



Smart Fibers for Self-Powered Electronic Skins

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Abstract

Smart fibers are considered as promising materials for the fabrication of wearable electronic skins owing to their features such as superior flexibility, light weight, high specific area, and ease of modification. Besides, piezoelectric or triboelectric electronic skins can respond to mechanical stimulation and directly convert the mechanical energy into electrical power for self-use, thereby providing an attractive method for tactile sensing and motion perception. The incorporation of sensing capabilities into smart fibers could be a powerful approach to the development of self-powered electronic skins. Herein, we review several aspects of the recent advancements in the development of self-powered electronic skins constructed with smart fibers. The summarized aspects include functional material selection, structural design, pressure sensing mechanism, and proof-to-concept demonstration to practical application. In particular, various fabrication strategies and a wide range of practical applications have been systematically introduced. Finally, a critical assessment of the challenges and promising perspectives for the development of fiber-based electronic skins has been presented.

Keywords Smart fibers · Electronic skins · Self-power · Piezoelectric effect · Triboelectric effect

Introduction

The largest organ in the human body, the biological skin, can correctly detect external stimuli like pressure, strain, temperature, humidity, etc., and quickly transmit these signals into the brain so that humans can actively react to these stimuli and respond to them [1]. Bionic skin known as “electronic skin” can mimic or duplicate the fundamental properties and capacities of human skin, typically in addition to other extra functionality [2]. In particular, electronic skins with pressure sensing ability have extended promising potential in health monitoring, artificial prosthetics, and smart robotics, since they can precisely distinguish the texture and shape

of external objects and even record real-time physiological information like heart rate and pulse wave from the human body [3]. These conformal skin-adhesive electronics can transform physical impulses into quantifiable measurements, which can serve as a solid foundation for disease surveillance and prevention [4, 5]. Additionally, some electronic skins give robotics and prosthetics the ability to alter and detect their surroundings. To meet the growing demand for practical applications, researchers from all over the world have created a variety of advanced electronic skins that are ultra-thin, ultra-conformal, highly sensitive, robust, and biocompatible. Despite the enormous advances and accomplishments made in tactile sensing electronic skins, there are still significant obstacles to be overcome in the areas of material selection, development of long-lasting power sources, and subsequent practical applications.

Electronic skins are first required to adhere seamlessly to biological skins or on the curvilinear surface of robotics and prosthetics to prevent them from delaminating from each other. Additionally, electronic skins are subjected to prolonged stresses of diverse nature, which may cause damage to the electronic device and shorten its lifespan. Therefore, it is of substantial great significance to select the constructing raw materials with the required characteristics such as excellent flexibility and desired stretchability. Currently,

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most reported flexible and stretchable electronic skins are made from airtight plastic films or dense elastic rubbers serving as the electrodes, substrates, and sensing layers [6–8]. Despite having exceptional mechanical stability, these electronic skins are not permeable to air or water vapors, and they may irritate human skin over time, rendering them unsuitable for widespread usage on human skin. Thus, the discovery of comfortable and breathable raw materials for the construction of electronic skins has become necessary to facilitate their uninterrupted operation and sustainable development. In contrast, attractive fiber materials are thought to be exciting and promising options to build intrinsically air-permeable electronic skins. Fiber-based technologies allow the human skin to breathe freely to satisfy the physiological necessity for thermal-wet comfort because of the interconnected network offered by numerous small pores constricted within fibers. Additionally, fiber materials with a high degree of flexibility and softness can be blended into or attached to any desired surface in a seamless and conformable manner. These easily processed, readily available materials can be directly woven into fabrics or clothes, making them accessible and simple to wear. Additionally, because fiber materials come in a variety of morphologies and can have their structures altered chemically, fiber performance can also be improved. Owing to the recent advancements in nanoscience and microfabrication technology, diverse fiber structured electronic skins are increasingly developed and nowadays it has become a cutting-edge research direction in the field of smart wearable electronics [9–13].

Electronic skins can be conventionally categorized into capacitive [14], piezo-resistive [15], piezoelectric [16], and triboelectric [17] electronic skins based on their sensing mechanism and working mode. Due to their reasonably consistent sensing performance and sophisticated preparation procedures, piezo-resistive and capacitive electronic skins are the ones that are used the most frequently. Electronic skins based on the piezo-resistive and capacitive effects, however, require extra power supply components, such as batteries, which are large and heavy and require frequent recharging or replacement, making them much more unfavorable in continuous operation [18]. The inherent hurdle that significantly restricts the extensive long-term application of electronic skins is its heavy dependency on external power supplies. Fortunately, piezoelectric and triboelectric electronic skins can gather ambient mechanical energy to power themselves without battery components, in addition, to quickly and precisely responding to dynamic situations [19]. Utilizing self-powered sensing technology seems to be the most sensible solution to simplify the entire sensing system while also improving the microminiaturization and flexibility of the electronic skins. Therefore, the combination of smart fiber materials and self-powered mechanisms is an advantageous approach to develop new conceptual electronic

skins with high breathability and flexibility. Figure 1 illustrates the characteristics and applications of self-powered electronic skins constructed with fiber materials.

In this review, the functional building materials in the current electronic skin system have first been introduced from three aspects, including a flexible substrate layer, a conductive electrode layer, and an active sensing layer. This review aims to present the current state of the art of self-powered electronic skins constructed with fiber materials and present clear design pathways for future wearable electronics. Following that, the working modes, representative materials, and application scenarios for the piezoelectric and triboelectric electronic skins have been summarized. A thorough analysis of the structural design and fabrication methods for self-powered fiber-based electronic skins follows. Finally, fresh perspectives have been offered on the solution of the problems currently present in fiber-based electronic skins and their potential future solutions. The discussion in the end will shed light on the future of wearable electronics in the Internet of Things era and further encourage the development of smart fibers in academia and industry.

Functional Building Materials

The development of wearable electronics has been aided by numerous advances in material science and process engineering, which have sparked an increase in demand for electronic skins with a range of functionalities, including high sensitivity, dependable safety, good biocompatibility, stable mechanical property, ultra-flexibility, non-toxicity, and eco-friendliness. The choice of practical building materials with integrated mechanical and functional properties required by electronic skins, whose relevance is comparable to that of blood circulation to human life, is one crucial consideration throughout the manufacturing process of electronic skins. Additionally, the qualities and traits of building materials define the right applications for them. Therefore, it is crucial to have a thorough understanding of functional materials and the appropriate preparation techniques. A fundamental rule that must be followed is that the original features and performance of electronic skins must not be compromised, regardless of the type of construction materials used. Construction materials can be broadly categorized into three groups, namely substrate layer, conductive electrode layer, and active sensing layer, from the perspective of functional classification. The next section of this article is devoted to reviewing a thorough comparison of the most often utilized functional building materials.

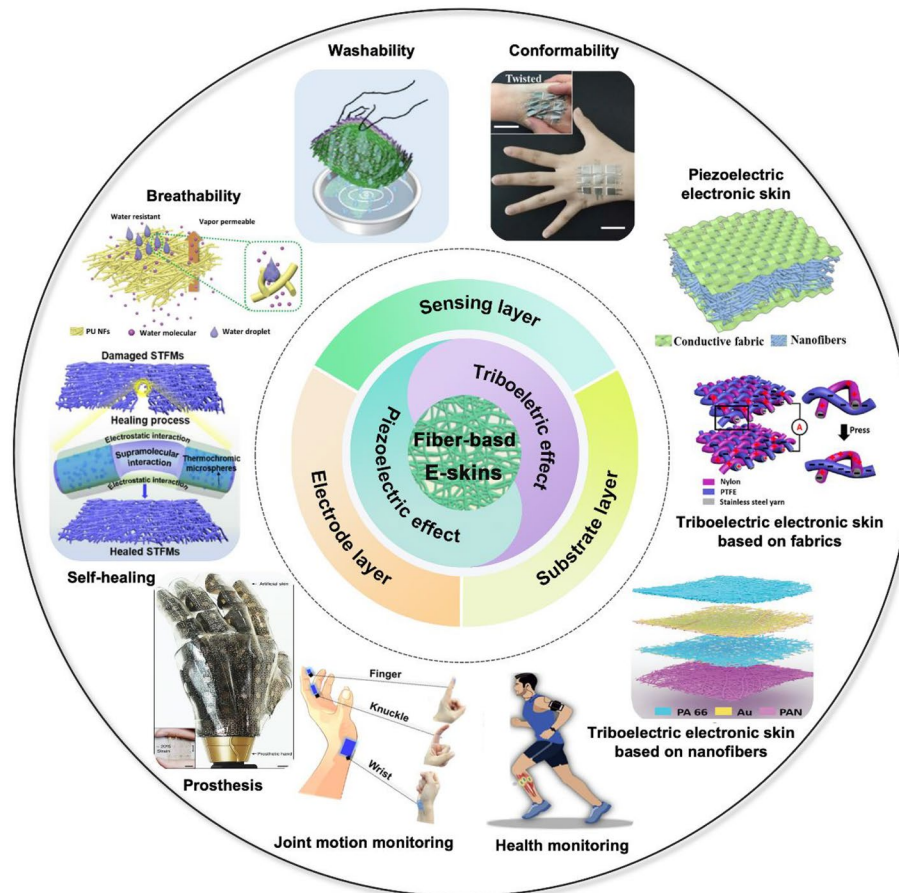


Fig. 1 Characteristics and applications of self-powered electronic skins constructed with fiber materials. “Self-healing properties”. Reproduced with permission [20]. Copyright 2022, John Wiley and Sons. “Breathability”. Reproduced with permission [18]. Copyright 2019, John Wiley and Sons. “Washability”. Reproduced with permission [21]. Copyright 2019, Elsevier. “Conformability”. Reproduced with permission [22]. Copyright 2020, Elsevier. “Piezoelectric electronic skin”. Reproduced with permission [22]. Copyright 2020,

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Substrate Layer

The substrate layer, also referred to as the supporting layer, is a structure that holds up the electronic skin and acts as a link between it and human skin or soft robots. It gives the constructed object excellent flexibility and mechanical strength so that it can maintain its original function even when bent or pressed [27, 28]. Selecting acceptable and advantageous substrate layers with both great mechanical properties and transduction performance is a crucial issue that should be taken into consideration due to the complicated and changeable morphological surface of the electronic device. Additionally, flexible and stretchable substrates can be coated or doped with nanoscale conductive and active sensing materials to fabricate conductive electrodes or sensing functional layers with high flexibility and mechanical stability using

dip-drying [29, 30], spin-coating [31], electroless plating [32], and vapor deposition [33]. Primary substrate materials can be divided into four categories based on their various architectures and physical characteristics. These categories include plastic film materials, elastic rubber materials, fiber-based materials, and paper. Table 1 compares the characteristics of substrates that are frequently used to make electronic devices. The next part includes a complete summary and comprehensive comparison, as well as information on the benefits, drawbacks, uses, and production processes.

Film Materials

In comparison to stainless steel substrates with high mass density and non-deformability, plastic film materials are much more advantageous and promising in a variety of

Table 1 Characteristic comparison of commonly used substrates for electronic devices

Substrate	Representatives	Stretchability	Young's modulus	Breathability	References
Human skin	n/a	100%	0.5–1.95 MPa	Intrinsically breathable	[34]
Film materials	PI, PU, Ecoflex	20–1000%	50 kPa ⁻¹ GPa	Airtight	[28, 34, 35]
Rubber materials	PDMS, SEBS	40–4000%	0.5–3 MPa	Airtight	[28, 34]
Porous polymers	Porous PU/PDMS	60–320%	n/a	Extrinsically breathable	[36, 37]
Fiber materials	Textile, nanofibrous membrane	50–500%	n/a	Intrinsically breathable	[18, 38, 39]

applications for flexible electronic skins [34]. This is because they naturally possess mechanical flexibility, durability, and light weight. Plastic film substrates also have several advantages, including easy device integration, compatibility with vast areas, processability, low cost, and seamless heterogeneous integration, which makes them widely used in the field of electronic skins [40]. Polyimide (PI) [41], polyethylene terephthalate (PET) [42], polyurethane (PU), polyethylene naphthalate (PEN) [43], and polyetherimide (PEI) [40] are the most common examples of representative plastic film materials. Due to its high tensile strength of about 231 MPa and high thermal and chemical resistance with a glass transition temperature of between 360 and 410 °C, which enables the device to withstand thermal cycling and chemical damage [44, 45]. PI is one of the most commonly used plastic film substrates for electronic skins. Yellow color is an intrinsic barrier that limits PI film's application in optical and transparent electronic devices. Researchers have worked on improving the transparency of PI films, while preserving its original mechanical and chemical properties, to find a solution to the aforementioned issue. A more extensive electronic application platform for PI material has recently become feasible, by the fabrication of transparent PI film using approaches such as molecular structure design [46]. Another common plastic film substrate is transparent PET film, which has substantial strength, dimensional stability, good chemical resistance, a moderate Coefficient of Thermal Expansion (CTE), cheap cost, and plentiful resource availability [42, 47]. In reality, biological skin or tissue is not only stretchable but also flexible (the human brain is 10% elastic, the human heart is 20–35% elastic, and the human skin is around 100% elastic) [1]. Since periodic strain in numerous directions can damage electronics, a substrate with good stretchability can shield them from those damages. It is also commonly accepted that PU with high stretchability is an ideal substrate for electronics. Additionally, the nontoxic PU film can be used for implantable healthcare monitoring applications because of its high tensile strength, waterproofing, flexibility, and biocompatibility [28, 48]. Ecoflex is a new type of stretchable plastic film that exhibits excellent flexibility with Young's modulus of 50–100 kPa and a high stretchability of up to 1,000% [28, 35].

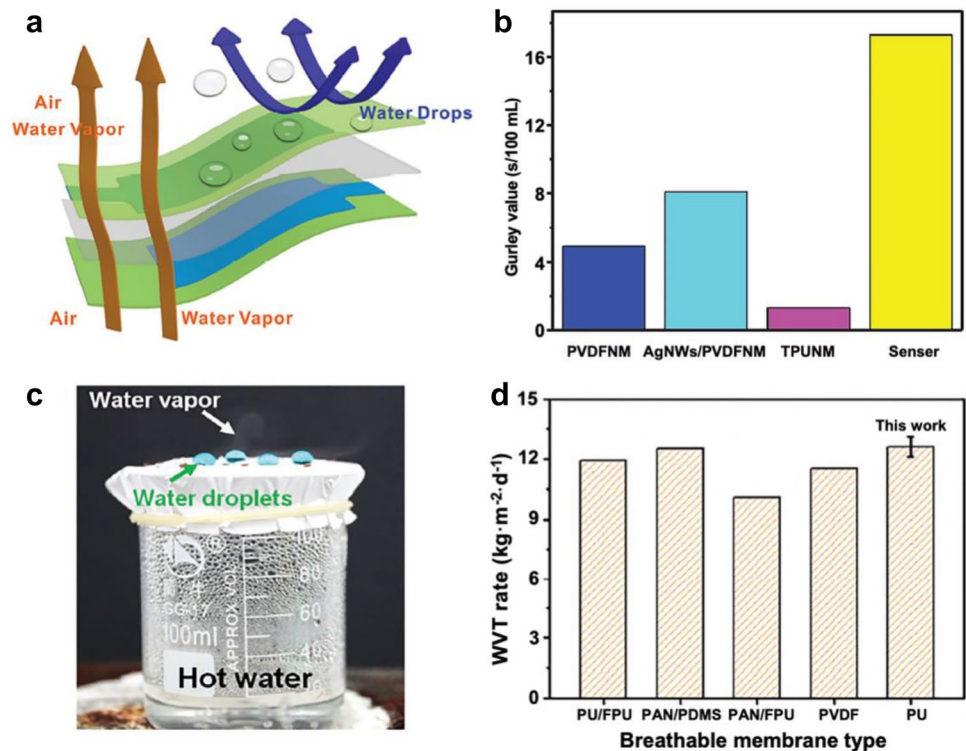
Rubber Materials

Rubber-based materials are a promising replacement for conventional plastic film substrates, with stretchability ranging from 40 to 4000% [34]. The stretchy substrate of sensing electronics has primarily been made of polydimethylsiloxane (PDMS), a transparent, flexible, biocompatible, thermally and chemically resistant, and commercially available elastic polymer [5, 44]. With Young's modulus of 0.5–3 MPa and a strain of up to 200%, the PDMS substrate has exceptional mechanical and thermal stability [28]. Additionally, it is possible to tune the mechanical properties of chemically crosslinked PDMS by varying the quantities of crosslinking agents or the crosslinking temperature [28]. Additionally, it is possible to alter the surface features of PDMS to achieve particular chemical or mechanical qualities [35]. Poly(styrene-co-ethylenebutylene-co-styrene) (SEBS) is also widely applied as a stretchable substrate, which is a type of physically crosslinked elastomers with an elastic limit of about 700% [35].

Fiber Materials

The plastic films and elastic rubbers listed above are often dense materials with low air permeability, which could be uncomfortable for human skin when worn for an extended period. Due to their exceptional breathability and light weight, a variety of innovative electronic gadgets based on porous substrate/platforms are being developed to successfully address this issue. Porous polymers and fiber materials make up the majority of porous substrates that have been studied. Representative porous polymers that can be created include porous PDMS and PU [36]. Other porous polymers include gas foaming, solvent casting/particulate leaching, and template technique. Their preparation procedures take a lot of time and effort. As an alternative, fiber materials with inherent interconnected porous structures give the electronic skins a high air or water vapor permeability (Fig. 2a), ensuring that the devices have good thermal-wet comfort without the need for additional processes to create a lot of pores within substrates [18]. For example, Yang et al. [38] developed a sensitive and breathable sensor constructed with

Fig. 2 **a** The illustration of waterproof and breathable properties of the fiber-based electronic skin. Reproduced with permission [38]. Copyright 2017, John Wiley and Sons. **b** The Gurley value of different fiber materials. Reproduced with permission [38]. Copyright 2017, John Wiley and Sons. **c** A photograph demonstrating the excellent waterproof and breathable properties of the fiber-structured electronic skin. Reproduced with permission [18]. Copyright 2019, John Wiley and Sons. **d** The water vapor transmittance rate of diverse hydrophobic PU NFs. Reproduced with permission [18]. Copyright 2019, John Wiley and Sons



nanofibrous membranes, which possessed a high-pressure sensitivity of 4.2 kPa^{-1} and excellent breathability with Gurley value (Gurley value presents the time of 100 mL air to pass through the sample, and it reflects the difficulty of air to pass through the membrane) up to $17.3 \text{ s}/100 \text{ mL}$ (Fig. 2b). Similarly, Li et al. [18] developed a breathable waterproof electronic skin with a water vapor permeability of up to $10.2 \text{ kg m}^{-2} \text{ d}^{-1}$ (Fig. 2c, d). Fiber-based materials primarily consist of conventional fabrics and nanofibrous membranes, depending on the structural designs and manufacturing processes [17, 49]. Fabrics are one type of useful material that serves as a flexible supporting substrate and may be produced on a wide scale using low-cost techniques including weaving, braiding, knitting, and melt-blowing. Additionally, fabric substrates give electronic skin a platform that can be seamlessly integrated with clothing, which is advantageous for the creation of smart wearable technology [21]. In contrast, nanofibrous membranes are usually prepared through the electrospinning technique, which exhibits a higher porosity but lower mechanical strength. Nanofibers with a high specific surface area are commonly combined with conductive or sensing materials to further improve the conductivity of electrodes or the sensitivity of the functional sensing layer. For instance, Deng et al. [50] added ZnO nanoparticles into polyvinylidene fluoride (PVDF) spinning solution and fabricated PVDF/ZnO nanofibers with cowpea-structure, which showed a bending sensitivity of 4.4 mV deg^{-1} and a pressing sensitivity of 0.33 V kPa^{-1} . More importantly, fiber

materials are easily accessible and low cost, making them ideal materials to serve as flexible substrates for electronic skins.

Paper Materials

Paper, as an environmentally friendly biodegradable material ubiquitously utilized in our daily life, can serve as a flexible substrate attributing to its high flexibility, substantially low cost, breathability, and environmental friendliness [51]. The high degree of surface roughness, porous structure, and optical opaqueness of paper that is often used naturally restrict the paper that houses electronic skins to some extent [52]. Surface modifications, such as chemical vapor deposition and plasma atomic layer deposition, have been extensively investigated to address these issues. As an alternative, nanocellulose paper with a smooth surface and built-in optical transparency has been developed for electrical devices and has shown significant promise as a flexible substrate. An all-nanocellulose paper-based flexible pressure sensor with a sensitivity of 1.5 kPa^{-1} and the ability to sustain respectable sensing performance in a bent condition was created by Gao et al. [15].

Conductive Electrode Layer

By functioning as the electronic skins bridge, a conductive electrode layer can transmit electrical signals and link

external circuits. It is not an exaggeration to say that a good electronic skin's conductivity should be comparable to a person's normal blood flow because effective transmission depends on the material's conductivity. Electrical conductivity and resistivity, two crucial indicators, can be used to evaluate conductivity, a property of conductive materials [53]. Selecting materials with superior conductivity, high stretchability, and stability is a successful and popular technique for developing sensing transduction devices. The most often reported conductive materials at the moment include carbonaceous materials, conductive ceramics, metals and their derivatives, conductive polymers, and liquid metals [54].

Metals

Metals, such as Ag, Cu, and Au, as abundant and widely used natural resources on the earth, were first utilized as conductive materials in the field of electronics owing to their high electrical conductivity, strong mechanical stability and durability, dimensional stability. However, traditional metals have a high weight and are inherently non-transparent, brittle, and rigid, thus making them unfavorable for flexible, light weight, and transparent wearable electronic devices. There are two main methods to address this challenge, namely strain engineering and nanocomposites [55]. To create wavy structures for flexible and stretchable conductors via strain engineering, prestrain-release-buckling is a key technique. For instance, Wu et al. [56] prepared PDMS composite film with Ag nanowires (Ag NWs) using the sacrificial substrate approach (Fig. 3a). Following the release of the prestretched substrate, an Ag NWs/PDMS composite film was applied to the Eco-flex prestrained substrate. Finally, a highly stretchable and flexible conductive electrode was created using an Ag NWs/PDMS composite film that had partially delaminated from the substrate into a wavy structure. This electrode exhibited exceptional stability and could maintain a relatively constant resistance (less than 3%) even when subjected to 100% of the strain. Another important method for making conductive electrodes adaptable to numerous pressure and stretch cycles is by incorporating conductive materials within a flexible and elastomeric matrix [55].

Conductive Polymer

Conductive polymers have been developed and investigated by researchers for functioning as conductive electrodes in sensing electronics owing to their numerous favorable characteristics, including light weight, good flexibility, reliable electrochemical stability, solution processibility, and favorable electrical and mechanical properties [57]. A group of conductive polymers including polypyrrole (PPy)

[57], poly[3,4-(ethylenedioxy) thiophene] (PEDOT) [58], Poly[3,4-ethylenedioxythiophene]/poly[styrenesulfonate] (PEDOT:PSS) [59], and polyaniline (PANI) [57] have been extensively studied. Specifically, PEDOT: PSS, with good water solubility, high conductivity, and good thermal and environmental stability, is the most widely employed conductive polymer [54]. Zhou et al. [60] reported a mechanically stable and highly conductive aerogel, assembled from cellulose nanofibrils and PEDOT: PSS, which demonstrated a conductivity of 0.12 S m^{-1} .

Carbon Materials

Carbon allotropes such as carbon black (CB), carbon nanotubes (CNTs), graphene, graphene oxide (GO), and reduced graphene oxide (rGO), have been extensively utilized as conductive electrodes owing to a myriad of merits including high electrical and thermal conductivity, outstanding environmental stability, and large surface area [54]. With their excellent intrinsic electrical conductivity, superior mechanical attributes, optical transparency, and high thermal stability, CNTs, as one-dimensional nanomaterials have made significant progress in the field of electronics. CNTs can be created by arc discharge, chemical vapor deposition, and laser ablation [61]. Two-dimensional graphene is another representative carbonaceous electrode that is made up of thin carbon atoms organized in a honeycomb lattice [61]. Ma et al. [62] screen-printed graphene ink onto the PVDF film serving as the electrode (Fig. 3b). Using this electrode, a triboelectric piezoelectric-pyroelectric multi-effect sensor was created, with a pressure and temperature sensitivity of $0.11 \text{ V/}^\circ\text{C}$ and 0.092 V/kPa , respectively. Interestingly, as depicted in Fig. 3c, laser-induced graphene foams have demonstrated remarkable potential for the fabrication of conductive electrode layers due to their superior electrical conductivity, high porosity, and strong mechanical flexibility [63, 64]. Besides, laser-induced graphene with predesigned patterns can be directly prepared on various carbon materials with controllable microstructure [65]. However, the currently applied fabrication methods can only produce thin laser-induced graphene on carbon substrates, leading to a lower volumetric capacitance.

Liquid Metals

Liquid metals, for instance, gallium and its alloys, are appealing and promising conductive alternatives that offer an integration of conductivity and stretchability within one material, ideal for the fabrication of soft and flexible conductive electrodes. Gallium-based eutectic alloys possess myriads of favorable characteristics, including high electrical conductivity, liquid state at ambient temperature, low Young's modulus, high bendability, high surface tension,

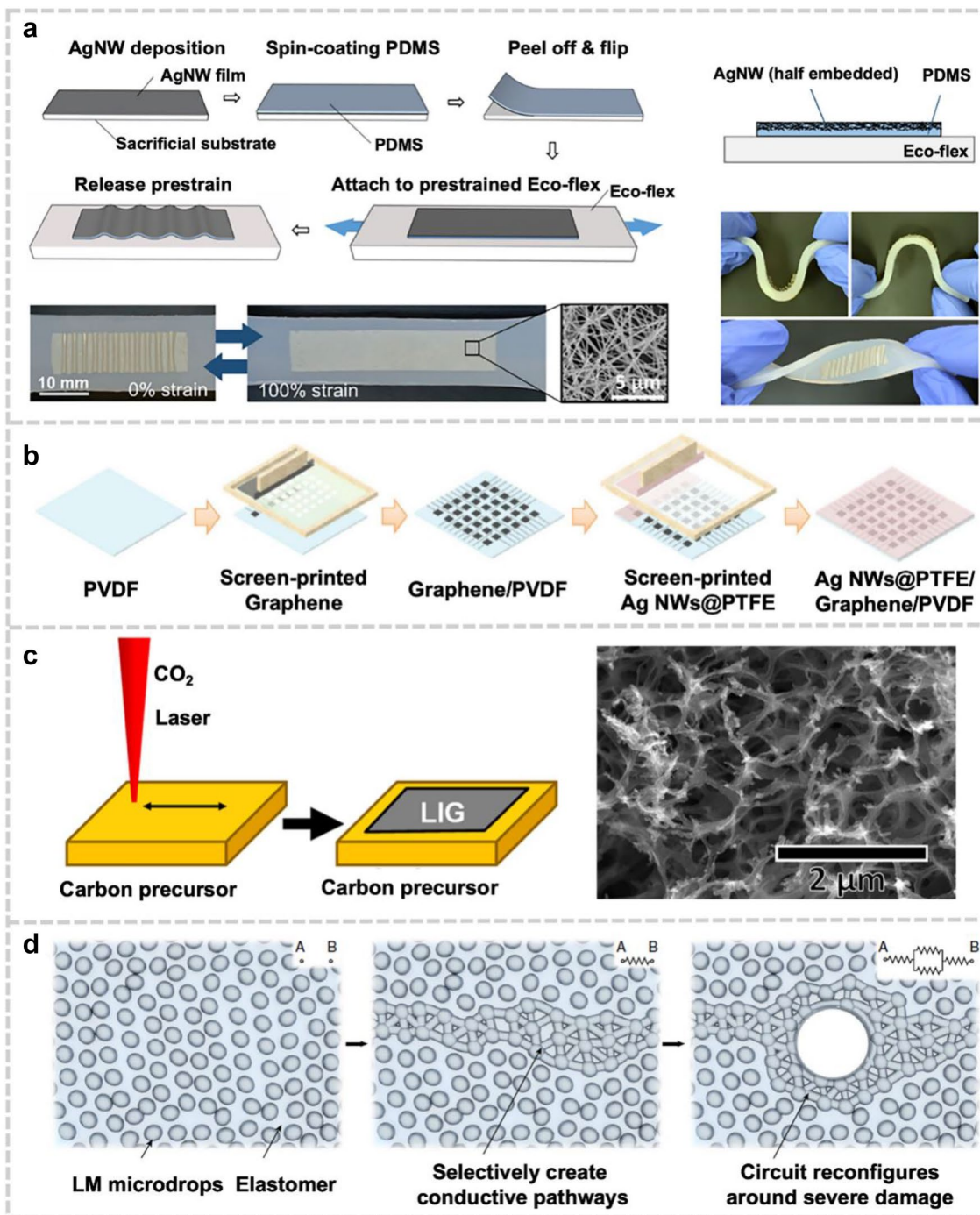


Fig. 3 Representative non-fibrous conductive materials. **a** Highly stretchable conductive Ag NWs/PDMS composite film. Reproduced with permission [56]. Copyright 2020, American Chemical Society. **b** Graphene/PVDF electrode layer fabricated via screen-printing. Reproduced with permission [62]. Copyright 2019, Elsevier. **c** Schematic representation of lasing a carbon precursor to synthesize

laser-induced graphene and SEM image of the microstructure of laser-induced graphene on the PI. Reproduced with permission [64]. Copyright 2019, American Chemical Society. **d** Self-healing mechanism of liquid metal microdroplets embodied electrode. Reproduced with permission [68]. Copyright 2018, Springer Nature

low toxicity, and almost negligible vapor pressure [66, 67]. They also have excellent thermal stability and low toxicity. More importantly, gallium-based liquid metals can

be directly incorporated into elastomers, demonstrating significant and enormous potential in the applications of soft sensors and electronic skins. These elastomers can be

easily used as conductive electrodes or circuits with flexible, stretchable, self-healing, and shape-reconfigurable features [68]. An extremely flexible circuit connection was created by Markvicka et al. [68] using liquid metal droplets embedded in a soft elastomer. The droplets can even self-heal after considerable damage. The self-healing mechanism of this flexible circuit has been shown in Fig. 3d. Besides, benefiting from excellent liquidity and metallic property at room temperature, numerous developed printing methods have been adopted in fabricating flexible liquid-metal-based conductive electrodes, including direct painting or writing, high-resolution nanoimprinting, and 3D printing techniques [69, 70]. Despite several merits, there are still some challenges in the application of liquid metals, such as high cost and the requirement of encapsulations, that need to be addressed [70].

Fiber-based Conductive Materials

Along with the aforementioned flexible conductive electrodes, other examples of electrodes that combine high conductivity and exceptional deformability are conductive fabric and nano-fibrous membrane. To impart metallic conductivity to fabrics, conductive materials including CNTs, Ag NWs, and graphene are coated or deposited on their surface. For example, Chen et al. [32] synthesized a PAN nanofiber membrane with palladium chloride, before electrolessly plating it with silver (Fig. 4a). The manufactured silver-plated PAN nanofibrous membrane provided the electrode for the capacitive sensor and had a high electrical conductivity. Zhu et al. [71] also developed a flexible and transparent PVDF/Ag NWs nanofibrous membrane as the electrode through a facile filtration and drying method (Fig. 4b). However, the conductive materials coated on the fabric or nanofibrous membrane can be easily detached and damaged. Alternatively, specifically structured conductive yarn, such as core-shell structured yarn can be processed into fabric through weaving, knitting, and braiding techniques, which imparts stable and high electrical conductivity to the conductive fabric. Li et al. [18] developed a flexible carbon nanofibrous membrane as the electrode. As shown in Fig. 4c, PAN nanofibers doped with SiO₂ nanoparticles were fabricated through the electrospinning method and the membrane was subsequently pre-calcined to carbonize. A flexible carbon nanofibrous membrane was obtained, following annealing under the atmosphere of high-purity nitrogen.

Active Sensing Layer

The active sensing layer is an extremely essential part of tactile sensing electronic skin, which can recognize tactile information as well as the skin. The selection of active sensing materials plays a critical role in highly sensitive

and broad-range responsive electronic devices. According to their sensing mechanisms and structural design, active sensing layer materials with self-powered capability can be categorized into two groups, namely, piezoelectric materials and triboelectric materials. The following section is a summary and comparison of active sensing materials, including representative materials, material selection criteria, and their merits and disadvantages.

Piezoelectric Materials

Since the discovery of piezoelectric effect, numerous piezoelectric materials have been widely reported to construct nanogenerators and self-powered systems. The primary metric used to describe the electromechanical characteristics of piezoelectric materials is the piezoelectric constant, which may be expressed as follows:

$$d_i = \left(-\frac{\partial D_j}{\partial T_j} \right) E$$

where d is the piezoelectric constant, D is the electric displacement vector, T is the applied stress, and E the electric field vector, respectively. In most cases, the degree of polarization determines the piezoelectric constant. Therefore, the higher the polarization degree of piezoelectric materials, the higher sensitivity, and energy conversion efficiency the piezoelectric device will demonstrate. The two types of piezoelectric materials that are most frequently employed are piezo-ceramics and piezoelectric polymers. Representative piezo-ceramics include ZnO, Pb[Zr_xTi_{1-x}]O₃ (PZT), BaTiO₃ (BTO), ZnS, and others. These materials have good piezoelectric performance, high strength, chemical inertness, and high energy conversion efficiency [47, 72, 73]. In general, phase structure and microstructure management by elemental doping or heterovalent-ion doping technique can be used to significantly improve the dielectric and piezoelectric properties of piezo-ceramics [74, 75]. It is important to keep in mind that piezoceramics have certain evident drawbacks, which limit their applications. These constraints include intrinsic mechanical brittleness, high weight, toxicity, and poor durability. To use them practically in flexible electronics, piezoelectric ceramics are frequently embedded in or on a flexible substrate. For instance, Shin et al. [76] formed a piezoelectric layer with synthesized Li-doped Ag NWs and mixed them well with PDMS solution, which was spin-coated on PET substrate. According to Fig. 5a, Yu et al. [73] added Ecoflex A-prat and Ecoflex B-prat to the mixture after adding BTO powder directly. Finally, using an applicator, flexible BTO/Ecoflex film was successfully fabricated.

Alternatively, piezoelectric polymers have been extensively applied in piezoelectrical applications owing to their

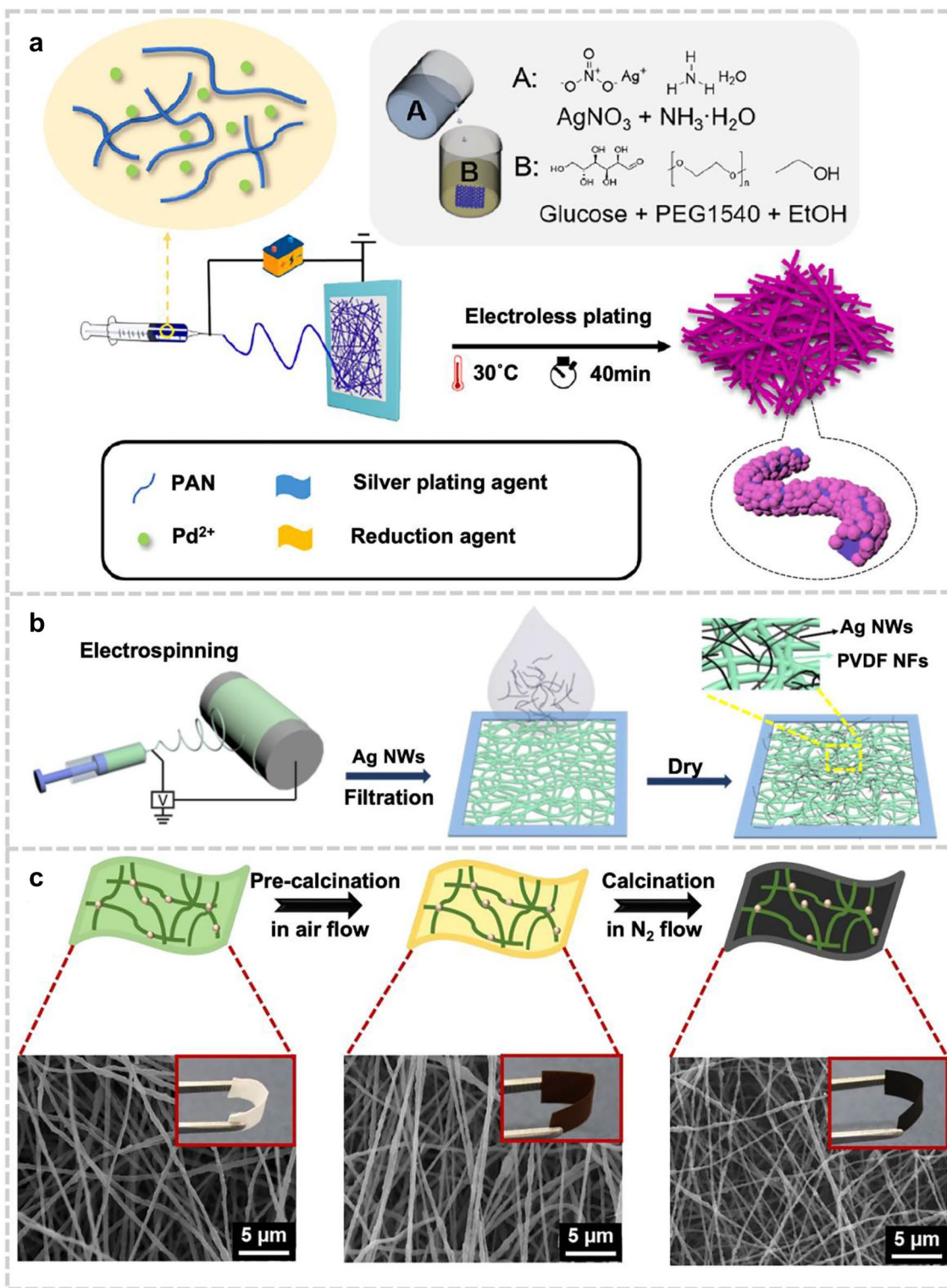


Fig. 4 Fiber-based conductive electrodes. **a** Silver-plated PAN nanofibrous membrane. Reproduced with permission [32]. Copyright 2022, Elsevier. **b** Transparent PVDF/Ag NWs nanofibrous membrane fabricated through facile filtration and drying method. Reproduced with

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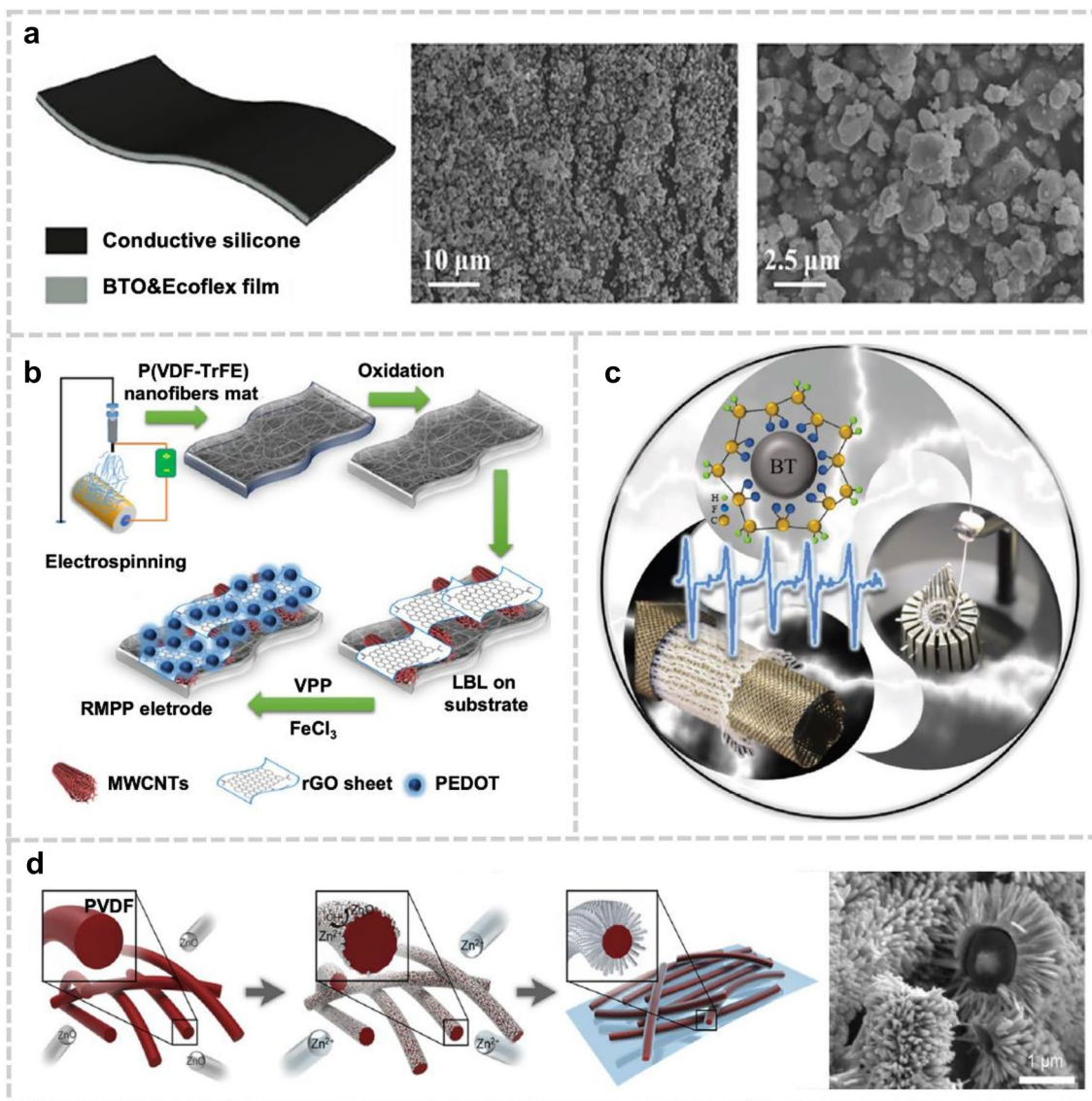


Fig. 5 Piezoelectric materials. **a** BTO/Ecoflex film fabricated via an applicator. Reproduced with permission [73]. Copyright 2020, Elsevier. **b** P(VDF-TrFE) decorated with PEDOT-CNT/rGO. Reproduced with permission [79]. Copyright 2019, Springer Nature. **c** PVDF/BTO composite fibers prepared through melt spinning method.

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intrinsic flexibility, advantageous biocompatibility, non-toxicity, and remarkable chemical resistance. Among them, PVDF manifests excellent piezoelectric characteristics, which is, consequently, one of the most popular piezoelectric polymers for the design of high-performance electronic skins. PVDF is a semicrystalline polymer with more than five different crystal phases, such as α , β , γ , δ , and ϵ [77]. The polarized β phase, in particular, has the highest electrical activity because its unique molecular conformation and structure provide the highest spontaneous polarization, thus promoting the piezoelectric sensitivity and electrical power output [78]. Therefore, converting other crystal phases into

β phase is an effective approach to improve the degree of piezoelectricity for PVDF.

In situ poling, thermal drawing, mechanical drawing, electric field polarization, high-pressure annealing, and grinding are currently the most often used methods to increase the β phase. As a common ferroelectric polymer with a known Curie transition temperature and favorable electromechanical conversion properties, P(VDF-TrFE) is a copolymer of PVDF. Through electrospinning, Ahmed et al. [79] created P(VDF-TrFE) nanofibrous membranes that were adorned with PEDOT-CNT/rGO composite, which has a high conductivity of 3916 S cm^{-1} (Fig. 5b). The newly

built piezoelectric sensor demonstrated exceptional sensitivity up to 67.4 kPa^{-1} . However, piezo-polymers show lesser sensitivity and lower mechanical–electrical energy conversion efficiency when compared to piezo-ceramics. Additionally, by effectively integrating piezoelectric polymers and piezo-ceramics, it is possible to achieve synchronous functions of high sensitivity, substantial power output, and amazing flexibility. For instance, the P(VDF-TrFE) nanofibrous membranes' output performance is 200% greater with BTO added compared to those nanofibrous membranes without BTO [80]. A piezoelectric energy generator based on PVDF/BTO composite fiber, made by melt spinning approach was also described by Mokhtari et al. (Fig. 5c) [31]. The power density of the as-prepared energy generator was an impressive 87 W cm^{-3} , 45 times higher than that of the other known piezoelectric energy generators made of fiber materials. Additionally, as shown in Fig. 5d, a three-dimensional hierarchically interlocked PVDF/ZnO nanofibrous membrane was fabricated by growing ZnO nanorods on the surface of the electrospun PVDF via a hydrothermal process [25]. The as-prepared sensor demonstrated outstanding pressing and bending sensitivity of 3.12 mV/kPa and 16.89 V/mm , respectively. Additionally, coating, doping, and electrospinning appropriate amounts of conductive media into piezoelectric materials—such as multi-walled carbon nanotubes (MWCNTs), Au, and Ag NWs—is another efficient and advantageous method to raise the piezoelectric constant. P(VDF-TrFE) nanofibers containing MWCNTs were obtained by electrospinning with a higher degree of P(VDF-TrFE) chain alignment, and they had a d_{33} value of roughly 50 pm/V [81].

Triboelectric Materials

It is possible and convenient to design and fabricate the devices with the ability to detect the delicate and subtle mechanical stimuli, harvest external energy and generate power, self-sufficiently. This may occur due to this fact that, the triboelectric effect is known to be omnipresently found in any two different materials. Therefore, any existing materials can serve as the triboelectric materials for self-powered sensing applications. Triboelectric materials can be categorized as triboelectric positive materials and triboelectric negative materials based on their polarities. Triboelectric polarities are related to material's propensity to gain or lose electrons during friction process. Rationally selecting appropriately matched materials is a prerequisite and simple principle to enhance triboelectric performance [82]. More specifically, the more charges are induced during periodically occurring contact–separation movement, the greater the difference between the two materials in the triboelectric series [83, 84]. PTFE (polytetrafluoroethylene), PVDF, and PDMS are the key examples for commonly

used triboelectric negative materials, taking into account their triboelectric polarity, flexibility, and other features, as illustrated in Fig. 6a. Due to its relatively strong ability to attract electrons, hydrophobicity, and biodegradability, Poly[lactic-co-glycolic acid] (PLGA) has also been reported as the triboelectric negative layer [49]. Representative triboelectric positive materials mainly include nylon and EC nanofibers. For instance, to create a sensing textile with sensitivity of 1.33 V kPa^{-1} and 0.32 V kPa^{-1} in the range of $1.95\text{--}3.13 \text{ kPa}$ and $3.20\text{--}4.61 \text{ kPa}$, respectively, nylon and PTFE filament were chosen as the positive and negative layers, respectively (Fig. 6b) [23]. Some of sensing devices also directly use conductive metallic electrode as triboelectric positive layer. For example, Liu et al. [85] developed a self-powered sensor to distinguish endocardial pressure with Al foil acting as both conductive electrode and positive layer (Fig. 6c). Similarly, Lin [17] took conductive fiber arrays and wavy-shaped PET film as the positively and negatively charged friction layers, respectively (Fig. 6d). With a rational structural design, the pressure sensor exhibits a high sensitivity of up to 0.77 V Pa^{-1} and a quick response time of less than 80 ms. Regarding the single-electrode mode, the surface of a robot or other touched object, such as human skin, can behave as the triboelectric positive layer. For improved triboelectric performance, surface roughening and nanofibrous materials can significantly increase the effective contact area. Increasing separation distance during operations using a three-dimensional (3D) textile configuration is an additional advantageous strategy. Triboelectric materials provide advantages including a wide range of material options and high power output, but they are also vulnerable to environmental dampness and need a packaging technique. Furthermore, due to repeated use, triboelectric devices are susceptible to abrasion, which has an impact on the stability of sensing performance and power output efficiency.

Fiber-based Self-powered Electronic Skins

Electronic skins are required to acquire desirable flexibility and stretchability to conveniently mount on dynamically curved biological skin. This can furnish the essential mechanical degrees of freedom to prevent the damage of electronic skins during use [1]. Fiber materials that are composed of considerable single fibers stacked in a certain way have emerged as powerful candidates to fabricate satisfactory electronic devices. First, innumerable interconnected fiber architectures enable exceptional flexibility, stretchability, and super-fatigue resistance because of the soft, thin fibers and mutual slip motion between them [37]. Second, with fibrous materials, there are a lot of interconnected channels between the fibers. As depicted in Fig. 1, such inherently linked porous structures enable the passage of heat, water

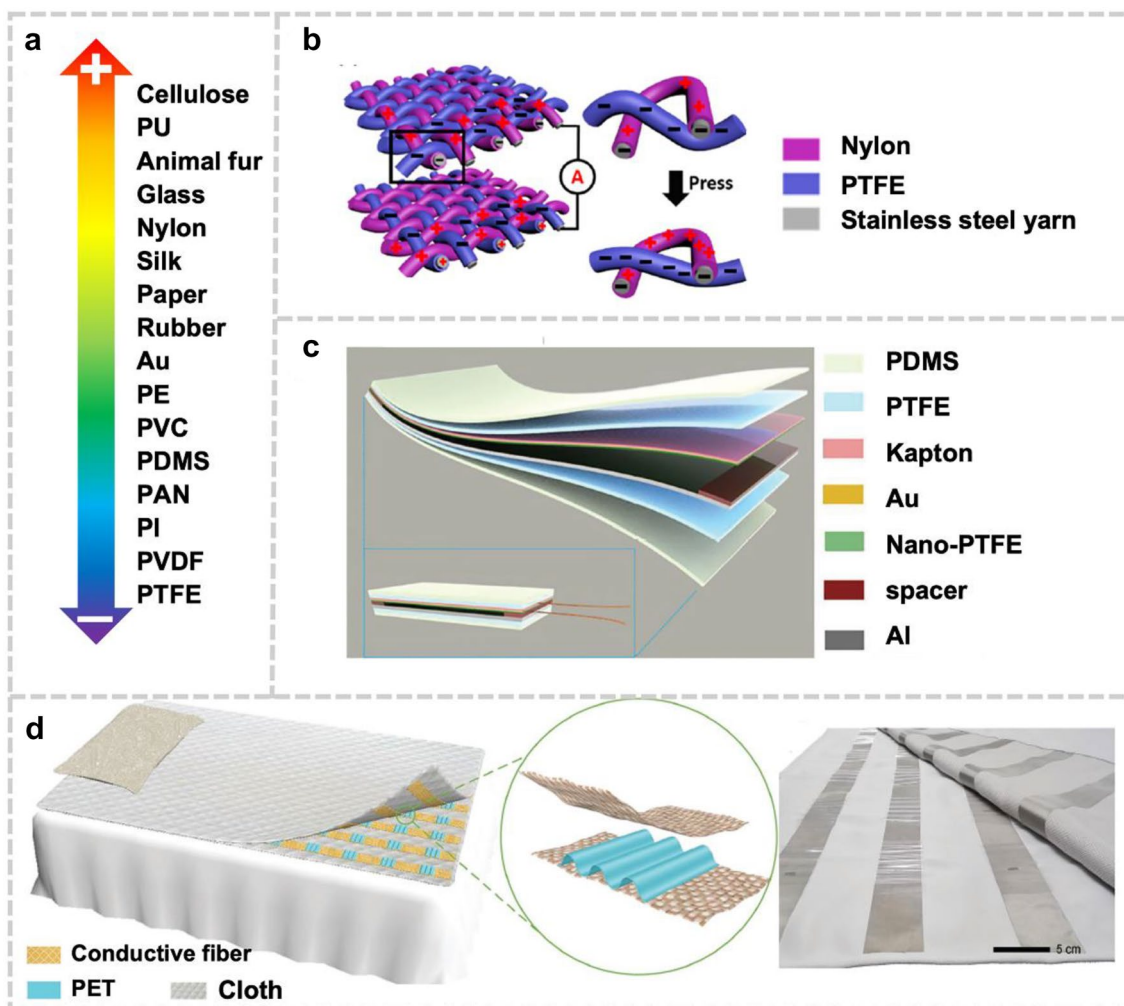


Fig. 6 Triboelectric series and representative triboelectric materials. **a** Triboelectric series of commonly used materials. **b** Sensing textile based on nylon and PTFE filament. Reproduced with permission [23]. Copyright 2019, Elsevier. **c** Aluminum foil functioning as a both

positive layer and conductive electrode. Reproduced with permission [85]. Copyright 2018, John Wiley and Sons. **d** Ag-coated carbon fibers acting as a positive layer. Reproduced with permission [17]. Copyright 2017, John Wiley and Sons

vapor, and air between the skin and the environment, which is essential for controlling and preserving the equilibrium of temperature and humidity on the human surface. Third, when compared to other material systems, readily accessible and inexpensive fiber materials with an inherent porosity structure may be quickly integrated or assembled to create fabrics, apparel, and clothing, which helps boost large-scale industrial production [86]. Furthermore, smart fibers provide ease of surface modification and can be integrated with other functional materials, which allows for more possibilities in a broader application [25, 50].

The integrated sensing arrays are significantly hampered by the energy consumption of pressure sensors. Numerous efficient methods, such as designing sensor arrays with the proper operating voltage and resistance, have been suggested to reduce energy consumption. Additionally, a large number

of capacitive and piezo-resistive sensing arrays must be coupled to a hard, bulky power supply module, preventing their widespread use in soft, thin electronic skins. Utilizing self-powered sensor arrays is a suitable alternative and ultimate solution to this problem. Due to its self-powered capability, low cost, and simple fabrication properties, flexible triboelectric and piezoelectric nano-generators or sensors for electronic skin systems have recently attracted dramatically ever-increasing attention. Furthermore, self-powered electronic skins that can recognize a variety of external stimuli have shown significant potential to achieve flexibility, breathability, washability, and other functions. These skins were inspired by intriguing and advantageous nano- to microstructures and fabrication techniques of fiber materials. This section will provide a thorough summary of

self-powered mechanisms as well as the use of the piezoelectric and triboelectric effects in fiber-based electronic skins.

Piezoelectric Electronic Skins

Piezoelectric Mechanism

Piezoelectricity, which is based on the positive piezoelectric effect, is the successful conversion of physical mechanical interactions like strain, pressure, and vibration into recognizable electrical impulses [2]. A specific characteristic of piezoelectric materials, such as piezoceramics and piezoelectric polymers, is the piezoelectric effect caused by the shift in dipole moments [87]. In a normal resting or relaxing mode, the piezoelectric materials are unable to generate an electrical charge. When the charge centers with opposing polarization overlap with one another (Fig. 7i). Under applied external pressure, piezoelectric material deforms in a certain direction and electric dipoles get changed, resulted from relative displacement of spatially separated polarization charge centers (Fig. 7ii) [54]. Equivalent negative and positive polarized charges accumulate on the surface of both electrodes, which allows for the formation of piezopotential and the movement of electrons through the external circuit [88, 89]. When the maximum deformation is reached, the maximized pressed state is achieved with the highest piezopotential (Fig. 7iii). With the withdrawal of the mechanical pressure, the centers of the opposite charges gradually coincide with each other, and piezoelectric material becomes electrically neutral again (Fig. 7iv) [90]. The electrons return to their initial state and the direction of the current is reversed [73]. On this basis, applying a reciprocating pressure will enable continuous piezopotential and steady stream of pulse current. Piezoelectricity exhibits tremendous potential in energy autonomous and self-powered electronic skins

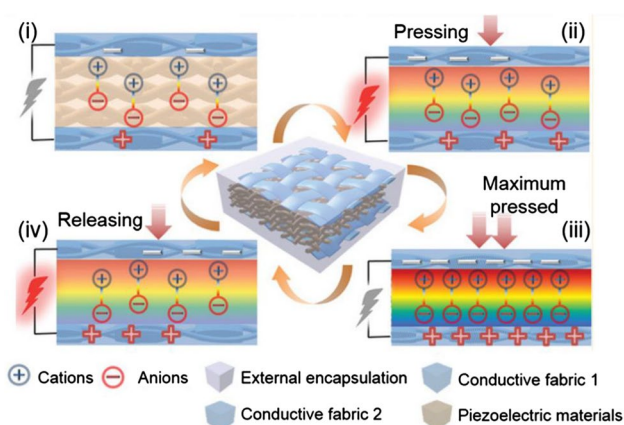


Fig. 7 Mechanism of piezoelectric sensing. Reproduced with permission [54]. Copyright 2019, John Wiley and Sons

because of its advantages of high sensitivity, quick dynamic response time, and self-power capability [48, 54, 90].

Fiber-based Piezoelectric Electronic Skins

There are a variety of fiber-based electronic skins based on piezoelectric mechanisms. In contrast to previously reported piezopolymer doped with conductive and piezoelectric ceramics, BTO-PVDF/GO core-shell nanofibers were employed to enhance the piezoelectric sensitivity and flexibility by coaxial electrospinning with PVDF/GO and PVDF/BTO forming the sheath and the core (Fig. 8a, b), respectively [22]. Additionally, to create a sandwich structure, commercially available conductive textiles were conformally connected to both sides of the piezoelectric nanofibrous membranes. The surface of the electronic skin was later covered with two bigger PU substrate layers as packages. The electronic skin was fabricated with a unique characteristic of shape adaptation and possessed remarkable sensing performance, with sensitivity reaching $10.89 \text{ mV kPa}^{-1}$ in a broad range of 80–230 kPa, owing to the synergy of coaxial structure and piezoelectric polymer doping (Fig. 8c). It also manifested a distinct power output with a maximum power density reached to $121 \text{ } \mu\text{W/m}^2$ (Fig. 8d). Additionally, the electronic skin demonstrated an outstanding long-term mechanical durability, retaining consistency in sensing function even after operating for more than 8500 cycles (Fig. 8e).

Triboelectric Electronic Skins

In addition to serving as a mechanical pressure sensor, a triboelectric electronic skin also functions as an energy harvester that can turn omnipresent but otherwise useless mechanical energy into reliable electrical power. Moreover, intrinsic interaction of fiber assembly and the high specific surface area of fibers have given fiber-based triboelectric electronic skins a lot of attention. In this part, an extensive evaluation of these electronic skins has also been carried out.

Triboelectric Mechanism

Based on the synergies of triboelectrification and electrostatic induction effects, triboelectric electronic skins realize transduction of mechanical stimuli into easily detected electrical signals. They also harvest energy from the ambient environment, through the periodical cyclic contact and separation movements induced by external mechanical actions [7, 49, 91, 92]. In general, triboelectricity can be categorized into four working modes based on the structural design and configuration, namely vertical contact–separation (CS) mode, lateral sliding (LS) mode, single-electrode (SE) mode, and freestanding triboelectric-layer (FT) mode.

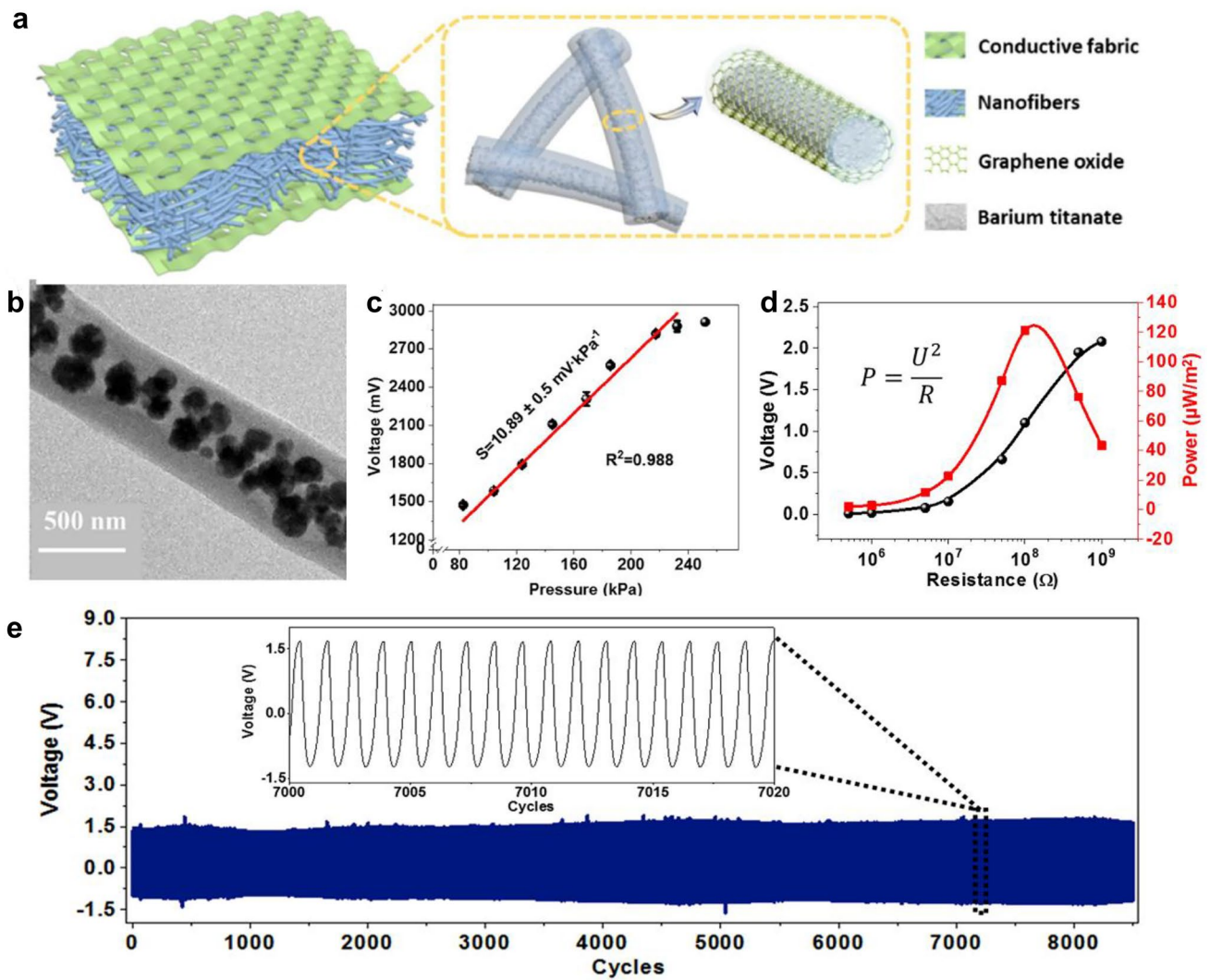


Fig. 8 Structure design of fiber-based piezoelectric electronic skin. Reproduced with permission [22]. Copyright 2020, Elsevier. **a, b** Schematic illustration and optical photograph of the piezoelectric

electronic skin. **c** TEM image of a core-shell piezoelectric nanofiber. **d** Pressure sensing sensitivity of the coaxial structured electronic skin

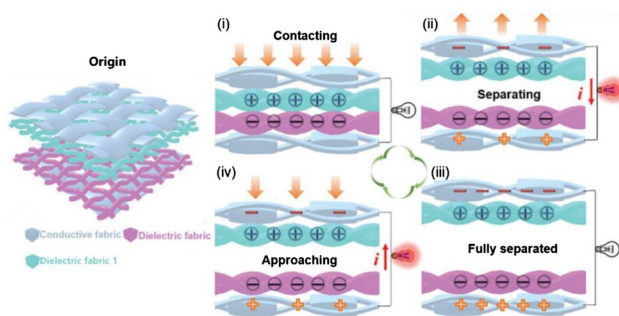


Fig. 9 Mechanism of triboelectric sensing. Reproduced with permission [54]. Copyright 2019, John Wiley and Sons

All of these working modes can utilize the same sensing mechanisms [54, 90]. Hence, for practical demonstration,

a thorough examination of the vertical contact–separation mode is carried out. Figure 9 schematically depicts the structure and mechanism of this working mode. A conductive electrode is coupled to electronegative and electropositive friction materials that make up the device [93]. No charge is introduced in the initial state since there was no electrical potential. Due to the difference in their electron affinities, these two friction materials generate an equal amount of negative and positive charges at their interface when they come into contact with one another, a process known as contact electrification (Fig. 9i) [94]. Upper and lower frictional layers will induce opposite charges as they gradually separate from one another, and these charges will then build up at the corresponding friction surfaces due to the phenomenon of electrostatic induction (Fig. 9ii). An electrical potential difference can be created through this technique, which

causes electrons to flow from the top electrode to the bottom electrode and create an instantaneous current [95]. The sensor enters a static equilibrium condition (Fig. 9iii) when they are completely separated, with the negative charges in the electrode being equivalent to the positive charges in the triboelectric materials [96]. When the top and bottom layers are getting close to each other with the applied mechanical pressure, electrons will accordingly flow back from the bottom electrode to the top electrode and generate a current in reversed direction (Fig. 9iv) [3]. As a result, the sensor can perceive stimuli and harvest energy during cycles of contact and separation of the two layers. This allows the triboelectric sensor to only detect dynamic signals and not static ones. Even yet, triboelectric sensors have drawn a lot of research interest due to their advantageous qualities of high sensitivity, self-powered, and environmental friendliness.

Fiber-based Triboelectric Electronic Skins

Diverse fiber materials have been chosen to build flexible, permeable, and extremely sensitive electronic skins by making use of the triboelectric effect. The classic textiles, such as woven or knit clothing, may be the first thing springing to mind. For instance, a complete cardigan stitch was used to create highly sensitive and cosy textile arrays using nylon yarn as a second triboelectric positive surface and core-shell structured stainless steel/one-ply Terylene yarn as the conductive electrode [97]. The well-developed sensor arrays benefited significantly from the full surface contact between the coil head of the core-shell yarn and the adjacent tuck stitch head of the nylon yarn as opposed to just a point contact, which led to a higher sensitivity of 7.84 mV Pa^{-1} when compared to the traditional plain stitch structured pressure sensor arrays. As shown in Fig. 10a, the machined-knitted sensor arrays can be facily integrated with clothes. The sensor arrays also demonstrated good machine washability up to 40 washing cycles, a quick response time of 20 ms, and excellent operational stability up to 100,000 cycles (Fig. 10a). Nanofiber materials, as opposed to conventional textile materials, have been widely used to create electrification layers due to their higher specific surface area and ease of nanoscale modification, which can significantly increase the surface charge density and enhance sensing sensitivity and power output. An all-fiber constructed electronic skin with a self-powered triboelectric mechanism was reported by Li et al. [18], which significantly increased the sensitivity to over 0.18 V kPa^{-1} and increased the pressure-detecting range to 175 kPa. The ultra-sensitive electronic skin, which is schematically represented in Fig. 10b, was made up of three layers of nanofibers: a sensor layer made of PVDF nanofibers, an electrode layer made of carbon nanofibers, and a substrate layer made of PU nanofibers. The pressure sensitivity of this manufactured electronic skin may maintain

a largely steady condition even after 50% elastic deformation was applied. Another all-nanofiber constructed electronic skin with a vertical contact-separation working mode was created in a similar manner (Fig. 10c) [24]. The electronic skin has a maximum power density of 330 mW m^{-2} and a high-pressure sensitivity of up to 0.217 kPa^{-1} , allowing it to track even slight respiration accurately. Additionally, this intriguing study demonstrated significant promise for enhancing clinical sleep breathing illness identification and human sleep quality.

Other Electronic Skins

Electronic skins based on piezoelectric and triboelectric mechanisms can transform pressure stimuli into measurable electrical signals and are capable of self-charging. Piezoelectricity and triboelectricity being combined into one device have been viewed as the best technique to further improve the functionality of electronic skins because each mechanism has advantages and disadvantages of its own. To address the additional broad-ranging practical application demands, efforts to construct electronic skins with multimodal sensing properties have also attracted a lot of attention [2]. These synthetic electronic skins with a variety of sensor components may electrically separate a variety of physical sensations from a complicated environment, such as pressure, humidity, and temperature [98]. For long-term practical use of electronic devices, many additional attributes, such as self-healing and antibacterial properties, are also essentially sought [20, 49]. The fiber-based self-powered electronic devices are especially favorable for next-generation electronic skins with multiple attributes. Therefore, applications of fiber-based hybrid electronic skins, multimodal electronic skins, and multifunctional electronic skins have been discussed in this section.

Hybrid Electronic Skins

Although triboelectric sensors can detect distance, identify different materials, and generate high power output, they possess relatively lower sensitivity and there will be no electrical signal change without contact–separation movement. Piezoelectric sensors, on the other hand, have a higher sensitivity and can detect even minute material deformation brought on by pressure, but they have lower electromechanical conversion efficiency. To improve sensing performance and electric power production, triboelectric and piezoelectric sensor combinations may be mutually beneficial. The creation of hybrid electronic skins is still a challenging and intricate task. For the actual implementation of hybrid structure in electronic skin, the integration of sensor arrays, particular structural design, and material

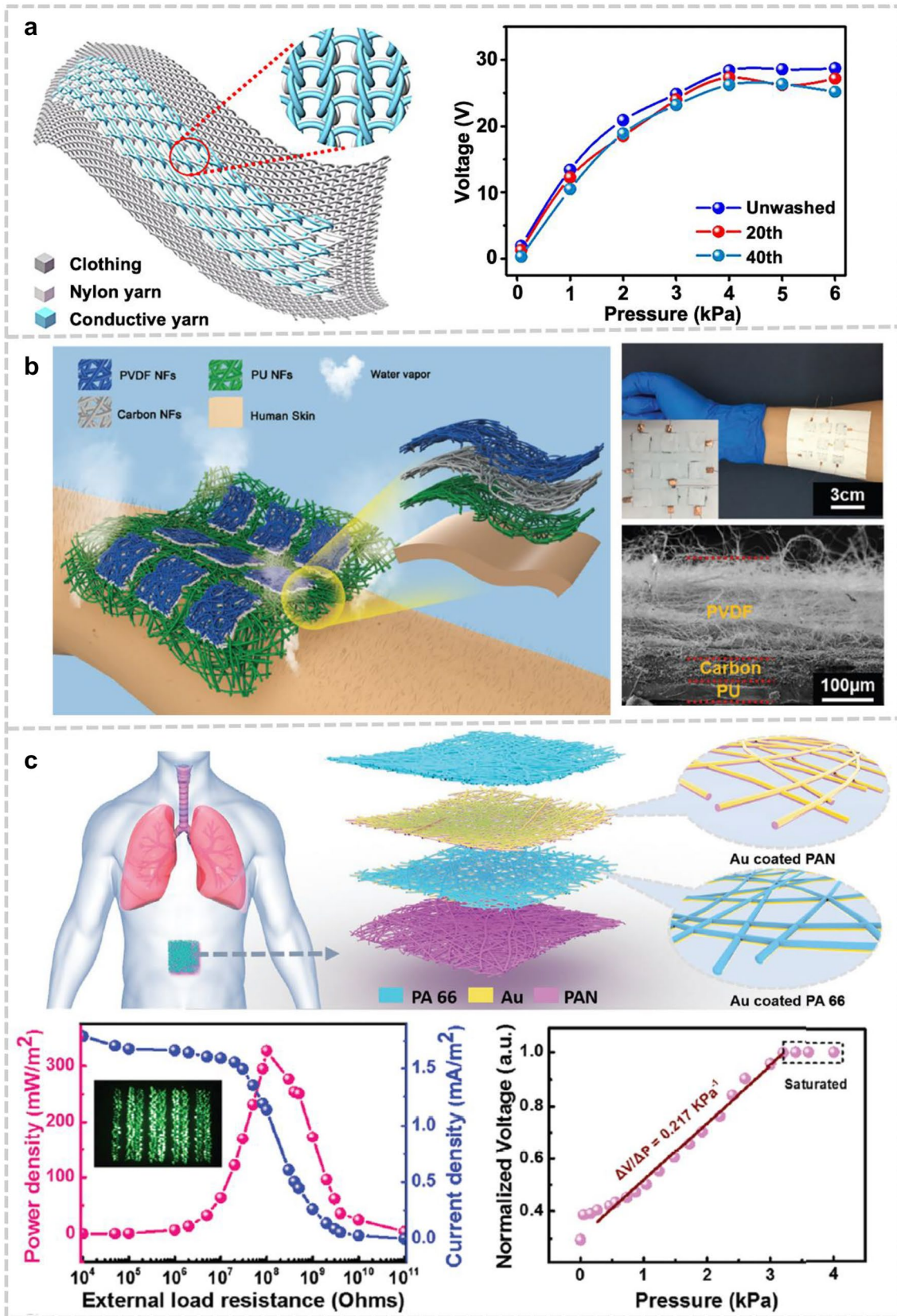


Fig. 10 Fiber-based triboelectric electronic skins. **a** Schematic illustration of the combination of sensing textile and clothes and its washable property. Reproduced with permission [97]. Copyright 2020, American Association for the Advancement of Science. **b** All-fiber structured electronic skin based on single electrode working mode. Reproduced with permission [18]. Copyright 2019, John Wiley and Sons. **c** All-nanofiber structured electronic skin based on vertical contact–separation working mode. Reproduced with permission [24]. Copyright 2021, John Wiley and Sons

choice is crucial. Some research has gone into creating the hybrid sensors used in flexible electronic skins. A flexible energy-autonomous hybrid electronic skin with vertically integrated single-electrode triboelectric and piezoelectric pressure sensor arrays was created by Zhu et al. (Fig. 11a) [99]. Specifically, PVDF nanofibers doped with MWCNTs functioned as the piezoelectric layer, and porous PDMS fabricated via lotus leaf-mold patterned approach served as a triboelectric layer. With smooth PDMS and conductive fabric serving as the substrate and electrode, the hybrid electronic skin was successfully fabricated. Consequently, the hybrid electronic skin can directly adhere to human skin to enable the monitoring of physiological signals, such as human pulse detection, click sensing, respiration monitoring, head motion recognition, and vocal cord vibration discrimination. Besides, with the detection range of 0–80 kPa and 80–240 kPa, the pressure sensitivity was achieved over $54.37 \text{ mV kPa}^{-1}$ and 9.80 mV kPa^{-1} (Fig. 11b), respectively. Peak output power density of up to 2.7 mW m^{-2} is possible with an external load of $50 \text{ M}\Omega$ (Fig. 11c). In the next years, it is projected that the hybrid electronic skin will play a particularly important role in intelligent prosthetics, intelligent robots, and health monitoring.

Multimodal Sensing Electronic Skins

There is currently a lot of interest in prostheses, intelligent robotics, and healthcare diagnostics and monitoring for mimicking the full sensory function of human skin [2]. To have a better understanding of the external environment, and to avoid lasting damages, temperature, humidity, and gas detection and differentiation are also sought in addition to pressure sensing capacity [20, 100]. There have been several reports of electronic skins based on fiber materials that feature multimodal sensing capabilities.

Ambient temperature is one of the basic indicators in the surrounding environment that dramatically affects human activities and even breaks the thermal balance of the human body. Temperature detection is, therefore, extremely important. Electronic skins with temperature and pressure sensing abilities have been fabricated to perceive dynamic ambient environments. For instance, Wang et al. [100] proposed electronic skin textile, capable of pressure-temperature detection, which can accurately perceive and distinguish ambient

pressure and temperature with high resolution. As shown in Fig. 12a, this integrated electronic skin textile was composed of thermal-resistance carbon nanofibers functioning as temperature perception layer, electrospun PVDF/ZnO nanofibrous membrane serving as piezoelectric sensing layer, and conductive fabric acting as the electrode layer. This dual modal electronic skin displayed exceptional linear pressure sensitivity of $15.75 \text{ mV kPa}^{-1}$ and $52.09 \text{ mV kPa}^{-1}$, respectively, in the pressure ranges of 4.9–25 kPa and 25–45 kPa. With a satisfactory temperature resolution of $0.381\% \text{ }^\circ\text{C}^{-1}$, it can also achieve a broad temperature detection range from 25 to $100 \text{ }^\circ\text{C}$. The piezoelectric effect-based electronic skin textile also demonstrated self-powered ability, with a maximum power density of 17.1 Wm^{-2} and the capacity to run continuously under 5500 loading–unloading cycles. Given that temperature-resistant carbon nanofibers may serve as a sensor component as well as a substrate, the temperature–pressure detecting electronic skin can be produced in large quantities using this reduced structure and inexpensive fabrication technique.

Humidity-sensing is another significant environmental factor that has attracted considerable interest to better emulate the basic functions of human skin. Fiber-based humidity–pressure electronic skins have effectively been fabricated in recent years. For example, Bi et al. [101] proposed an ultrasensitive, multipurpose sensor that can sense pressure and humidity. A simple coating of GO was first applied to a stretchy Modal/Spandex fabric, which was then subjected to a chemical reduction procedure. To increase the robustness and sensing performance of the multifunctional sensor, the rGO fabric was fabricated and then layered with carbonic pen ink and PVA by dip-coating process. This was a simple and affordable method for the extensive integration of humidity and strain sensors. Although several humidity–pressure electronic skins made of fiber materials have been described, no such piezoelectric or triboelectric electronic skins have been fabricated. Due to the increase in the conductivity of the contact surface because of the absorbed water molecules, surface charges brought on by contact–separation processes or loading–unloading cycles will dramatically decrease in high humidity circumstances. Additionally, the fiber materials' large interconnected holes encourage capillary action, which results in the absorption of water molecules from the surroundings. Therefore, the sensitivity and power output of self-powered electronic skin will be largely compromised. Numerous humidity-resisting self-powered electronic applications have been created to improve the stability in high humidity circumstances to deal with this challenge [102]. A problem that needs to be solved in the future is how to combine a humidity sensor and a self-powered pressure sensor in one system. Interestingly, the electronic device based on the triboelectric or piezoelectric effect can successfully serve as a humidity detector based

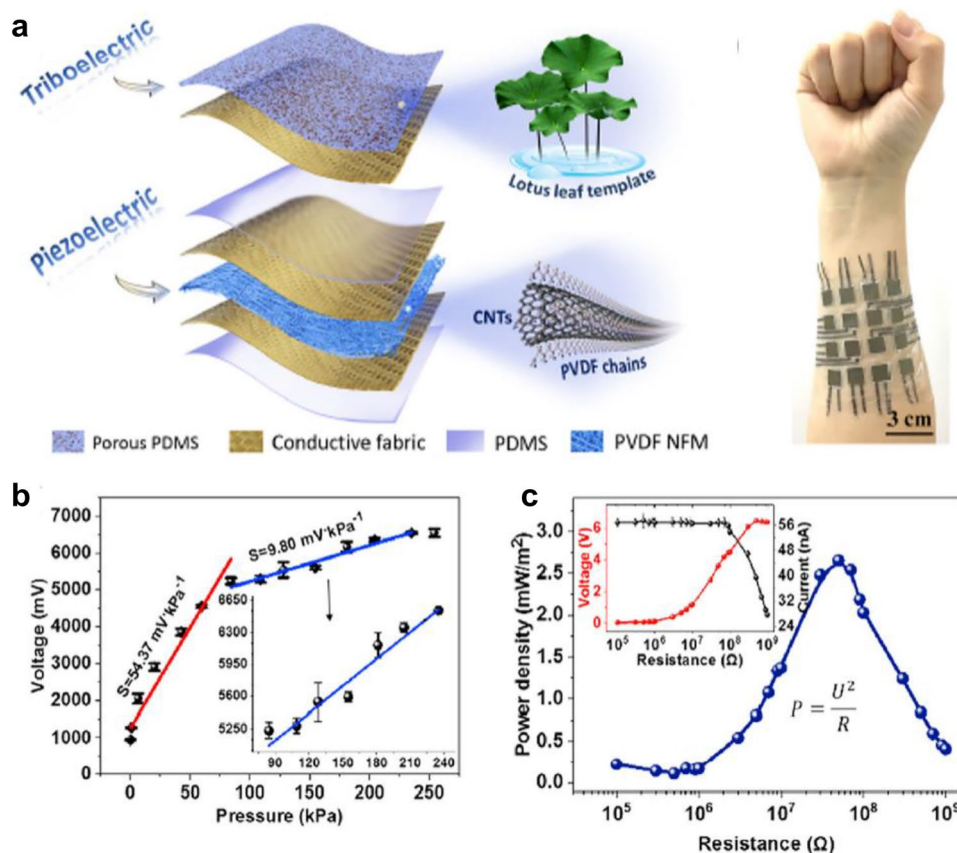


Fig. 11 Hybrid electronic skin based on piezoelectric and triboelectric effect. Reproduced with permission [99]. Copyright 2020, Elsevier. **a-c** Structure illustration, pressure sensing sensitivity, and power output of hybrid electronic skin

on the premise that surface charges decrease with ambient humidity [103].

The surge in air pollution has prompted the development of gas sensors, which are crucial to prevent respiratory diseases such as chronic bronchitis and emphysema [104]. For example, as shown in Fig. 12b, an electronic skin with both pressure perception and atmosphere detection was developed with PVDF and tetrapod ZnO (T-ZnO) nanostructures integrated on a flexible fabric substrate [105]. T-ZnO/PVDF endowed this reported multifunctional electronic skin with both self-powered and pressure sensing properties, which can successfully achieve elbow bending or finger pressing detection. Since the piezoelectric output varied depending on the type of atmosphere, it was possible to build a motion-powered electronic skin that detects the presence of gases. Cui et al. [106] combined an ammonia (NH_3) nanosensor and triboelectric nanogenerator into a single device using PAN nanofibers that served as both a frictional layer and an NH_3 active sensing layer in another published work. The as-prepared NH_3 nanosensor had a detection limit of 500 ppm at room temperature and exhibited outstanding selectivity and sensitivity. These intriguing and innovative efforts demonstrate significant promise for the development of flexible, self-powered, multifunctional e-skin, which is the next generation of electronic skin.

Multifunctional Electronic Skins

Aimed at improving the comprehensive performance of electronic skins, special characteristics, including biodegradability, self-healing, and antibacterial are required to be integrated, which are crucial for the electronic skins' prolonged application on human skin.

Electronic trash disposal management has become a global issue due to the surge in the development of electronic items [107]. Researchers have therefore shown a great deal of interest in materials that degrade naturally over time. Electronic devices have been made using a variety of biodegradable or environmentally friendly materials. The majority of commonly used biodegradable materials come from naturally occurring substances, including cellulose [108], chitosan, silk [39, 109], silk fibroin [110], and cellulose [111]. Additionally, the paper that primarily comprises cellulose has long been used as flexible substrates that can be used to create electronic skins [112]. It's interesting how simple it is to use classic spinning or electrospinning methods to transform cellulose and silk into fibers for wearable electronics. For example, Wu et al. [113] reported a biocompatible/biodegradable electronic textile for dual-model sensing by taking advantage of functionalized silkworm fiber coiled yarns and weaving technology (Fig. 13a). Bacterial cellulose, the

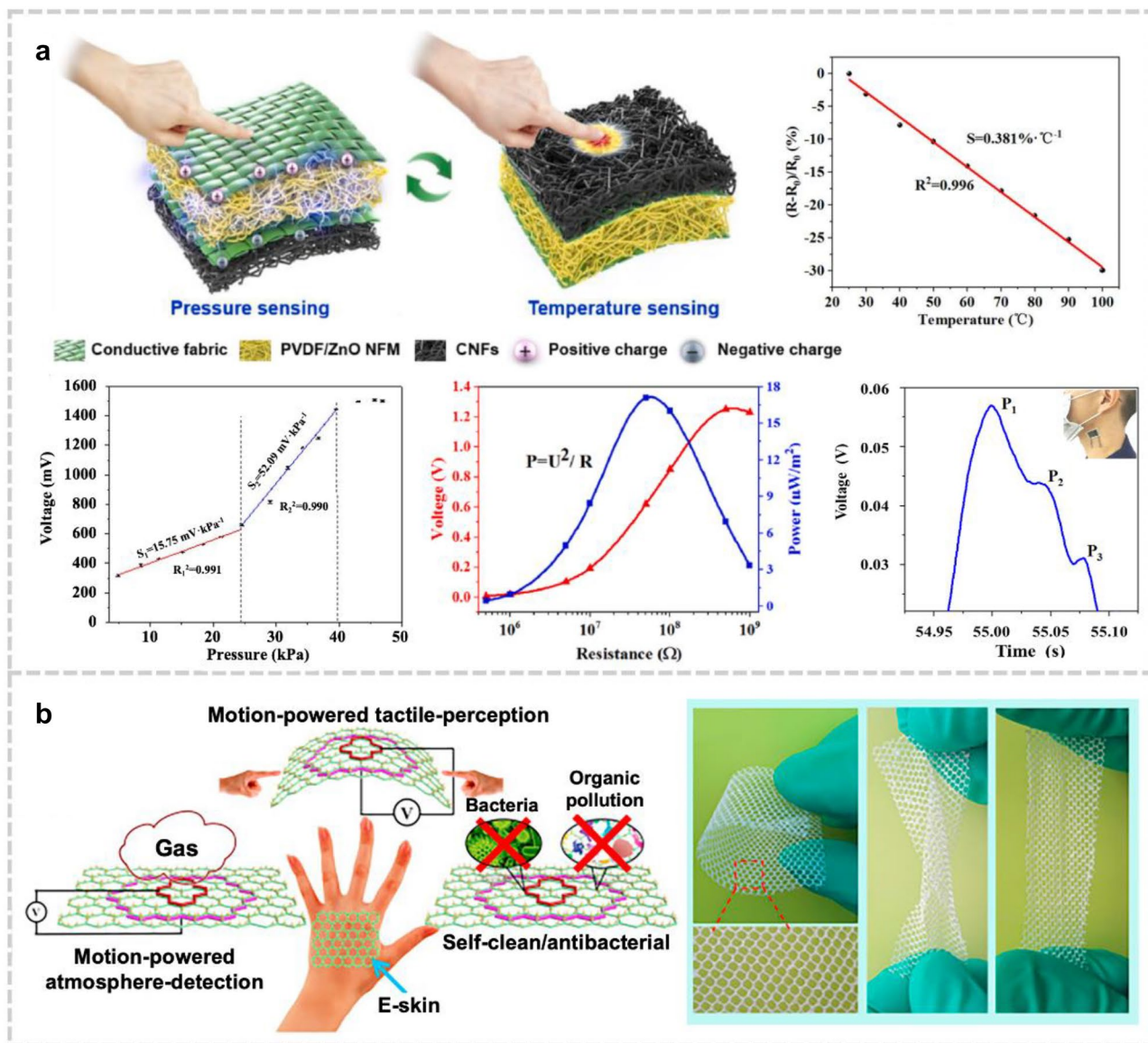


Fig. 12 Multimodal sensing electronic skins. **a** A pressure–temperature electronic skin. Reproduced with permission [100]. Copyright 2021, Elsevier. **b** A pressure–gas electronic skin. Reproduced with permission [105]. Copyright 2016, Elsevier

cellulose generated by bacteria, also possesses biodegradable characteristics and has been extensively utilized in flexible electronics, biomedical devices, and wound dressings [114]. Biodegradable synthetic polymers offer more opportunities for polymer architectural control than naturally biodegradable products. The majority of biodegradable polymers that have been extensively studied rely on the hydrolytic cleavage of chemical bonds like ester, amide, and anhydride [115]. For instance, PLGA is a well-established biodegradable polymer due to the presence of an ester bond [116]. A particular class of degradable materials called bioresorbable can break down in vivo in a living environment and produce biologically safe components. Considering that

they can prevent inflammation or other side effects brought on by long-term implantation and lessen the discomfort of patients’ second operations, such bio-resorbable materials have shown substantial potential in wearable and implantable biomedical applications.

Given that electronic skins may be an excellent medium for bacterial growth owing to prolonged exposure to human skin and less healthy surrounding environment, the antibacterial potential is another performance optimization for skin-attachable electronics, which can prevent the human skin from bacterial infection and inhibit the growth of bacteria. The typical antibacterial materials include Ag NWs [62], chitosan [117], and commercial antibacterial

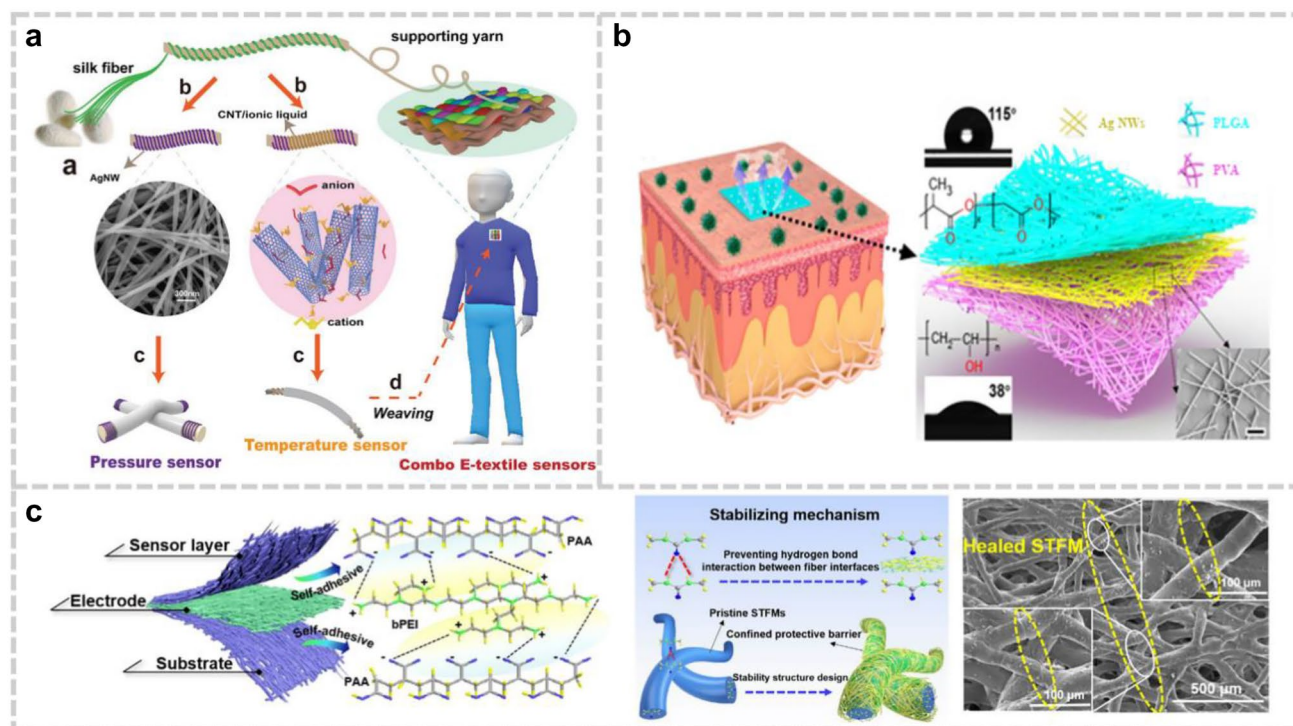


Fig. 13 Multifunctional electronic skins. **a** A biodegradable electronic skin based on silk. Reproduced with permission [113]. Copyright 2019, John Wiley and Sons. **b** An antibacterial electronic skin based on PLGA and PVA. Reproduced with permission [49]. Copy-

right 2020, American Association for the Advancement of Science. **c** A self-healing electronic skin based on bPEI and PAA. Reproduced with permission [20]. Copyright 2022, John Wiley and Sons

agents (such as Glycerol Monolaurate compound material) [71], which present excellent antibacterial potential against gram-positive *Staphylococcus aureus* (*S. aureus*) and gram-negative *Escherichia coli* (*E. coli*). An antibacterial all-nanofiber structured electronic skin was reported by Peng et al. [49] and was made by simply sandwiching an Ag NWs conductive electrode between PLGA and PVA nanofibers (Fig. 13b). The electronic skin, as it was developed, demonstrated good antimicrobial activity against two representative bacteria, with bactericidal efficacy for *E. coli* and *S. aureus* reaching over 54% and 88%, respectively. This is attributable to using Ag NWs as the electrode. Additionally, the all-nanofiber constructed electronic skin had a large specific surface area due to the sizeable micro-to-nano hierarchal pores between the nanofibers, which in turn raised contact electrification charges. The electronic skin based on the single electrode mode had a peak power density of more than 130 mWm^{-2} and a high sensitivity of 0.011 kPa^{-1} . Additionally, it was noted that the combined antibacterial activity of Ag NWs and chitosan, as well as the air permeability of fibrous membranes, presented effective bacterial inhabitation [117]. A further exemplary antibacterial material is poly(ionic liquids; PILs), which demonstrates strong inherent antibacterial activity against germs and can

create a hygienic wearing environment between the contact interfaces [118].

Human-made electronic skins degrade over time owing to fatigue or damage incurred during long-term operation, eventually leading to electrical failure [119]. Inspired by the powerful capability of biological systems to autonomously heal, self-healing materials have emerged in recent years as a promising approach for constructing flexible electronic devices that are mechanically robust and can self-repair to restore electrical functionality [68]. Another essential, unmatched quality of next-generation electronic gadgets is their self-healing capability. To prevent irreversible failure, the majority of researched solutions rely primarily on self-healing chemicals or coatings. The strategy of applying self-healing chemicals or coatings, however, cannot sustain the original fibrous morphology and configuration after healing, for fiber materials. As a result, substantial morphological modifications to flexible electronic coverings significantly limit breathability and even result in unstable sensing performance [120]. Additionally, the consumption of the encapsulated agents limits the number of healing cycles when using a self-healing agent [120]. On the other hand, strategies based on chemical bond interactions or molecular chain interdiffusion that achieve intrinsic self-healing also show

promise in electrical devices. Thermoplastic polymers are typically the starting point for self-healing materials based on molecular chain interdiffusion. Such materials are more susceptible to external interference since their capacity for self-healing is highly dependent on the load on the “nano heaters,” the intensity of the ambient light, and the duration of illumination [121]. Due to the autonomous molecular contact between covalent and non-covalent bonds, fibers in self-healing materials based on chemical bond interactions will eventually become cohesive with one another, resulting in the removal of porous structures and changes in fiber morphology [122]. Zhu et al. [20] created an innovative interface protection method to create intrinsically self-healing fibrous membranes with a bionic restricted structure (Fig. 13c). To inhibit supramolecular interactions and guarantee the durability of the shape, restricted protective layers made of polyacrylic acid (PAA) and branched poly ethyleneimine (bPEI) were used. Through interfacial hydrogen bonding, these particular fibrous membranes can be combined to form an all-fiber structured electronic skin, successfully enabling soft electronics to become self-healing and breathable.

Conclusion and Outlook

A comprehensive review and detailed discussion have been carried out concentrating on research progress in self-powered electronic skins constructed with smart fibers. A brief introduction of functional constructing materials and pressure sensing mechanisms has been presented. Besides, a summary of various self-powered electronic skins constructed with fiber materials is shown in Table 2. Due to their exceptional flexibility, lightweight, breathability, and affordability, fiber materials provide a significant supporting carrier and pervasive technological platform for flexible

electronic applications. They also demonstrate promising advantages in the production of electronic skins. Even though plastic films and elastic rubbers with relatively advanced processing techniques have excellent flexibility and stretchability and are frequently used in electronic skins, they are unable to transport heat, humidity, or gases between human skin and the outside environment, which can easily lead to bacterial growth and itching when worn for an extended period. From this point of view, fiber materials with inherent porous structure provide considerably connected channels for thermal-moisture transition, which can create a comfortable micro-environment for long-term wearing applications. Additionally, fiber materials are inexpensive and simple to manufacture, particularly because they can be easily and directly incorporated into fabrics, apparel, and clothing, which is advantageous in terms of large-scale industrial production. Electronic skins based on the piezoelectric and triboelectric effects have demonstrated great potential and strong vitality. They exhibit significant practical application prospects in the field of human health monitoring, smart prosthetics, and human–computer interfaces. They also serve as a new mechanical energy harvester and a self-powered pressure detection technology. Generally speaking, the power output of a piezoelectric sensing system is much lower than that of a triboelectric sensing system, whereas a piezoelectric sensing system has considerable advantages over a triboelectric sensing system in terms of sensitivity and stability. The most frequent and fundamental structure of a piezoelectric sensing system is the electrode–insulator–electrode. According to the operating modes, triboelectric sensing systems often use various construction structures, such as the contact–separation mode, lateral sliding mode, single-electrode mode, and freestanding triboelectric-layer mode. The two working modes that are most frequently used are contact separation and single

Table 2 Summary of various self-powered electronic skins constructed with fiber materials

Sensing mechanism	Active material	Sensitivity (mV kPa ⁻¹)	Detection range (kPa)	Power output (mW/m ²)	Durability (cycles)	References
Piezoelectric	BTO-PVDF/GO core-shell NMs	10.89	80–230	0.121 (100 MΩ)	8500	[22]
	PVDF/ZnO NMs	15.75, 52.09	4.9–25, 25–45	0.0171 (50 MΩ)	5500 (100 MΩ)	[100]
Triboelectric	PVDF NMs	180	0–170	Lighting up 50 LEDs	1400 (100 MΩ)	[18]
	Porous PDMS	71.52, 10.87	0–75, 5–250	9.27 (100 MΩ)	23,000	[71]
	PA and PA 66 NMs	217	0–3	330 (10 N, 3 Hz)	n/a	[24]
	PLGA NMs and Ag NWs	11	0–40	130	40,000 (40 N, 3 Hz)	[49]
Piezoelectric&Triboelectric	PVDF NMs, Porous PDMS	54.37, 9.80	0–80, 80–240	2.7 (50 MΩ)	14,000 cycles	[99]

electrodes. To more closely resemble the sensing capabilities of human skin, electronic skins must also have hybrid sensing and multimodal sensing capabilities. Currently, efforts are also being made to incorporate other desirable qualities, such as biodegradability, self-healing, and antimicrobial properties, into electronic skins.

Although tremendous efforts have been devoted to developing self-powered electronic skins constructed with fiber materials, there are certain challenges. The continuous investigation is needed for further development of scalable and low-cost electronic skins with integrated capabilities. Below, we systematically highlight some of the existing challenges and provide an overview of the potential future directions.

(1) Both triboelectric and piezoelectric sensing devices will generate polarization charges while they are operating, and these charges are sensitive to the humidity of the surrounding air. Due to the sizeable pores inside fibers that allow for the absorption of large water molecules, especially in the case of hydrophilic fiber materials, the performance of sensing and power generation is severely hampered. The first solution that springs to mind is the use of an encapsulation or package layer, however, this compromises the special air permeability provided by fiber materials and inevitably increases the weight of the device [123, 124]. The engineered surface wettability is an alternate technique that can prepare the electronics for the target application in varying humid conditions, since the surface wettability of the electronics easily yet efficiently modulates their interaction with liquids [125]. Integrating hydrophobic and oleophobic coatings into smart textiles or fibers is an alternative to achieve liquid repellency without compromising the remarkable breathability of fibrous materials [126]. To guarantee super-hydrophobic surfaces and achieve steady operating performance, it is also appropriate to graft oleophilic functional groups [91]. Moreover, the bio-inspiration from many living organisms, such as lotus and leaves, also promotes the development of micro or nano-hierarchical structures for hydrophobic surfaces [127]. These techniques, though, are difficult and unsuitable for the widespread use of self-powered gadgets. Additionally, utilizing waterproof fabric (such as Gore-tex) or super-hydrophobic fiber materials directly as the substrate layer can stop moisture absorption and further reduce performance degradation in highly humid environments [128]. Nevertheless, a systematic study of related hydrophobic materials and existing waterproof textiles, along with an in-depth understanding of the involved fabrication approaches, is highly required for large-scale production and long-term reliability. Interestingly, a novel type of humidity-resisting self-powered device has been developed to enhance charge density by taking advantage of water molecules in humid conditions. For instance, a triboelectric nanogenerator that resists humidity was created

using a PVA/LiCl film as the percentage positive layer. In highly humid settings, PVA with plenty of hydroxyl groups can absorb water molecules and produce higher fractional positive surface polarity [129]. Additionally, LiCl has the power to control how much water a PVA/LiCl film can absorb. As a result, the triboelectric nanogenerator gradually produced more power. Another intriguing strategy to increase the ability of self-powered devices to resist humidity is amino modification. This technique can give some transferred mobile ions under high humidity, increasing the surface potential of the contact layer [130]. However, this method is limited to some specific materials that are suitable for amino modification. Hence, a broader range of applicable methods is urgently required, and their working mechanisms need to be further explored as well. Even though numerous approaches have been developed, advanced methods are still highly desired to ensure water repellency and washability.

(2) The pressures generated by normal activities and human body circulation are primarily distributed in the low-pressure range (< 10 kPa, such as intraocular pressure and intracranial pressure), medium-pressure range (10–100 kPa, such as sound pulses, blood pressure, pulse wave, and human touch) and high-pressure range (> 100 kPa, such as pressure produced in the foot by human body weight) [98, 99]. Widening the sensitivity range of the pressure sensors or electronic skins could enable full-range detection of human motions and broaden their application range, enabling previously unheard-of levels of diagnostic and monitoring capabilities. Although many electronic skins with broad detection ranges have been described recently, their typical sensitivity is too low to meet the demands of a variety of applications. A lot of work has gone into designing micro/nanostructures and choosing materials to solve this issue. In addition, the development of adjustable pressure sensors is a viable strategy [60, 131]. Novel fibrous materials and micro/nanostructure are supposed to be developed further to render outstanding sensitivity and broaden the detection range at the same time. The development of ultra-sensitive electronic skins that even have better sensing properties than biological human skin is dependent on a sensitive response to slight pressure (1 Pa–1 kPa) caused by weak contact with small objects [132, 133].

(3) Individual fibers are porous, and the pores can promise a thermal-wet comfort microenvironment between the interfaces. For triboelectric and piezoelectric devices, a massive porous structure further complicates the dynamic process of charge generation, transport, storage, and capture. Diversified micropore structure gives the triboelectric layer in triboelectric systems a greater specificity, which encourages excellent sensing capabilities and larger power output. The triboelectric charge density, however, may drop if there are too many holes. The triboelectric characteristic can also be weakened by interconnected holes that can readily absorb

water molecules in highly humid environments. By contrast, using an electron gun to introduce external charges into the pores may improve the durability and humidity-resistance properties. The performance of piezoelectric devices can be significantly improved by the formation of gigantic dipoles on the two internal surfaces of micropores or other small defects [134]. However, it is still challenging to fabricate fiber materials with uniform micropores, which makes fabrication techniques and processes more demanding. Additionally, the effect of porous structure on polarization processes needs to be further studied. Furthermore, more precise testing methods and systematic characterization techniques are required to provide detailed and advanced analyses.

(4) Traditional micro-scale fiber materials can be produced on a large scale, nevertheless, it's still difficult to mass produce nano-scale fibers with high production efficiency. Additionally, because of the rise in parasitic resistance and capacitance, which ultimately leads to an increase in impedance and noise level for the entire system, it is difficult to guarantee excellent spatial resolution for large-area electronic skins. As a result, novel electronic skin architectures and epidermal electrodes with excellent conductivity are desperately needed. Additionally, porous fiber materials are uneven and rough, rendering them unsuitable for advanced lithography or etching processes and significantly impeding the advancement of spatial resolution. Therefore, the development of new fabrication methods and structural designs is urgently needed. Fortunately, new strategies to print thin-film transistors and circuits with high-resolution on curvilinear or moving surfaces have been reported recently. Intense pulsed light-induced mass transfer of zinc nanoparticles, for instance, has demonstrated its viability for 3D glass beakers and seashells with complicated surface geometries [135]. Functional circuits can also be directly printed onto free-form surfaces. These presented works have opened many potential methods for fiber-based electronic skins with high resolution.

(5) Electronic skins are expected to exhibit multimodal sensing capabilities and multifunctional properties to truly mimic or even exceed the basic functions of human skins. However, some functions of electronic skins will compromise or even lose when integrating multiple modes into one system. There have been several methods documented for decoupling various input signals to eliminate multimodulus interference and create true multimodal sensors. The two most commonly employed techniques used to identify the appropriate signals and enable more precise multimodal sensing are interference suppression and signal correction. To discern between various signals, it is also a promising technique to integrate the characteristics of materials, structural layouts, and sensing systems [136]. Additionally, additional desirable properties like biodegradability, self-healing, and antibacterial potential have significant practical

benefits and require comprehensive investigation. Biodegradable materials are environmentally benign and in line with national and international strategic goals for technical and scientific advancement. Additionally, electronic skins with self-healing abilities similar to those of human skin would be capable of self-healing mechanical or electrical damage, extending the useful life of electronics. Moreover, antibacterial electronic skin can reduce and inhibit bacterial growth, providing a relatively safe environment for the human body during long-term wearing.

Overall, self-powered electronic skins constructed with smart fibers have shown great potential in developing wearable electronic skins, which may revolutionize the health care field by providing accurate health monitoring technologies, and unprecedented diagnosis and treatment proficiency. The working mechanisms of these sensing systems require further investigation to improve the overall performance of electronic skins. Besides, new fabrication materials and novel device structures need to be developed to achieve improved, functioning electronic skins, ultimately leading to improved quality of life in the era of the Internet of Things.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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