutional neural network, Zhou et al. presented multimodal artificial skin for underwater haptic sensing and human-computer interface, achieving a 95% classification accuracy for seven types of marine creatures and litter.[181] Besides, the development of anti-swellable hydrogels, exhibiting minimal long-term swelling in water, also represents a solid step toward enabling hydrogel-based underwater wearable devices.[182] These works underscore the importance of material innovation in achieving intrinsic environmental resistance for wearable electronics, paving the way for next-generation self-powered wearable systems capable of reliable operation across extreme scenarios.

The wearing experience is crucial for the commercialization of wearable self-powered electronics. Good breathability, moisture management, biocompatibility, etc., can make the devices more popular among consumers.[183,184] Generally, breathability depends on the porosity of materials. Textiles and electrospun membranes inherently form pores during processing. Porous structures can also be artificially engineered, although this usually requires additional processing steps. Recently, He et al. fabricated a breathable and long-term durable thermoelectric fabric (Figure 7G).[174] Using advanced knitting techniques, multiple static air channels were fixed in this breathable fabric, thus generating an exceptional ultra-low thermal conductivity ($\kappa < 0.05\ Wm^{-1}\ K^{-1}$). Unidirectional moisture-wicking can be achieved by rationally distributing yarns with different water absorbencies in the textile interlayer. Adopting this strategy, Fan et al. constructed a three-dimensional piezoelectric fabric sensor, rapidly moving sweat from the skin-facing inner layer to the outer layer within 4 s, thereby maintaining a dry and comfortable microenvironment.[185] Notably, exposure to sweat does not compromise the piezoelectric performance of the fabric, but enhances it. Fiber-based BFCs enable the harvesting of biochemical energy from sweat in textile platforms. Their integration with other textile-based energy harvesters offers a route toward breathable, woven hybrid self-powered fabrics. Zhou et al. designed a power management circuit that enabled efficient matching of these two energy harvesters, which can enlarge the output power by about 46.1 times.[186] The inherent adhesion of skin-interfaced devices can avoid the use of adhesives and is, therefore, also important for the wearing experience. Figure 7H shows a poly(siloxane-diphenylglyoxime-urethane) (PSDU)-based porous composite elastomer with enhanced adhesion by perovskite, surpassing pure PSDU by approximately 60%.[175] This robust and enduring adhesive strength stems from the oximes and hydroxyl groups, along with a cohesive hydrogen bonding network between perovskites and polymers. This multifunctional composite can be used as gas-solid TENGs and shows promising potential in wearable electronics and smart agriculture.

Besides, the concept of sustainability and environmental friendliness has become increasingly ingrained in public consciousness, drawing attention to the recyclability and biodegradability of wearable devices. In addition to their functional performance, there is growing interest in developing wearable electronics that minimize environmental impact throughout their life cycle, from material selection to end-of-life disposal. Following this concept, numerous innovative strategies have been introduced to advance the sustainability of wearable devices, ranging from recyclable structural designs to the integration of environmentally benign and biodegradable materials. For example, a mechanical architecture design of ‘‘soft motherboard-rigid plugin modules’’ for wearable TEGs was proposed to combine the recycle of modular thermoelectric chips and self-healing ability (Figure 7I).[176] Meanwhile, the application of natural biomaterials with biodegradability for self-powered wearable devices has been actively explored. As an illustration, cellulose nanocrystals with piezoelectricity have been developed for

(G) Schematic of highly breathable 3D thermoelectric device.[174]
(H) Strong adhesion of poly (siloxane-diphenylglyoxime-urethane) (PSDU)-perovskite with metal plate, curved glass, and plastic film.[175]
(I) Schematic illustration of the design, fabrication process, and key characteristics of thermoelectric generator including self-healing ability, recyclability, and Lego-like reconfigurability.[176]
(J) Photograph of the biodegradable device on the right ventricle of an adult swine heart and *in vivo*-recorded voltage response of the device as a function of time.[177]

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implantable sensors exhibiting excellent biodegradability and biocompatibility (Figure 7J).[177]

Integrated systems

Driven by the rapid progress in fields such as intelligent health monitoring, the Internet of Things, human-machine interaction, and soft robotics, numerous ideas around intelligent perception, medical monitoring, data transmission, and output management have been transformed into reality, all of which are implemented through system-level integration, forming a strong technical argument for the commercialization of devices. In this section, we summarize representative application scenarios achieved by combining energy harvesters or self-powered sensors with various functional components, aiming to provide insights and guidance for the future design of integrated self-powered wearable systems.

Intelligent perception and output management are important functions of advanced wearable electronic devices. Taking human body temperature management as an example, keeping the human body within an appropriate temperature range is crucial for comfort and safety. The integration of temperature-sensing unit and power consumption module enables continuous temperature sensing and corresponding thermal regulation, which shows great potential for application in scenarios such as thermal protection under polar or underwater conditions.[187] Wang et al. developed a flexible and sustainable personal thermoregulatory clothing system by integrating a flexible organic photovoltaic module and bidirectional electrocaloric devices, which allows 24 h of controllable and dual-mode thermoregulation with 12 h of sunlight energy input and extends the human thermal comfort zone from 22°C–28°C to 12.5°C–37.6°C with a fast thermoregulation rate (Figure 8A).[188] Although this work marks an important step toward the adoption of smart fabrics for personal thermal management without external power sources, substantial challenges remain with respect to washability and recyclability.

By integrating the data transmission module, the self-powered sensing unit can transmit various types of collected information (such as motion captured through TENGs, PENGs, and MEGs, as well as biomarkers captured through BFCs [Figures 8B and 8C]) to mobile devices or cloud-based AI systems for real-time analysis, thereby providing practical solutions for personalized treatment.[189,190] For example, Wang et al.[196] reported the first fully wearable, self-powered sensor driven by multiplexed green biofuels. By integrating a microfluidic unit, sensing elements, laser-induced graphene electrodes, and custom electronics, it enables highly sensitive, non-invasive detection of glucose and alcohol across multiple biofluids including sweat, breath, saliva, and tears while simultaneously tracking daily activities such as temperature, pressure, and touch. However, such enzyme-based BFCs tend to suffer from performance degradation over long-term operation due to enzyme inactivation. By contrast, spore-based microbial fuel cells offer a promising route to overcome this limitation due to the dormancy characteristics of spores. Alarms for harmful gas concentrations and temperature in the working environment can also be achieved through a similar integration (Figure 8D).[191]

In order for wearable devices to perform specific actions or provide feedback, thereby enabling human-computer interaction, it is necessary to systematically integrate actuator units. For instance, by utilizing magnetoelastic responses, muscle movements in the throat can be captured and converted into electrical signals to drive actuators, thereby achieving assisted vocalization (Figure 8E).[192] In contrast to the unidirectional information flow in human monitoring, human-computer interaction systems generally involve the machine-to-human communication. For example, haptic feedback from machine provides direct and intuitive physical cues in human-machine interaction. Xu et al.[193] demonstrated a self-powered electrotactile textile haptic glove based on TENGs and gas breakdown discharge, which holds great potential for tactile feedback and control in prosthetic applications (Figure 8F). Looking ahead, the development of advanced integrated human-machine interaction systems continues to face enduring technical challenges, including improving environmental robustness and applicability, lowering fabrication and deployment costs, simplifying device architectures and manufacturing processes, and enhancing user adaptability and flexibility.

Bionic electronic devices aim to emulate the sensing, signal processing, and adaptive capabilities of biological systems, enabling next-generation neuromorphic and intelligent electronics.[197] In particular, highly distributed artificial synapses can be effectively driven by portable and ubiquitous power sources, facilitating the integration of self-powered, distributed, and wearable electronics. Commonly, artificial synapses include a self-activation component, a synaptic transistor, and a functional circuit (Figure 8G).[194] The self-activation component is used to capture human signals, convert them into electrical signals, and then send the electric signals into a synaptic transistor. The propagation of electrical signals through the synaptic transistor can be regarded as an in-sensor computation, which enables information compression and consequently reduces the power consumption associated with external communication.[198]

By combining energy harvester modules, sensing units, and drug delivery components, it is possible to achieve maintenance-free intelligent drug administration. Advanced medical implants and wearable patches implementing such systems have already been reported.[199,200] Furthermore, in the medical field, self-powered devices also offer promising solutions for portable electrotherapy-based wound treatment. Figure 8H demonstrates a flexible electrotherapy dressing that which integrates MIEGs, an antibacterial hydrogel dressing, and concentric molybdenum (Mo) electrodes to provide a self-sustaining electrical supply and potent antibacterial activity.[195] Nonetheless, MIEGs and other self-powered electrotherapy platforms remain constrained by limited and fluctuating energy output, device stability, and long-term biocompatibility, highlighting the need for improved materials and integration strategies.

In complex application scenarios, self-powered wearable devices are increasingly dependent on both multifunctionalization and integrations. Future research should focus on the development and application of advanced functional materials, while also addressing cost reduction and large-scale production. Moreover, advanced interconnection and integration strategies

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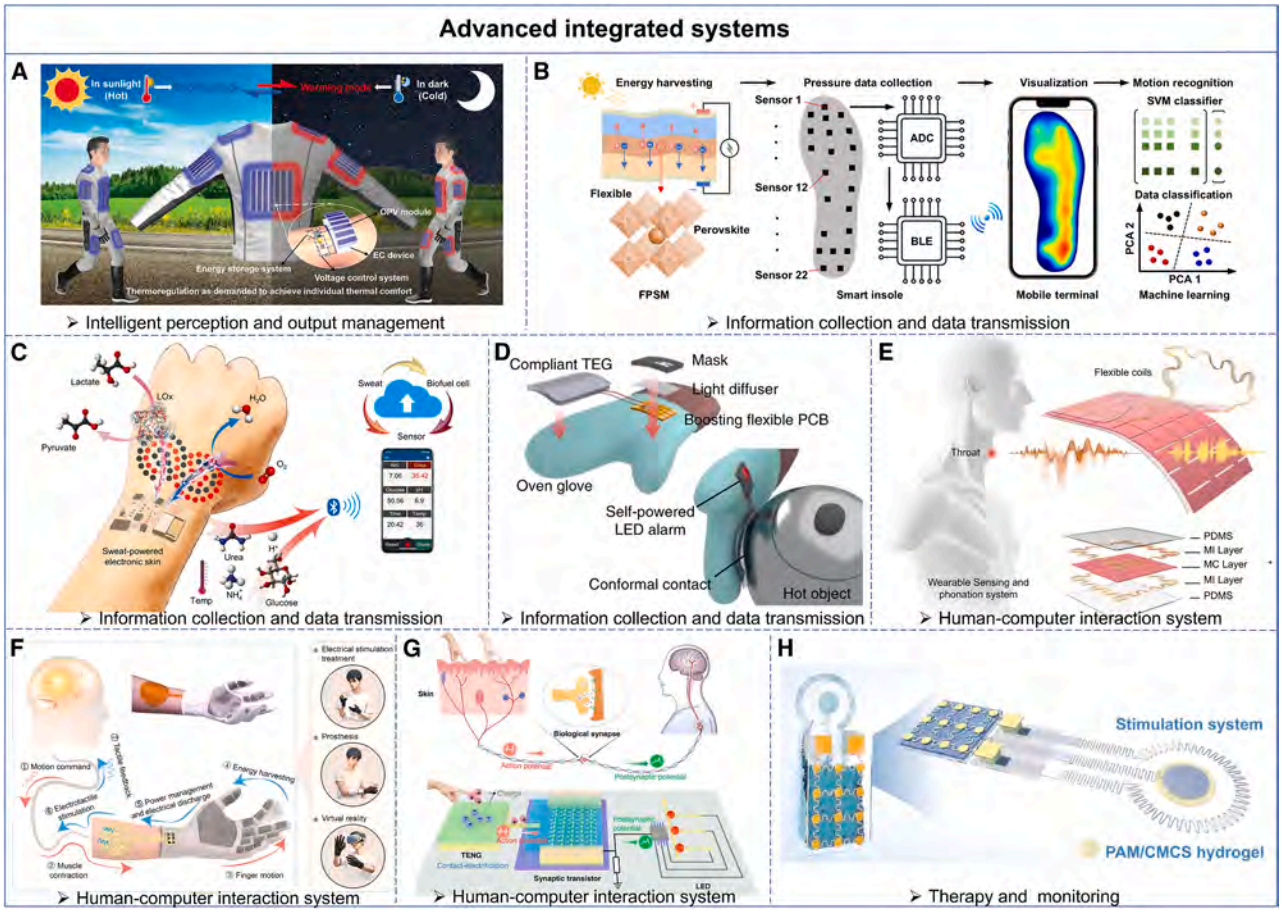

Figure 8. Multi module systematic integration for energy harvesting, sensing, data transmission, and health monitoring

(A) Working schema when wearing intelligent fabric to achieve individual thermal comfort in a cycle between hot (in sunlight) and cold (in dark) environments as demanded.[188]

(B) The workflow of the smart insole system includes energy harvesting, pressure data collection, visualization of plantar pressure distribution on a mobile terminal, and data classification using the learning model.[189]

(C) Schematic illustrating a wearable sweat sensor system that integrates human motion energy harvesting, signal processing, microfluidic-based sweat biosensing, and Bluetooth-based wireless data transmission to a mobile user interface for real-time health status tracking.[190]

(D) Schematic illustration of hot surface warning gloves with a self-powered LED system and light masking packages.[191]

(E) Illustration of wearable sensing and phonation system attached to the throat.[192]

(F) Illustration of a comfortable-to-wear self-powered electrotactile textile haptic glove and its applications.[193]

(G) Schematic illustration of bionic principles and basic structure of artificial afferent.[194]

(H) Schematic illustration of autonomous, moisture-driven flexible electrogenerative dressing designed to accelerate wound healing.[195]

are critical for achieving stable operation, miniaturization, and reliable performance of integrated systems.

CONCLUSION AND OUTLOOK

Self-powered wearable electronics have attracted significant attention owing to their portability, intelligence, and integration, which facilitate the development of efficient health monitoring, environmental perception, human-machine interaction. The exceptional flexibility is essential for self-powered wearable devices, as it directly influences their performance and comfort. To meet the diverse requirements of various application scenarios, it is crucial to impart characteristics such as ice resistance and self-healing capabilities to the devices. This review provides a comprehensive overview of two distinct strategies for the development of efficient self-powered wearable devices: flexible design and functional design. Flexible design includes the design of intrinsically flexible materials and structural flexibility design. The flexible materials are first discussed including conductors, semiconductors, and insulators, which exploit their inherent flexibility to enable wearable applications. Their collaborative designs across multiple fields are highlighted to argue the necessity of this strategy. Then, the design of specialized structures is examined to enhance properties such as flexibility,

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mechanical performance, and power density. Additionally, this review also summarizes the modification methods that enable devices to achieve specialized functionalities for different application scenarios, addressing specific operational demands, including freeze resistance, high transparency, thermal stability, and self-healing capabilities. Finally, integrated systems for wearable products in different fields are reviewed.

To advance the practical application of self-powered wearable devices, future research should focus on the following directions.

(1) Material innovation: to effectively support the high integration, miniaturization, and enhanced wearability of self-powered wearable devices, the material design strategies should focus on functional composites (e.g., synergistically incorporating energy-harvesting, energy-storage, and sensing functionalities into a single material system via composite engineering of low-dimensional nanomaterials with elastic matrices such as hydrogels or biodegradable polyesters), nanostructured and lightweight material construction (e.g., electrospun nanofibrous membranes) to reduce device thickness/weight while maintaining mechanical flexibility and conformability to human skin, and biocompatible/breathable material selection (e.g., porous elastomers and moisture-permeable composites) to mitigate discomfort from long-term wear. The underlying optimization mechanism of collaborative design of ''conductor-semiconductor-dielectric'' multi-materials remains to be further elucidated as current research is often limited to finite exhaustive matching and lacks mechanistic insights, which are critical for transcending the conventional trade-offs between mechanical compliance and electrical performance.

(2) Functional synergy: further improving the energy conversion efficiency and power density of devices is one of the crucial directions for future enhancements. This can be achieved through the development of novel composite materials and the integration of additional functionalities. For instance, the integration of flexible radiative cooling materials at the cold end of TEGs can be employed. These materials have the capacity to reflect solar radiation while emitting thermal energy in the form of infrared radiation. This mechanism facilitates the dissipation of heat to cold space, thereby enhancing the temperature gradient and subsequently improving the thermoelectric conversion efficiency.

(3) AI empowerment: with the rapid development and convergence of AI and materials science, using machine learning to guide material design represents a significant direction for future progress. By optimizing parameters to select the most suitable configurations, high flexibility, comfort, and long lifespan can be achieved in flexible devices. Meanwhile, AI can integrate additional intelligent functionalities, enhancing the device's smart interaction with both the environment and the human body. This diversified design approach will better accommodate personalized needs, paving the way for more adaptive and multifunctional wearable devices.

(4) Sustainable biocompatibility: with the increasing awareness of environmental protection, it is essential to place greater emphasis on the biocompatibility, environmental friendliness, and sustainability of the materials used in self-powered wearable devices. This will help minimize environmental pollution and further promote the development of green self-powered wearable devices.

In conclusion, with the continuous advancement of material design and micro-/nanofabrication techniques, the challenges faced by self-powered wearable electronic devices are expected to be gradually overcome. In the future, these devices hold significant potential to drive substantial progress in fields such as health management, environmental monitoring, and virtual reality.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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