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Application Challenges in Fiber and Textile Electronics

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Modern electronic devices are moving toward miniaturization and integration with an emerging focus on wearable electronics. Due to their close contact with the human body, wearable electronics have new requirements including low weight, small size, and flexibility. Conventional 3D and 2D electronic devices fail to efficiently meet these requirements due to their rigidity and bulkiness. Hence, a new family of 1D fiber-shaped electronic devices including energy-harvesting devices, energy-storage devices, light-emitting devices, and sensing devices has risen to the challenge due to their small diameter, lightweight, flexibility, and weavability into soft textile electronics. The application challenges faced by fiber and textile electronics from single fiber-shaped devices to continuously scalable fabrication, to encapsulation and testing, and to application mode exploration, are discussed. The evolutionary trends of fiber and textile electronics are then summarized. Finally, future directions required to boost their commercialization are highlighted.

1. Introduction

With the advance of human civilization, people have been increasingly seeking for self-cognition, communication, and cooperation. On the one hand, we have tried to explore inward to get a better knowledge of ourselves such as memory, learning, disease, and aging.[1] On the other hand, we are falling into the incremental connection with others by relying on the portable electronics including smartphones and laptops.[2] Those needs have accelerated the development of wearable electronic devices to deal with related information fast, accurately, directly, and conveniently.[3] For example, we can use the Apple Watch to monitor movement status and communicate with others when we exercise, free of holding the other bulky electronic devices. It is important to note that wearable electronic devices often have close contacts with our bodies that are soft and locally movable. Hence, the devices must be flexible and stretchable enough to accommodate the deformation. Moreover, to ensure the comfort and hardly disturb the normal work of recipients, the devices must be lightweight. However, conventional 3D and 2D electronic devices fail to efficiently meet the above requirements due to the rigid and bulky features.

Fiber-shaped electronic devices, adopting 1D structure with small diameters from tens to hundreds of micrometers, have attracted broad interests for wearable electronic fields.[4] Typically, fiber-shaped electronic devices can be prepared on the basis of coaxial, twisting, and interlacing architectures. These fiber-shaped electronic devices are lightweight and flexible, and they can adapt to various deformations like bending, distortion, and stretching. More importantly, it is feasible to weave the fiber-shaped electronic devices into flexible, deformable, and breathable textiles that can facilitate practical applications. Hence, quite lots of researchers have devoted themselves to enhancing device performances.[5] To make full use of the advantages of fiber and textile electronics, stretchable,[6] self-healing,[7] or shape-memory,[8] fiber-shaped electronic devices have been further developed; people have also realized self-powering devices, by integrating energy harvesting with energy storage[9] or by integrating energy device with sensors.[10] The progresses made in fiber and textile electronics have inspired the industry like electronic and clothing industry. The foremost reason lies that fiber-shaped electronic devices can be woven through the well-developed commercial textile technology.[11] For instance, Google and Levi have co-launched Jacquard smart jacket using fiber-shaped sensors.[12] However, it has only one function of reminding the smartphone owner not to leave the smartphone behind. To realize more functions, intense efforts should be made to develop a variety of advanced fiber-shaped electronic devices.

Quantities of fiber-shaped electronic devices that have been reported till now can be mainly divided into the following four classes: 1) fiber-shaped energy-harvesting devices convert the other forms of energy including light and body movement to electricity. They include solar cells[13] and piezoelectric and triboelectric nanogenerators.[14] As the most studied ones, fiber-shaped solar cells, piezoelectric, and triboelectric nanogenerators can be incorporated into clothes efficiently and are primarily expounded in this review. 2) Fiber-shaped energy storage devices have been widely explored to store electric

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energy and then deliver it to power other electronic devices whenever we want. The existing fiber-shaped energy storage devices include the supercapacitor,[15] the lithium (Li)-ion battery,[16] the lithium–sulfur battery,[17] the lithium–air battery,[18] the zinc–air battery,[19] the aluminum–air battery,[20] the sodium-ion battery,[21] the zinc-ion battery,[22] and the silver–zinc battery.[23] Among them, the supercapacitor has been reported mostly due to the easy fabrication, and lithium-ion battery has laid the foundation for the development of other fiber-shaped batteries, which are thus discussed mainly in this review. 3) Light-emitting devices have been developed for various applications such as display, illumination, and phototherapy. According to the working mechanisms, there are electroluminescence,[24] mechanoluminescence,[25] photoluminescence,[26] thermoluminescence,[27] sonoluminescence,[28] and chemiluminescence.[29] Among these, fiber-shaped electroluminescent devices have been developed extensively due to their good controllability, driven by direct current (DC)[30] or alternating current (AC)[31] electrical method, which are expounded mainly later. 4) Fiber-shaped sensors have found great potentials in the field of wearable medical devices for fitness monitoring and medical diagnostics especially as aging populations grow. By virtue of the 1D structure, fiber-shaped sensors can be implanted into the body with little injure or they can detect multiple signals simultaneously after integration into a tiny unit.[32] Fiber-shaped sensors generally work via physical processes on the basis of conducting fiber[33] and optical fiber,[34] and chemical processes based on chemical ligand.[35] Thereinto, fiber optic sensors have already been used in petrochemical, electric power, medical, civil engineering, etc. The detailed discussions about the above three fiber-shaped sensors are presented in the later section.

Despite the great progress made in fiber and textile electronics, we have to realize that most of the research results are far from practical applications due to several existing obstacles. The performances of fiber-shaped electronic devices are not good enough to attract investors. For instance, although fiber-shaped solar cells have achieved a record power conversion efficiency (PCE) of 10%,[36] this value falls far below the certified efficiency of 24.2% for planar solar cells.[37] Besides, fiber-shaped electronic devices often decay in performance further as their lengths increase. Apart from low performances, scalable fabrication is another hard nut to crack if fiber-shaped electronic devices are to be commercialized. For one thing, researchers usually can only realize fiber-shaped electronic devices with the lengths from several to hundreds of millimeters at present owing to the absence of appropriate scale-up processes.[38] For another thing, it seems heavy and complicated to electrically connect these numerous fiber-shaped electronic devices as required. When it comes to the wearable application, safety and stability should be the two key issues to deal with as many fiber-shaped electronic devices involved poisoning and/or flammable components such as lead[39] and acetonitrile.[36] Under the circumstances, researchers should abandon these poisoning and/or flammable components as much as possible or develop reliable encapsulation technologies if these cannot be avoided.

Herein, we have discussed the challenges faced by fiber and textile electronics through all the development stages, namely, from a single device, to continuously scalable fabrication, to encapsulation and testing, and to application mode exploration. Finally, the research status embodied by published papers and patents is summarized, followed by the future directions to boost their commercialization. We hope this review will give those who are interested in the application of fiber and textile electronics a comprehensive knowledge of opportunities and challenges at each stage.

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2. Fiber-Shaped Electronic Devices

As can be seen, the advance of fiber-shaped electronics is often premised on the development of fiber electrodes. Fiber electrodes are the key part to realize high-performance fiber-shaped electronic devices. In the following section, fiber electrodes will be outlined first from the view of materials, followed by the discussion of four families of fiber-shaped electronic devices. Considering that fiber-shaped electronics may work where current commercial counterparts cannot, it is reasonable to highlight the unique advantages to improve further and ignore the unimportant disadvantages.

2.1. Fiber Electrodes

For practical applications, electrical conductivity and mechanical strength are the first two parameters to assess fiber electrodes. Besides, mass density, specific surface area, and cost should also be taken into account.

2.1.1. Metals

Metals feature high mass densities and unexceptionable electrical conductivities. Generally, metal wires, metal nanomaterial hybrid/composite fibers, and metal-coated polymer fibers are used to fabricate fiber and textile electronic devices.

Metal wires have been extensively developed as fiber electrodes for their outstanding conductivities and 1D geometry.

Bare metal wires can be directly used as fiber electrodes in fiber-shaped batteries (e.g., lithium wire)[40] or as the counter electrode (CE) in fiber-shaped solar cells (e.g., platinum (Pt) wire)[41] due to their high electrochemical properties. Metal wires with appropriate work functions, such as titanium (Ti) wire modified by aligned titanium dioxide (TiO_2) nanotube array, have found wide applications in fiber-shaped solar cells.[42] This Ti/TiO_2 wire can also serve as a fiber current collector in fiber-shaped supercapacitors because the TiO_2 nanotubes provide high specific surface areas to deposit active materials such as polyaniline (PANI).[43] Actually, it is necessary to load active materials on metal wires owing to their limited electrochemical activity in most cases. Metal wires with porous surfaces are further prepared to improve the loading amount. For instance, nanoporous gold (Au) wires were explored by a multicyclic electrochemical alloying/dealloying method, followed by depositing manganese dioxide (MnO_2) nanoflowers.[44] Nanoporous Ni wires were also obtained using a similar method.[45] Besides, a simple and clean direct-flame approach using an alcohol lamp was developed to make porous Ni wires, which avoided the use of sacrificial materials or templates.[46] The flame provided the required heat and a gas mixture of H_2, CO, and O_2 for redox treatment of metallic Ni, allowing fast reconstruction of the metal to form micrometer-scale cellular architecture on Ni wire.

Considering the high mass density, low flexibility, and fatigue of metal wires, metal nanomaterial hybrids/composites with other conductive fibers have been thus developed to reduce the use of metals. Besides, metal nanomaterials show higher properties compared with macroscopic metal wires due to the nanometer-sized effect. For example, electrodepositing Pt nanoparticles on graphene fiber contributed to a higher catalytic activity than Pt wire.[47] It was derived from the high surface area and electrical conductivity of graphene fiber which resulted in the homogeneous distribution of Pt nanoparticles to produce more catalytic sites. Similar to metal wires, metal nanomaterials can also function as current collectors. For instance, silver (Ag) and MnO_2 were alternatively and repetitively deposited onto the surface of a commercial carbon nanotube (CNT) yarn to collect rapidly the electrons generated during the charge/discharge process.[48] A core–sheath structured composite fiber with Au-nanoparticle-incorporated hydrophobic CNT as core and PANI-electrodeposited hydrophilic CNT as sheath was fabricated to simultaneously improve electron transport and ion accessibility.[49] Besides nanoparticles, nanosheets were also used to prepare hybrid/composite fibers. A novel graphene/Au nanosheet composite fiber was developed as a fiber-shaped microelectrode nonenzymatic sensor for the electrochemical detection of hydrogen dioxide and glucose.[50]

Another solution to the heavy and fatigable metal wires is to coat metals on lightweight, cheap, and flexible polymer fibers. By weaving copper-coated polybutylene terephthalate (Cu-PBT) fiber counter electrodes and fiber-shaped photoanodes in an interlaced manner, flexible solar cell textiles with various knitting patterns were obtained.[51] The photoanode fibers were also prepared from the Cu-PBT fiber, followed by coating manganese, dye-sensitized zinc oxide (ZnO) nanoarrays, and copper iodide (CuI). Besides, commercial cotton yarn is rather flexible, economical, and lightweight, and can also be used as electrode after deposition of metals such as Ni.[52] To enhance the electrode activity, graphene can be further electrochemically incorporated. By replacing common polymers with elastic polymers, stretchable fiber-shaped electronic devices can be further achieved. For instance, stretchable fiber-shaped supercapacitors were fabricated based on ultrathin Au nanowires impregnated dry-spun styrene–ethylene/butylene–styrene (SEBS) polymer fiber coated by Au film and PANI sequentially.[53]

2.1.2. Conducting Polymers

Conducting polymers have enabled extensive applications in energy harvesting and storing, sensing, and actuating due to their excellent electronic properties.[54] It is challenging to fabricate freestanding fiber electrodes from pure conducting polymers due to their poor mechanical properties and processability. In most cases, conducting polymer fiber electrodes are prepared by coating conducting polymers onto commercial yarns or compositing with other conducting fibers.

To fabricate conducting polymer fibers, mechanical supporting materials are needed to maintain the fibrous shape. For instance, during the fabrication of hollow polypyrrole (PPy) fibers which were realized by electrodepositing PPy on removable Pt wire template, a thin helical Pt wire was embedded in the wall of hollow PPy fiber to support the fiber structure of PPy.[55] Learning from the preparation of helical microfibers in microfluidics using $CaCl_2$ solution to solidify the Na-alginate liquid, poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) fibers were realized by injecting PEDOT:PSS solution into the $CaCl_2$ coagulation bath.[54c] Besides, there might exist the interactions between Cl^- ions and positively charged PEDOT chains and between Ca^{2+} ions and negatively charged PSS chains to facilitate the formation of PEDOT:PSS fibers.[54d]

In most case, conducting polymer fiber electrodes were prepared by coating conducting polymers onto commercial yarns. For example, using commercial polyethylene (PE) terephthalate (PET) yarns as fibrous skeleton, PANI-coated PET yarns were obtained through modified coating processes.[56] Besides, nylon, cotton, and wool yarns were also developed for fiber electrodes by a continuous vapor polymerization of pyrrole.[57] These conducting polymer fiber electrodes can be used in fiber-shaped supercapacitor[58] and solar cells.[59]

Conducting polymers are usually composited with other conducting fibers to fabricate fiber and textile electronic devices. For example, a family of PEDOT/CNT biscrolled yarns was obtained by twist insertion of PEDOT-infiltrated CNT sheets, where the PEDOT was deposited via vapor phase polymerization.[60] Importantly, the PEDOT/CNT biscrolled yarns were weavable, sewable, knottable, and braidable, and were further used to fabricate fiber-shaped supercapacitor as a demonstration. Other conducting polymers like PANI were also used to prepare composite electrodes with CNT fiber through an easy electrodeposition process.[61] Adopting different in situ dilute polymerizations, ordered PANI nanowire arrays were realized in the CNT yarn.[62] Conducting polymers can also enable fiber-shaped smart devices as they can respond to various environmental stimuli. By incorporation of CNTs, the resulting PANI composite fibers showed colorimetric changes reversibly upon the application of currents or voltages, and the colors could be easily controlled by currents or voltages and perceived by the naked eyes, which contributed to smart fiber and textile electronic devices with displaying functionality.[63]

2.1.3. Carbon Materials

Carbon materials have been widely adopted in fiber and textile electronic devices for their relatively low mass density and simultaneously high tensile strength, electrical conductivity, and specific surface area. Among them, CNT, graphene, carbon fiber, and their hybrid/composite materials are generally explored to develop fiber electrodes. Besides, it is easy to prepare multifunctional fiber electrodes by combining carbon materials with functional polymer fibers.

The mechanical, electrical, thermal, and optical properties of individual CNTs and their 1D structure endow CNTs great potentials in fiber and textile electronics.[64] However, in most cases, CNT being used in composite materials as disordered fillers showed low performances. Developing ordered CNT architectures can more effectively extend the properties of individual CNTs to macroscopic materials such as aligned CNT fibers and sheets,[65] as the anisotropic properties of aligned CNTs match well the 1D geometry of fiber electrodes. Aligned CNT fibers can be fabricated by a spinning process from CNT solution,[65c] CNT aerogel in situ in the reactor,[65d] vertically aligned CNT array,[65e] or aligned CNT sheets.[65f] To improve the electrode performance, CNT hybrid/composite fibers including CNT/ordered mesoporous carbon (OMC),[66] CNT/Pt,[67] CNT/Ag,[68] CNT/PANI,[68] CNT/PPy,[68] CNT/reduced graphene oxide (RGO),[69] and CNT/MnO_2 fibers were synthesized.[69] Besides, CNT composite fibers can enable functional fiber electrodes by twisting CNT sheets equipped with functional materials such as fluorescent dye particles[70] or magnetic nanoparticles,[71] presenting fluorescence colors or magnetic response.

Graphene materials have extensive applications in 2D and 3D electronic devices owing to their 2D structure and high specific surface area.[72] To fabricate 1D fiber-shaped electronics, macroscopic graphene fiber with high mechanical strength, electrical conductivity, and flexibility should be realized at first. Hence, a scalable nonliquid-crystal spinning process was developed to produce continuously graphene fibers with tailored structures.[73] Note that CNT can also be introduced to achieve hybrid fibers by a coaxial wet-spinning assembly approach[74] or a hydrothermal process in a silica capillary column microreactor.[75] To improve the electrode performances, graphene composite fibers are further developed by incorporating one kind of active materials such as conducting polymer, PEDOT:PSS,[76] or more kinds of active materials such as metal oxide MnO_2 and conducting polymer PPy.[77]

Compared with CNT and graphene, carbon fiber may be very promising from a viewpoint of applications for its industrial availability and lower cost.[78] However, carbon fiber demonstrates low electrochemical properties and specific surface area,[15] and further modification of carbon fiber is required in most cases. For instance, PEDOT:PSS,[79] molybdenum disulfide (MoS_2),[80] and Pt nanoparticles[9] were incorporated to improve the electrocatalytic properties; MoS_2[80] and hydrated ruthenium dioxide ($RuO_2 \cdot xH_2O$)[9] were coated to improve the specific capacitance. Besides, biomaterials such as juglone-doped active materials can also be incorporated.[18]

To prepare functional fiber electrodes for dynamic wearable applications, carbon materials are coated onto functional polymer fibers. For example, stretchable fiber electrodes and electronic devices were produced by loading CNT or CNT/PANI composite sheets on elastic polymer fibers.[81] Replacing the elastic polymer fiber with self-healing and shape-memory polymer fibers, self-healing[7] and shape-memory[8] fiber electrodes and electronic devices can be achieved further.

For commercial applications, long fiber electrodes with high electrical conductivities should be realized, which is related to massive product throughputs and reduced industrial costs. Although metals, conducting polymers, and carbon materials have been reported in numerous studies, they are not all suited for commercial applications. On the one hand, conducting polymers (electrical conductivities of 10^{-3}–10^3 S cm^{-1} usually)[82] and carbon materials (electrical conductivities of 10–10^4 S cm^{-1} usually)[83] are not high enough in electrical conductivity to realize long and effective fiber electrodes. In contrast, frequently used metals show electrical conductivities around 10^5 S cm^{-1}.[83c] On the other hand, due to the costly or/and time-consuming process, such as slow in situ spinning based on high-temperature chemical vapor deposition (CVD)[84] or slow wet spinning accompanied by a coagulating bath and drying process,[47] most fiber electrodes from carbon materials and conducting polymers are realized only at the laboratory now. Hence, metal-based electrodes show the best potential in practical applications among which metal-coated fibers may provide the optimal choice exempting from the high mass density and low flexibility of metal wires. More efforts are required to develop effective methods to realize thin and uniform deposition of metal on fiber substrates.

2.2. Energy-Harvesting Devices

2.2.1. From Solar Energy

Photovoltaic technologies are typically divided into three categories: wafer-based (first-generation photovoltaics, e.g., crystalline silicon), thin-film (second-generation photovoltaics, e.g., amorphous silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS)), and emerging solar cells (third-generation photovoltaics, e.g., dye-sensitized solar cells (DSSCs), polymer solar cells (PSCs), and perovskite solar cells (PeSCs)). So far, silicon solar cells dominate the photovoltaic market overwhelmingly with PCEs of commercial modules at around 20% and stability over 20 years.[85] Instead, the research spotlight has been shining on the third-generation photovoltaics which promise to be more flexible, less expensive, and easily functionalized such as transparent, stretchable, and color/shape controllable, compared with traditional silicon solar cells.[85,86]

Developing the third-generation solar cells into 1D fiber form potentially makes them well conformed to a curved surface, independent of incident light angle, easily integrated with automobiles, and portable, implantable, and wearable.[5b,87]

Generally, fiber-shaped solar cells are made up of two fiber electrodes with one coated by electron transport materials (ETM, e.g., TiO_2 and ZnO), photoactive materials (e.g., dye N719 for DSSCs, poly(3-hexylthiophene):[6,6]-phenyl-C_{61}-butyric acid methyl ester (P3HT:PC_{61}BM) for PSCs, and perovskite materials for PeSCs), and hole-transport materials (HTM, e.g., PEDOT:PSS and CuI) in succession. Effective ETM and HTM possess appropriate energy levels to extract aimed carriers and block the opposite ones where electrons are extracted at the fiber electrode/ETM interface and holes at the other fiber electrode/HTM interface. Generally, PCE and lifetime are used to evaluate the photovoltaic performances of fiber-shaped solar cells similar to traditional solar cells. **Figure 1**a summarizes the development of fiber-shaped DSSCs,[13,36,42a,47,49,67,80,88] PSCs,[11b,89] and PeSCs[39,90] in terms of the PCE.

Fiber-shaped DSSCs are composed of fiber photoanode, fiber CE, dye, and electrolyte in general. Fiber photoanodes should have appropriate energy levels to match the dye and electrolyte, and large specific surface areas to absorb dye molecules besides the necessary electrical conductivity and mechanical strength. Therefore, a fiber-shaped DSSC based on two CNT fibers, one absorbing dye twisted with the other, showed a much low PCE due to the unmatched energy level.[91] ETM TiO_2 nanoparticles were introduced to the CNT fiber to load dye and contributed to a PCE of 2.94%.[92] The ETM was important for light harvesting and electron collection, and PCE could be enhanced from 6.72%[88f] to 8.07%[93] by replacing TiO_2 nanotube array with TiO_2 micrometer-cone array modified by a TiO_2 multilayer structure comprising compact, light scattering, and porous layers based on Ti wire. Pt wire is frequently used as fiber CE in fiber-shaped DSSCs. To replace the expensive and heavy Pt wire, fibers based on carbon materials and their hybrid/composite materials are adopted, which demonstrate higher flexibility and lower density than Pt wire. Further incorporation of Pt nanoparticles onto those fibers, such as graphene fiber, yielded a certified PCE of 8.45% which was higher than the Pt wire.[47] Considering the aqueous solution for Pt deposition, a core–sheath structured CNT fiber with hydrophilic CNT as the sheath was designed to realize effective deposition of Pt nanoparticles, resulting in a record PCE of 10% in the field of fiber-shaped solar cells.[36] Although fiber-shaped DSSCs based on liquid electrolytes as mentioned above have made great progresses, there exist the leakage and volatilization of liquid electrolytes especially under deformation and high temperature, which cause poor stability, short lifetime, and low safety. Hence, quasi-solid-state fiber-shaped DSSCs were developed based on a stable gel electrolyte consisting of polymer and ionic liquid with a PCE of 5.47 % that could be maintained by 90% after 30 days.[94] For better wearable compatibility, all-solid-state DSSCs were realized, which led to a PCE of 1.3%.[51a] Here, it was CuI HTM, not electrolyte, to complete the close circle of charge transfer.

Fiber-shaped PSCs show advantages of all solid state, thinness, and extended lifetime without encapsulation over fiber-shaped DSSCs based on liquid electrolyte but lower PCEs than the latter. The performances of fiber-shaped PSCs depend heavily on the processing condition due to the 1D electrode geometry. Different from the widely used spin-coating method in the conventional planar PSCs,[95] dip-coating and electrochemical methods are frequently used for the fiber-shaped PSC. By wrapping an aligned CNT fiber around a Ti wire coated by TiO_2 nanotubes, P3HT:PC_{71}BM, and PEDOT:PSS, a fiber-shaped PSC with a PCE of 0.15% was produced.[89d] To realize a higher efficiency, TiO_2 nanoparticles were grown on the TiO_2 nanotubes which contributed to a PCE of 1.78%.[89e] Another fiber-shaped PSCs with structure of stainless steel (SS) wire/ZnO/P3HT:PC_{61}BM/PEDOT:PSS/CNT achieved a PCE of 2.3% without encapsulation.[89c] After encapsulation and optimization, PCE reached 3.27%.[89b]

Fiber-shaped PeSCs were first realized in 2014 with a PCE of 3.3%,[90a] showing great potentials in practical applications thanks to both high efficiency and all solid state combining the advantages of DSSCs and PSCs. Increased research attention has since been paid to further enhance their performances. Different from the first report based on TiO_2 particle–modified SS wire, a novel fiber-shaped PeSC was prepared with the TiO_2 layer replaced by obelisk-like ZnO arrays that benefited effective penetration of perovskites into the voids of ZnO and a PCE of 3.8% was produced finally.[90b] Further, a higher PCE of 7.1% was achieved using an electrochemical deposition method, namely, anodization of the titanium wire to grow aligned TiO_2 nanotube array and a cathodic deposition of PbO to synthesize perovskite layer.[90c] Utilizing a polyethylene naphthalate/indium tin oxide (PEN/ITO) strip as the substrate, light-harvesting large crystals of perovskite layer were achieved, and a novel family of 1D strip-shaped PeSCs was obtained with a high

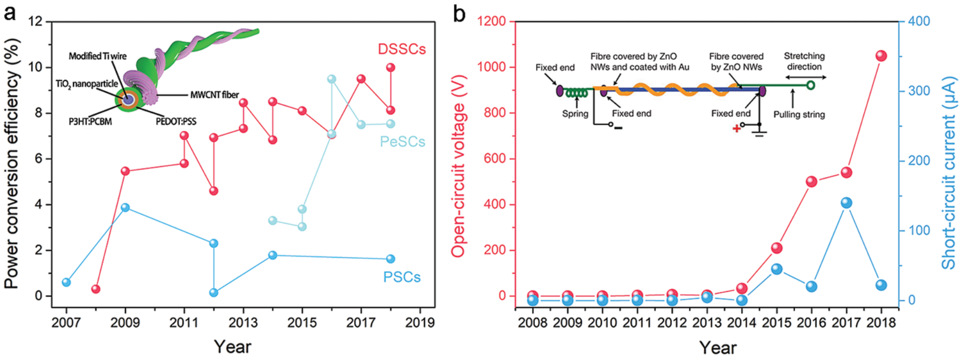

Figure 1. a,b) Recent progress in fiber- and textile-based solar cells (a) and nanogenerators (b). The inset structural illustrations show a typical DSSC (a) and PENG (b). Inset of (a): Reproduced with permission.[89e] Copyright 2014, Wiley-VCH. Inset of (b): Reproduced with permission.[98] Copyright 2008, Nature Publishing Group.

PCE of 9.49% where the CNT sheet acted as both hole transport and collection layers.[90d] For a better control of perovskite morphology and thickness, electrical-heating-assisted continuous coating was proposed based on metal wires, which allowed improved film coverage, controlled thickness, and reproducible and continuous fabrication.[90e] Besides, this electrical heating could accelerate film formation and perovskite transformation. The resulting devices realized an average PCE of 6.58% with the highest value at 7.50%.

Functional fiber-shaped solar cells including DSSCs, PSCs, and PeSCs were also developed for special applications, such as magnetic-field-responsive[71] and stretchable[96] power systems. Photovoltaic textiles have also been developed to meet the power requirements of commercial electronic devices as the output power of a single fiber-shaped solar cell is limited. A successful case of flexible and lightweight photovoltaic textile using an industrial loom was realized from fiber-shaped PSCs by interlacing cathode fibers with anode fibers, which could promote the commercialization of fiber-shaped PSCs.[11b]

Although PCE and lifetime are important for fiber-shaped solar cells, it is imperative to include other evaluation indicators to compare the widely reported fiber-shaped solar cells, including, but not limited to, power per weight ratio (W/g), cell length, cell diameter, bending radius (or angle), bending cycle, and efficiency retention, given the unique 1D structure and practical application of fiber-shaped solar cells. Besides, it is equally imperative to attempt large-scale weaving and electrical connection of photovoltaic textiles excluding expensive/scarce/toxic materials and complex processing conditions in view of processing ease and cost. The photovoltaic textiles obtained using an industrial loom represent key stepping stones for their commercialization.[11b] However, it is still challenging to realize scalable and continuous fabrication of high-performance fiber unit in the photovoltaic textiles, to be exactly, the fiber-shaped solar cell.

2.2.2. From Mechanical Energy

Mechanical energy is the most widely distributed energy source, and it is abundant in various forms and frequently locates in our local environment such as human motion, walking, mechanical triggering, and wind. However, vast majority of these kinds of mechanical energy are ignored and wasted. In the last dozen years, new technologies based on nanotechnology and nanomaterials emerge to harvest mechanical energy from the environment around us, which is expected to be used to power wearable electronic devices. Nanogenerators including piezoelectric nanogenerators (PENGs) and triboelectric nanogenerators (TENGs) are the main technology for converting mechanical energy into electricity. An outstanding feature of them is its simplistic and diverse structures that can be designed into fiber or textile-shaped configuration, which allows them to be well integrated with fiber and textile electronic devices as power systems.

The PENGs are based on the piezoelectric effect that forms piezopotential in the piezoelectric material under external force. Common piezoelectric materials include ZnO, $BaTiO_3$, $PbTiO_3$, $PbZrTiO_3$, and poly(vinylidenefluoride) (PVDF).[97] ZnO and PVDF are popular for the fabrication of fiber and textile-based PENG. Fiber-shaped PENG was previously made from piezoelectric ZnO nanowires radially grown around Kevlar fibers.[98] Two hybrid fibers were twisted to form the complete PENG, which generated power on pulling/releasing the string owing to the deflection and bending of the ZnO nanowires. A short-circuit output current of ≈5 pA and an open-circuit output voltage of ≈1 mV were achieved from a double-fiber PENG. To improve the performance, a hybrid-fiber PENG was proposed with ZnO nanowires and PVDF-coated conducting fiber.[99] By attaching this PENG with a length of 2 cm on a human arm that was folded and released at an angle of ≈90°, the output voltage, current density, and power density reached ≈0.1 V, 10 nA cm^{-2}, and 16 μW cm^{-3}, respectively.

Different from the piezoelectric effect, the triboelectric effect is conventionally known since the ancient Greek era, while usually taken as a negative effect. Until recently, the TENGs are developed to convert mechanical energy into electricity by a conjunction of triboelectric effect and electrostatic induction, which can serve as an energy source for the electronic device. For example, a fiber-shaped TENG was made by twisting a CNT-coated cotton thread and a CNT/polytetrafluoroethylene (PTFE)-coated cotton thread.[100] The TENG can efficiently convert biomechanical motion/vibration energy into electricity with an average output power density of ≈0.1 μW cm^{-2}. Moreover, it is demonstrated as a power shirt, which could drive a wireless body-temperature sensor system.

In order to more efficiently collect mechanical energy, the fiber-shaped hybrid nanogenerators were also developed based on principles of piezoelectric and triboelectric effects, as well as their cumulative effects. A fiber-shaped hybrid nanogenerator that exhibited a core–sheath structure with TENG at the core and PENG at the coaxial was demonstrated.[10] The coaxial design not only improves the collection efficiency of mechanical energy but also generates electricity when the TENG core does not work. The output power density of the PENG and TENG can reach 1.02 and 4.26 μW cm^{-2}, respectively. In addition, the PENG and TENG can also be fabricated by directly using the textile as substrates or by weaving the fiber electrode into textile. The textile-based nanogenerators usually have higher performances. For example, for a triboelectric textile using a commercially available 3D spacer fabric coated with poly(dimethylsiloxane) (PDMS), it generated an open-circuit voltage up to 500 V, a short-circuit current amplitude of 20 μA, and a peak power density of 153.8 mW m^{-2}.[101]

Since 2008, numerous studies have led to continuous improvements in the performance of fiber and textile-shaped nanogenerators as demonstrated in Figure 1b.[98,101,102] However, although the output voltage and current of the fiber and textile-shaped nanogenerators have been remarkably improved, especially the output voltage has exceeded 1000 V, and the output current is still a bottleneck. Most reported output currents from nanogenerators range from a few microamperes to a few hundred microamperes, which limit their applications. How to improve the output current of nanogenerators has become a huge challenge in this field. The development of effective weaving methods such as connection or integration in series may represent a promising strategy to solve the above problem.

2.3. Energy Storage Devices

Besides energy-harvesting devices, a variety of fiber-shaped energy storage devices have also been widely studied to meet the power demand of wearable electronics. A fiber-shaped supercapacitor was proposed by twisting single-walled CNT fibers as electrodes.[61] Later, fiber-shaped supercapacitors in a coaxial configuration also appeared.[103] Recently, deformable, chromic, and self-healing fiber-shaped supercapacitors were obtained to better satisfy the wearable and intelligentized applications.[104] The fiber-shaped supercapacitor exhibited some advantages such as a high power density of 10 kW kg^{-1}, rapid charging/discharging, and long cycle life above 10^5 cycles. However, their applications are greatly hindered by the low energy density. To this end, the fiber-shaped lithium-ion battery was developed to achieve high energy density.[105]

2.3.1. Fiber-Shaped Supercapacitors

Similar to the planar counterparts, the fiber-shaped supercapacitors are divided into electrostatic double-layer capacitor and pseudocapacitor according to the working mechanism. A typical fiber-shaped supercapacitor is composed of conductive fibers as electrodes and electrolyte as a separator. The fiber electrode is essential to efficient charge storage/transportation and mechanical flexibility. A variety of conductive fibers were developed to serve as electrodes, including metal wire,[106] CNT fiber,[103] graphene fiber,[74] and conductive polymer composited with CNT[61] or metal oxide.[107] Recently, the CNT fiber was of principal interest due to their advantages such as high conductivity, large specific surface area, high mechanical strength, lightweight, and flexibility.[103] Unfortunately, the CNT fiber is far from being usable from perspective of practical applications due to the challenges in continuous preparation and high cost. At present stage, the metal-based fiber, e.g., metal wire and metal-coated polymer fiber, was considered as one suitable electrode candidate due to its high conductivity and commercial availability.[106,108] The polymer gel including poly(vinyl alcohol) (PVA) and chitosan was generally favored as solid-state electrolyte for safety, flexibility, and even stretchability of fiber-shaped supercapacitors.[103,109] Typically, the fiber-shaped supercapacitor could be fabricated in twisting or coaxial configurations (**Figure 2**a,b). For twisting structure, fiber electrodes could be independently prepared prior to twisting operation.[61] For coaxial structure, it is composed of inner electrode, electrolyte, and outer electrode.[103] Compared with twisting structure, the coaxial structure provides higher mechanical and electrochemical stability under deformation because of the stronger contact interface based on the layer-by-layer structure.

In order to avoid breaking due to deformation during use, increasing efforts have recently focused on the development of stretchable fiber-shaped supercapacitors. An elastic rubber fiber was sequentially wound with aligned CNT sheet as two electrodes with PVA/H_2SO_4 electrolyte.[104a] The specific capacitance of the obtained fiber-shaped supercapacitor can maintain stability after stretched by 100 cycles at a strain of 75%. By gluing a fiber-shaped supercapacitor onto a prestrained spandex fiber with the additional gel electrolyte as an adhesive, a sinusoidal bucking fiber-shaped supercapacitor was also fabricated with a tensile strain of 100%.[104b]

Furthermore, considerable interests have been attracted to exploring the incorporation of more functionalities into the fiber-shaped supercapacitors, such as color change and self-healing. Electrochromic fiber-shaped supercapacitor has been designed to monitor the charging states by introducing PANI into aligned CNT sheet as a pseudocapacitive active component

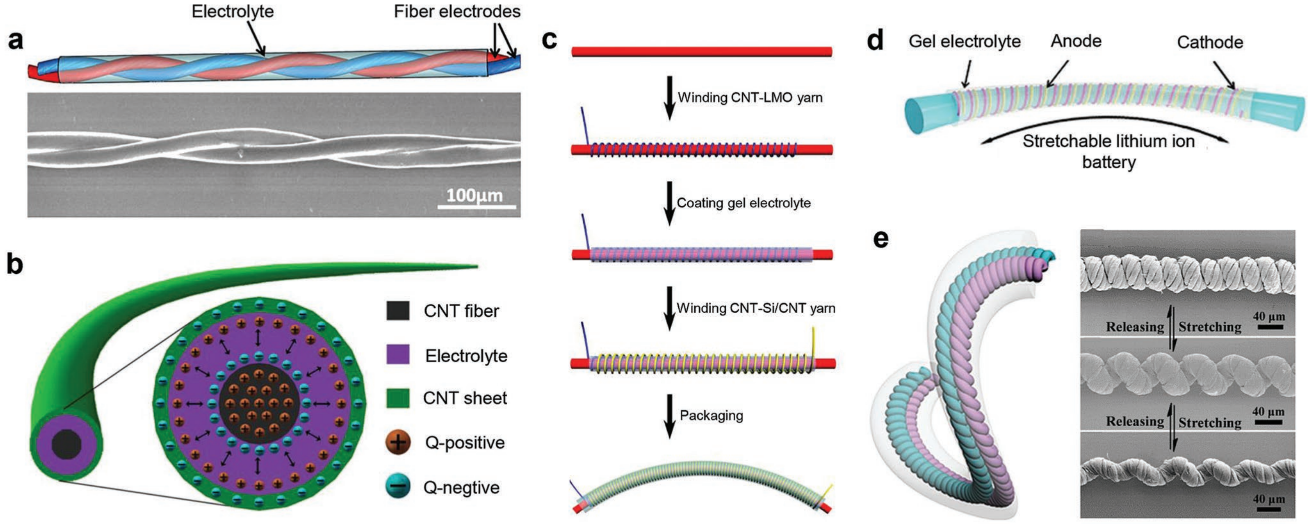

Figure 2. Fiber-shaped energy-storage devices. a) Schematic illustration and scanning electron microscopy (SEM) image of a fiber-shaped supercapacitor in a twisted configuration. Reproduced with permission.[61] Copyright 2013, Royal Society of Chemistry. b) Schematic illustration of a fiber-shaped supercapacitor in a coaxial configuration. Reproduced with permission.[103] Copyright 2013, Wiley-VCH. c) Schematic illustration of the fabrication of a fiber-shaped lithium-ion battery using CNT/Si and CNT/$LiMn_2O_4$ (CNT/LMO) as electrodes. Reproduced with permission.[111a] Copyright 2014, American Chemical Society. d) Schematic illustration of a stretchable fiber-shaped lithium-ion battery based on an elastic polymer substrate. Reproduced with permission.[110] Copyright 2016, Wiley-VCH. e) Schematic illustration (left) and SEM images of a stretchable fiber-shaped lithium-ion battery based on spring-like CNT fibers. Reproduced with permission.[112b] Copyright 2014, Wiley-VCH.

as well as electrochromic-active component.[63] The fiber-shaped supercapacitor showed rapid and reversible color changes among different working states. Self-healing function can recover fiber-shaped supercapacitor automatically from physical damages during body movements, which are generally achieved by introducing self-healing materials into the fiber electrodes. For example, a self-healing fiber-shaped supercapacitor was developed by assembling two self-healing CNTs/polymer composite fiber electrodes with PVA/H_2SO_4 electrolyte, which can maintain the high capacitance after breaking and self-healing.[7] The self-healing capability can be further improved by introducing magnetic partials (Fe_2O_3) into the electrode to assist the healing property under magnetic force.[104c]

2.3.2. Fiber-Shaped Lithium-Ion Batteries

Since it has been commercialized from 1990, lithium-ion battery has exhibited some superiorities of high energy density, long cyclic stability, high working voltage, and environmental benignity. It thus has become one of the most ubiquitous power supplies for electronic products. However, commercial lithium-ion battery is rigid and difficult to satisfy the requirements of wearable electronics. The fiber-shaped lithium-ion battery possesses a high flexibility and could be woven into fabrics with good air permeability, which is highly desirable for wearable electronics and arises a wide research interest.

Similar to the fiber-shaped supercapacitor, the fiber-shaped lithium-ion battery was also fabricated with twisting and coaxial configurations.[110] The comprehensive properties of fiber electrodes are essential to the device performances. For instance, the fiber electrode serving as a current collector is expected to be highly conductive to efficiently transport electrons. Besides, it is preferable that the fiber electrode processes a porous structure to efficiently incorporate electrochemically active materials. Furthermore, as the main mechanical skeleton of the battery, the fiber electrode is required to be strong and flexible for wearable applications. The metal wires with high electrical conductivities were preferred to serve as the electrodes at the early stage, but their relatively heavy weight and mechanical rigidity were disadvantageous from the viewpoint of high specific capacity and flexibility. Although polymer-based fibers and their composites are lightweight and flexible, they suffer from low electrical conductivities. To this end, increasing efforts have been made to develop a series of hybrid fiber electrodes based on aligned CNT fibers. A variety of efficient active materials including MnO_2, silicon, $LiMn_2O_4$, and $Li_4Ti_5O_{12}$ could be readily incorporated into the aligned CNT fiber by using electrochemical/physical deposition, dip-coating, and co-scrolling methods.[105,111] For instance, the fiber-shaped lithium-ion battery using CNT/MnO_2 hybrid fiber as the cathode exhibited a specific capacity of 109.62 mAh cm^{-3} or 218.32 mAh g^{-1} (Figure 2c), and a higher specific capacity of 1600 mAh g^{-1} at a current density of 1 A g^{-1} was achieved by a half-cell using a CNT/Si hybrid fiber electrode.[111a]

To better meet the requirements for wearable electronics, it is necessary to make fiber-shaped batteries stretchable. A stretchable fiber-shaped battery may be produced by using elastic fiber electrode or designing a spring structure.[112] Typically, the fiber-shaped lithium-ion battery could be fabricated by successively wrapping CNT/$Li_4Ti_5O_{12}$ and CNT/$LiMn_2O_4$ hybrid electrodes onto a poly(dimethylsiloxane) elastic substrate (Figure 2d), followed by coating a thin layer of gel electrolyte and inserting into a heat-shrinkable tube.[112a] The specific capacity of 88% was well maintained after a stretching strain of 600%. However, the use of elastic polymer substrate increased the weight and volume with decreased specific capacity. To this end, the elastic polymer substrate could be replaced by designing a spring-like CNT fiber through an overtwisting operation (Figure 2e).[112b] Compared with previous stretchable fiber-shaped lithium-ion batteries using elastomeric polymer substrates, the volume and weight were efficiently decreased with a higher specific capacity of 2.2 mAh m^{-1}. The specific capacity could be well maintained by above 85% under stretching by 100%.

Besides lithium-ion batteries, some high-energy-density fiber-shaped lithium–metal batteries, such as lithium–sulfur and lithium–air batteries, have been well developed although in just a few years. In 2016, a fiber-shaped lithium–sulfur battery was first developed from a carbon nanostructured hybrid fiber as the sulfur cathode and a lithium wire as the anode.[17] The fiber cathode showed a high capacity over 800 mAh g^{-1} at a current rate of 0.1 C. A fiber-shaped lithium–air battery was later developed by sequentially in situ polymerizing gel electrolyte on a lithium wire and wrapping a CNT sheet as the air electrode.[18] The fiber-shaped lithium–air battery showed a discharge capacity of 12 470 mAh g^{-1} and could stably work for 100 cycles in air. Although these kinds of lithium–metal batteries demonstrated extremely specific high capacities and energy densities, their serious side effects have not been well addressed yet, making them far away from practical applications.

Although obvious advances have been made to pursue high electrochemical performances, flexibility, and stretchability, the current fiber-shaped energy storage devices are still far away from satisfying the demands for practical applications. The fiber electrode material is one of the most important factors for electrochemical performance. An ideal fiber electrode should simultaneously show high electrical conductivity, large specific surface area, high mechanical strength, lightweight, and high flexibility or strechability. The metal wire shows the highest conductivity among the current electrode materials, but it suffers from heavy weight and insufficient flexibility. The CNT fiber seems to be a good candidate, but its relatively low conductivity tends to cause a large internal resistance, and fiber-shaped storage devices are thus limited to tens of centimeters in length. Hence, more efforts should be made to develop fiber electrodes for large-scale applications. Besides, it is urgent to optimize the active materials and structures for better interfaces among active material, electrolyte, and fiber electrode to enhance the energy storage capability. Additionally, the safety issue should be carefully addressed as flammability, toxicity, and leakage of the organic electrolyte may occur in practical applications. Both high-performance solid electrolyte and efficient encapsulation strategy are urgently needed to solve these problems.

2.4. Light-Emitting Devices

Wearable light-emitting devices have attracted extensive attentions as an emerging technology in the field of electronic

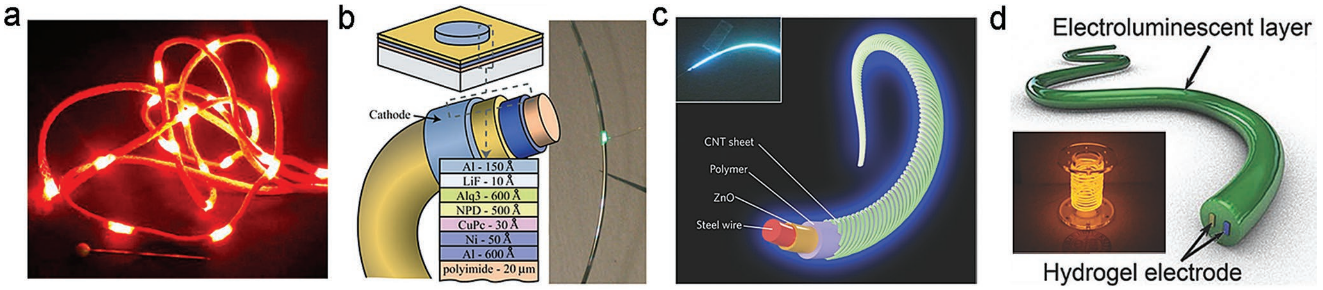

Figure 3. a) An optical image of an illuminated LED yarn. Reproduced with permission.[114a] Copyright 2018, MDPI. b–d) Schematic of device structure and photograph of fiber-shaped OLED, fiber-shaped PLEC, and ACEL fiber, respectively. b) Reproduced with permission.[114b] Copyright 2007, Wiley-VCH. c) Reproduced with permission.[114c] Copyright 2015, Nature Publishing Group. d) Reproduced with permission.[31] Copyright 2018, Wiley-VCH.

textile, which can be applied from wearable display to visual sensing, human–machine communication, and therapy. Numerous strategies have been developed to fabricate wearable light-emitting devices such as the use of ultrathin and/or stretchable polymer substrates.[113] Furthermore, strategies of directly achieving light-emitting devices in a fiber format have been pursued by utilizing inorganic light-emitting diodes (LEDs), organic LEDs (OLEDs), polymer light-emitting electrochemical cells (PLECs), and alternating current electroluminescent (ACEL) phosphors (**Figure 3**).[31,114] They have a competitive advantage over other strategies for the application of electronic textiles, i.e., they can be incorporated into clothes or others without losing the inherent properties of textiles such as flexibility, breathability, and comfort. According to the driving method, the fiber-shaped light-emitting devices can be categorized into DC- and AC-driven light-emitting devices.

2.4.1. Direct Current Light-Emitting Devices

The DC-driven light-emitting devices have the advantages of high efficiency and high luminance, which make them popular in display applications. Most of the earlier researches focused on developing the integration of traditional LEDs onto the yarns or fabrics (Figure 3a),[114a] which is simple and practical, and has been widely used in fashion shows. However, the traditional LEDs are rigid and thick, which cannot meet the requirements of flexibility. They are also easy to be damaged in the drape behavior. Another strategy is the integration of polymer optical fibers onto fabric.[115] Numerous tightly intertwined polymer optical fibers in fabrics enable efficient large-area light emission, which is particularly suitable for phototherapy. Nevertheless, the polymer optical fibers are rather thick and stiff in comparison to conventional textile fibers, and they also need a laser or LED as the light source.

Recently, with the progress of material science and processing technology, the flexible fiber–shaped light-emitting devices have made remarkable progresses. Fiber-shaped OLEDs from small molecule were constructed by sequentially depositing Al/Ni/copper phthalocyanine/*N*,*N*′-di-1-naphthyl-*N*,*N*′-diphenyl-1,1′-biphenyl-4,4′-diamine/tris(8-hydroxyquinoline) aluminum/LiF/Al on a polyimide (PI)-coated silica fiber using vacuum thermal evaporation (Figure 3b).[114b] The fiber-shaped OLED shows luminescence efficiency similar to those constructed on planar substrates. However, the vacuum deposition method is complex for the fabrication of fiber devices, which has limited suitability for large-scale preparation. Later, fiber-shaped polymer LEDs (or PLEDs) were designed to increase the life time.[30] In contrast to the OLED, PLED showed simpler device configuration that consists only of a polymer emissive layer (poly(phenylvinylene):super yellow) between two electrodes (PEDOT:PSS and LiF/Al). Moreover, a relatively simple dip-coating method was utilized to concentrically coat polymer layers onto fibers. The fiber-shaped PLEDs demonstrated a high luminance of over 1000 cd m^{-2} at an operation voltage less than 10 V, which is sufficiently high for application in wearable displays.[30] Unfortunately, the vacuum deposition method was required to deposit the LiF/Al layer, which is difficult for a continuous fabrication at large scale.

PLECs have also been widely studied for the construction of flexible light-emitting devices. Similar to PLEDs, PLECs have a structure that is composed of two electrodes connected to a polymer emissive layer. However, PLECs have mobile ions and an in situ light-emitting p–i–n junction that can be formed in the polymer emissive layer, thereby offering some advantages.[116] Compared with the OLEDs, PLECs do not require the use of low-work-function cathodes that are sensitive to air. More importantly, PLECs can be effectively operated with relatively rougher surfaces, which is significant for scaling them up aiming at practical applications. Fiber-shaped PLECs had been previously realized by all-solution-based processes. They showed a coaxial structure that included a ZnO nanoparticle-modified stainless fiber cathode and an aligned CNT sheet anode, with a polymer-emitting layer sandwiched between them (Figure 3c).[114c] They showed a maximal luminance of 609 cd m^{-2} at a bias of 13 V. Moreover, the luminance was maintained by above 90% after 100 bending cycles with a bending radius of 6 mm.

There are still some issues related to the performance and stability of the DC-driven light-emitting devices. For example, the emitting materials of OLED and PLEC are sensitive to oxygen and water, which lead to a rapid deterioration in performance. To this end, an encapsulation layer is required. A 30 nm thick Al_2O_3 layer was deposited to cover the surface of fiber-shaped PLEDs for encapsulation, but only 10 h operational half lifetime was achieved.[30] More efforts are needed to develop new sealing materials, and technologies that can be scaled up for a continuous fabrication are highly desired for practical applications.

2.4.2. Alternating Current Light-Emitting Devices

A typical AC-driven light-emitting device is fabricated by sandwiching an emissive layer between two electrodes. The emissive layer consists of an ACEL phosphor powder in a binder, and a dielectric layer can also be inserted between the emissive layer and rear electrode. When excited by an AC electric field, they can emit light, and the colors were controlled by the phosphor materials.[117] The most commonly used phosphor material was zinc sulfide (ZnS) and their alloyed materials,[118] which are cheaper than the organic materials for the DC-driven light-emitting devices. Moreover, in contrast to the DC-driven light-emitting devices, there was no strict requirement on the uniformity of the active layer, which favors a large-scale production. Therefore, AC-driven light-emitting devices may be better for practical applications of fiber-shaped lighting and displaying.

In a typical construction process, a silver-coated nylon yarn was used as the conductive core yarn, followed by sequentially coating the insulating paste, phosphor ink, and encapsulant layer. A second conductive yarn is then wound on the further modified core yarn.[119] All used materials are commercially available. The completed electroluminescent yarn showed a weight of 0.48 g m^{-1} and diameter of 0.72 mm, which can be inlayed into a knitted structure to produce electroluminescent fabric. However, the ACEL fiber showed poor illuminance that was less than 1 cd m^{-2}. Recently, a coaxial ACEL fiber consisting of silver-nanowire-based electrodes, a ZnS phosphor layer, and silicone dielectric and encapsulation layer was fabricated by all solution processes.[120] The as-fabricated ACEL fiber demonstrated uniform and bright luminance of 202 cd m^{-2} (195 V, 2 kHz). It also exhibited both high flexibility and mechanical stability, being capable of maintaining about 91% of luminance after 500 bending cycles.

It is highly desired to develop stretchable electroluminescent fibers to better fit textile electronics. However, it is challenging and has not been realized for the construction of fiber-shaped DC light-emitting devices due to the easy damage of active layers under stretching. For the AC light-emitting devices, the active layers can accommodate more deformations without failing to work, it is available to construct stretchable electroluminescent fibers. For example, a stretchable ACEL fiber was made by sandwiching elastic ZnS phosphors/silicone composite emissive layer with two aligned CNT sheets.[121] It showed a maximal luminance of 14.48 cd m^{-2} (6 V μm^{-1}, 1.5 kHz), and it can be stretched by over 200% without obvious decay in luminance property. Meanwhile, a one-step extrusion method was further developed to continuously produce electroluminescent fibers, in which the out emissive layer and two inner parallel hydrogel electrodes were simultaneously extruded through a custom-designed needle by three injection pumps (Figure 3d).[31] The luminance was significantly enhanced to 233.4 cd m^{-2} (7.7 V μm^{-1}, 1.5 kHz) with a high stretchability of 800%.

Although the ACEL fibers can be easily scaled up for a continuous production, there remain some problems that limit their practical applications. First, the luminance of ACEL fiber is lower than that of DC-driven light-emitting device. Numerous efforts have been thus made to improve the electroluminescence performance. For example, CNT was incorporated into phosphor to enhance the local electrical field, which significantly improved the brightness.[122] Graphene oxide nanosheets could also be added to increase the dielectric constant of the composites, which induced an enhanced electroluminescence.[123] The optimization of particle size, structure, and composition of the phosphor was also reported to offer higher luminous efficacy.[118] Second, the lack of full color capability limits its wide applications. Different elements such as Cu, Mn, Tb, Sm, and Ho have been used extensively as dopants in the phosphor powder to increase the possible color gamut.[118] Third, the brightness of phosphors rapidly deteriorates in ambient air due to the presence of moisture when an electric field is applied. Therefore, it is necessary to protect the phosphor particles by encapsulation. Typically, inorganic coatings such as AlOOH, TiO_2, and AlN are used for good moisture resistance.[117]

2.5. Sensing Devices

Fiber-based sensing technologies have attracted widespread interests in biomedical fields because they could efficiently monitor personal health conditions by detecting various physiological signals in real time. Over the past few decades, the fiber-shaped sensors have been not only demonstrated as conceptions but also used in practical applications from basic healthcare monitoring to clinical evaluation of disease states. Substantial progress in fiber-based sensing technologies has led to the development of commercial smart textiles, such as BodyPlus Aero (BodyPlus Technology Co., Ltd), Mbody 3 (Myontec, Ltd), and Mimo (Rest Devices, Inc.) for real-time personal health monitoring. **Figure 4** shows a comparison of different types of fiber-shaped sensors, which can be classified as conductive-fiber-based physical sensors, conductive-fiber-based chemical sensors/biosensors, and optical-fiber-based sensors. The first two rely on electrical signals for their transmission, while the latter relies on optical signals.

2.5.1. Conductive-Fiber-Based Physical Sensors

Many fiber materials acquire their sensing capability via conductive materials compounded onto fibers or fabrics. When they are subjected to mechanical deformation or environmental stimulation, their microstructure or intrinsic conductivity will change, which can be transduced into electrical signals such as resistance/capacitance changes or voltage/current generations. A variety of nanomaterials with high conductivity including carbon nanomaterials,[124] conducting polymers,[125] metallic nanowires,[126] and liquid metals[127] have been used to prepare conductive fibers for sensing devices.

The most mature application of conductive-fiber-based physical sensors is to monitor bioelectrical signals (e.g., electroencephalograms (EEG), electrocardiograms (ECG), and electromyograms (EMG)).[128] The traditional monitor systems of bioelectrical signals were based on wet Ag/AgCl electrodes directly attached to the skin using an electrolyte gel. These sensing systems were highly inconvenient and uncomfortable for long-term monitoring due to the potential risk of skin rashes and allergies. To this end, dry electrodes without the use

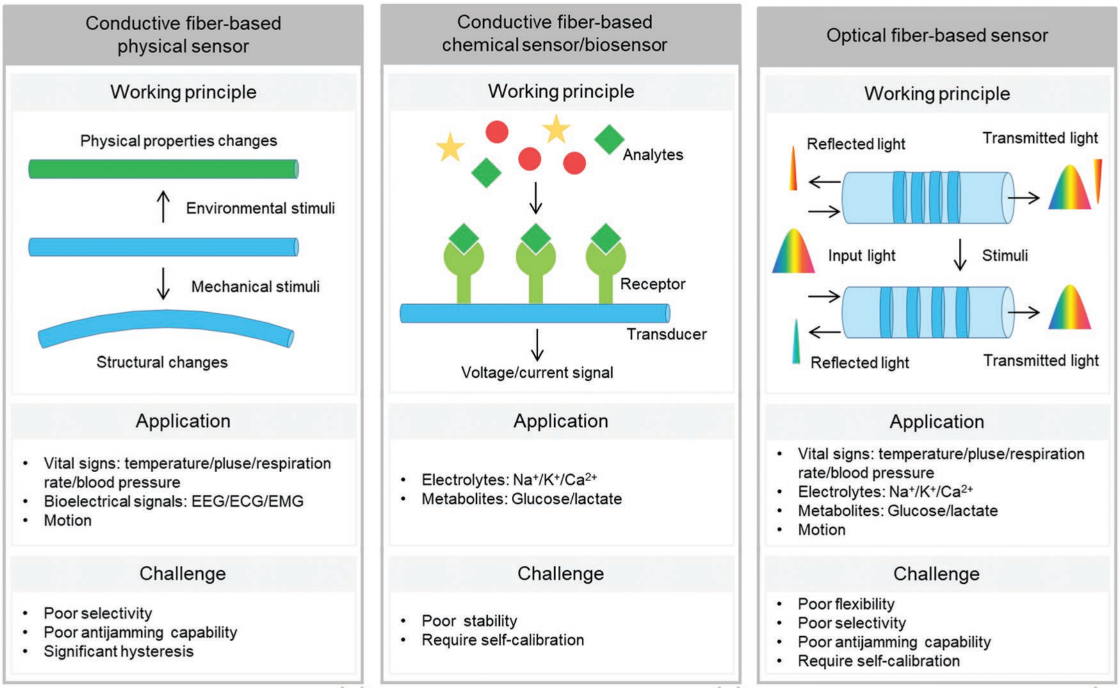

Figure 4. Comparison of different types of fiber-based sensors.

of electrolyte gel were developed. Corresponding to the growth of wearable applications, there has been a rise in the use of smart textiles for real-time monitoring of bioelectrical signals, where a conductive fiber or fabric can used as dry electrode.[129] At present, most of the commercial smart textiles are developed based on this kind of sensors.

Conductive-fiber-based strain/stress sensors are the most widely studied ones because of their broad applications in personalized signal monitoring (e.g., heart rate, blood pressure, and respiration rate) and human motion detection.[130] At the early stage, a fabric strain sensor was developed by coating PPy onto cotton–Lycra fabric, which could achieve the sensing capability of the detection of human body posture and gesture.[131] Graphene- or CNT-based composite conductive fibers had been also prepared to realize the ultrahigh sensitivity with fast response and high reproducibility.[132] However, these kinds of fiber sensors suffered from easy damage and inferior stability. Doping conductive fillers such as metal nanoparticles and nanowires into nonconductive elastomers represents a promising solution to improve the stability of the fiber strain/stress sensors.[126,133] It is worth noting that a textile triboelectric nanogenerator had been made for human respiratory monitoring by loom weaving Cu-based yarns in the conventional weaving process.[134] The resulting sensors are machine washable and fabrication scalable, and all used materials are acceptable at the textile industry, so they are attractive for practical applications.

Conductive fibers can also function as temperature sensors as they may show linear or nonlinear changes in electrical resistivity under varying temperatures. For example, PEDOT:PSS-dyed cotton threads showed a negative temperature coefficient characteristics with 167.1 $\Omega\ ^\circ C^{-1}$ sensitivity and 99.8% linearity at the temperature range of −50 to 80 °C.[135] They can be thus woven into the fabric to construct a temperature sensor array or network that can measure the spatial and temporal temperature gradients with high sensitivity and accuracy.

Some conductive fibers also show changes in electrical resistivity upon exposure to the different atmospheric humidity conditions of the surrounding environment, which can therefore be used as humidity sensors. Carbon nanomaterial–based fibers are widely studied due to their very large adsorption capacity and acceptable electrical conductivity. The chemisorption of the water molecules can act as a temporary dopant, resulting in an increase or decrease of the electronic property. For instance, a graphene-based fiber power generator output voltages that varied with humidity, so it can be used as a self-powering humidity sensor.[136]

Although conductive fiber can easily realize sensing capabilities, the inferior selectivity and poor antijamming capability remain a grand challenge. Almost all humidity sensors are strongly sensitive to temperature. Strain and stress sensitivities are also coupled in many strain sensors. Moreover, some conductive fibers and textiles exhibited serious hysteresis, which significantly influence the sensitivity. As a case of improvement, a CuI/Cu-decorated graphene fiber was designed to exhibit chemical-sensitive/temperature-insensitive or chemical-insensitive/temperature-sensitive characteristics, depending on the Cu concentration in the fiber.[137]

2.5.2. Conductive-Fiber-Based Chemical Sensors/Biosensors

Except for the detection of physical activities, the continuous monitoring of chemical/biological parameters such as electrolytes, metabolites, and biomarkers in body fluid is also significant in order to obtain complete information about a personal health at the molecular level. Therefore, the conductive-fiber-based chemical sensors/biosensors have also been developed over the past decade.

A typical chemical sensor/biosensor is composed of two basic units including a receptor and a transductor.[138] The receptor can transform the analyte concentration into an output signal, which can be then converted to a readable voltage or current by the transductor. Therefore, high electrical conductivity is important to ensure the efficient transmission of electrical signals. For example, glucose oxidase/chitosan was coated onto a highly conductive CNT fiber that had already been deposited with Prussian blue to construct a glucose-sensing fiber. The glucose oxidase can react with glucose to produce a current signal which can be detected. By depositing different active materials, different kinds of sensing fibers have been developed, which can be woven into textiles to simultaneously detect concentrations of glucose, Na^+, K^+, Ca^{2+} ions, and pH in sweat.[35] For another demonstration, it was easy to transform commodity cotton yarns into chemical sensor/biosensor by introduction of polyelectrolyte and CNTs.[139] The resulting sensor can detect albumin with high sensitivity and selectivity.

Additionally, a fiber-shaped organic electrochemical transistor (OECT) is also developed for chemical sensors/biosensors. The OECT is a typical potentiometric transducer that is sensitive to the change of potential on its channel or gate, and it has been widely used for chemical/biological sensing, including the detections of ion, glucose, dopamine, DNA, bacteria, and protein.[140] A fiber-shaped OECT was typically made by coating multilayer films with the structure of Cr/Au/PEDOT:PSS on nylon fibers as source/drain electrodes. The gate electrodes of OECT were then modified with biocompatible polymers, graphene-based nanomaterials, and enzyme to obtain sensing capability. The fiber-shaped OECT showed good bending stability and can be used for the detection of glucose concentration of artificial urine with high sensitivity and selectivity.[141]

There remain a lot of obstacles that limit their practical applications. First, the output signals of the sensors are easily drifted and require calibrations before using every time, which is incompatible with wearable technology. Second, the sensor is unstable for long-term storage and use. The biological recognition component such as glucose oxidase is sensitive to their local environments. Although some attempts have been made to overcome these problems, it is far from applications. Therefore, the development of fiber-based chemical sensors/biosensors is still at its infancy, and they lag behind fiber-based physical sensors.

2.5.3. Optical-Fiber-Based Sensors

Apart from conductive-fiber-based sensors, optical-fiber-based sensors have also gained extensive attentions for numerous applications in the fields of civil engineering, automotive industry, and medicine. Optical fibers have numerous metrological properties such as zero sensitivity drift, high accuracy, and high sensitivity. In particular, they are immune to electromagnetic interferences. These valuable characteristics make optical fibers an emerging solution for the measurement of physical and chemical parameters, which can compete with other traditional electrical sensors. During the last decades, optical fibers are attractive for applications in smart textiles because they allow both sensing and signal transmission.[142] They also show advantages of high durability, easy handling, simple connection, and good biocompatibility.

In comparison to the traditional silica-based glass optical fibers, the polymer optical fibers show good pliability and large breaking strain. Moreover, they are more biofriendly and less risky for injuries on human's skin. The polymer optical fiber is normally composed of two parts, i.e., the inner core part that has a refractive index of n_1 and the outer cladding part that has a refractive index of n_2 (here $n_2 < n_1$).[142a] Generally, the selection of material is limited by the processability, optical transparency, and flexibility. Till now, many materials such as polymethyl methacrylate (PMMA), polystyrene (PS), polycarbonate (PC), cyclic olefin copolymers (COC), and silicone are used for polymer optical fibers (**Figure 5**). Numerous manufacturing methods are also available, such as extrusion, coating, and fiber drawing.[142b]

The optical-fiber-based sensors can be designed using a large number of working principles. The typical technologies are fiber Bragg grating and intensity-based technology.[142a] The fiber Bragg grating sensors have very high sensitivity. They can be considered as a short segment (usually 3–6 mm) of an optical fiber that consists of periodic perturbation of the refractive index along the length of fiber. The wavelength of the reflected light is sensitive to some variables such as strain and temperature. Fiber Bragg grating sensors are employed in a large number of medical fields to monitor different physiological parameters such as Stroke volume, blood pressure, heartbeats, and respiration.[143] However, they often need complex compensation techniques to decrease the effect of temperature fluctuation in the monitor process. In contrast, the advantages of intensity-based optical fiber sensors are low-cost, easily coupling, and simple in design. They measure the change of light intensity in response to an environmental factor. For a typical configuration, the two optical fibers end to end. When light is transmitted from one optical fiber to another, the change of light intensity depends on the distance between the two fiber tips. Therefore, the light intensity can be seen as an indirect measurement of the distance between the two optical fibers or other physical variables that affect this distance. A similar configuration can also be designed either by using a single fiber with a mirror or by using more than one fiber. Another

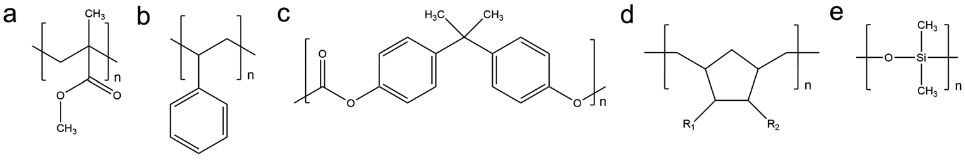

Figure 5. a–e) Chemical structures of poly(methyl methacrylate) (a), polystyrene (b), polycarbonate (c), cyclic olefin copolymers (d), and silicone (e).

configuration is designed based on the phenomenon where the light is lost from an optical fiber when it is periodically bent. Macrobending and microbending sensors based on heterocore optical fibers have been designed to monitor several physical parameters.[144] They may find applications in medicine mainly in the monitoring of respiratory movements, which are largely used in smart textiles.

The main concern regarding optical-fiber-based sensors for commercially available products is related to the reliability. Light coupling is a major factor of instability, particularly in long-term applications. Therefore, a stable connection is important. Self-calibration is still a huge problem due to the high variability of the optical properties. For wearable textile integration, the current polymer materials are rather stiff in comparison to conventional fibers and yarns, which need to be more flexible and durable. Furthermore, the relevant optical components should be standardized and simplified.

3. Large-Scale Production

3.1. Typical Structures of Fiber-Shaped Electronic Devices

The current fiber-shaped electronic devices generally have three main configurations, i.e., twisting, coaxial, and interlaced (**Figure 6**a–c). For the twisting structure (Figure 6a), the fiber-shaped devices are typically made by directly twisting the different fiber electrodes at a certain angle, which is proved to be a reliable and effective strategy. The individual fiber electrodes can be prepared independently, and the twisting devices are usually encased within a tube for protection. However, there are still some deficiencies and inadequacy in the twisting structure. For example, in the case of optoelectronic devices, the wrapped secondary electrode would shade the light from or to the primary electrode.[88e] The internal stress is also inevitably generated when two fiber electrodes are twisted. Therefore, the twisting structure is not mechanically stable, and two electrodes may slip off under severe bending or twisting deformation.

Distinct from the twisting structure where electrodes are placed in parallel, the coaxial structure exhibits a core–sheath configuration, which offers shorter ion transport path and better stability upon mechanical bending (Figure 6b).[145] CNT film, with the optical transparency of 80–85% in the visible range, can be easily employed as the counter electrode to form a coaxial dye-sensitized solar cell. Unlike the fiber electrode, the CNT film ensured full contact with the underlying active layer, as well as uniform illumination along circumference through the entire fiber-shaped solar cell.[146]

Recently, an interlaced structure has been also proposed to fabricate fiber-shaped electronic devices, especially in the solar cells.[147] Different from widely explored twisting and coaxial structures, the fiber-shaped photoanodes and counter electrodes were woven in an interlaced manner to form a single-layered textile. The holes generated at the active layer under solar irradiation transport to the anode fibers and electrons transport to the cathode fibers through the cross interface (Figure 6c).[11b] Therefore, it is possible and efficient to produce electronic textiles at the applicable scale of meters by the industrial loom.

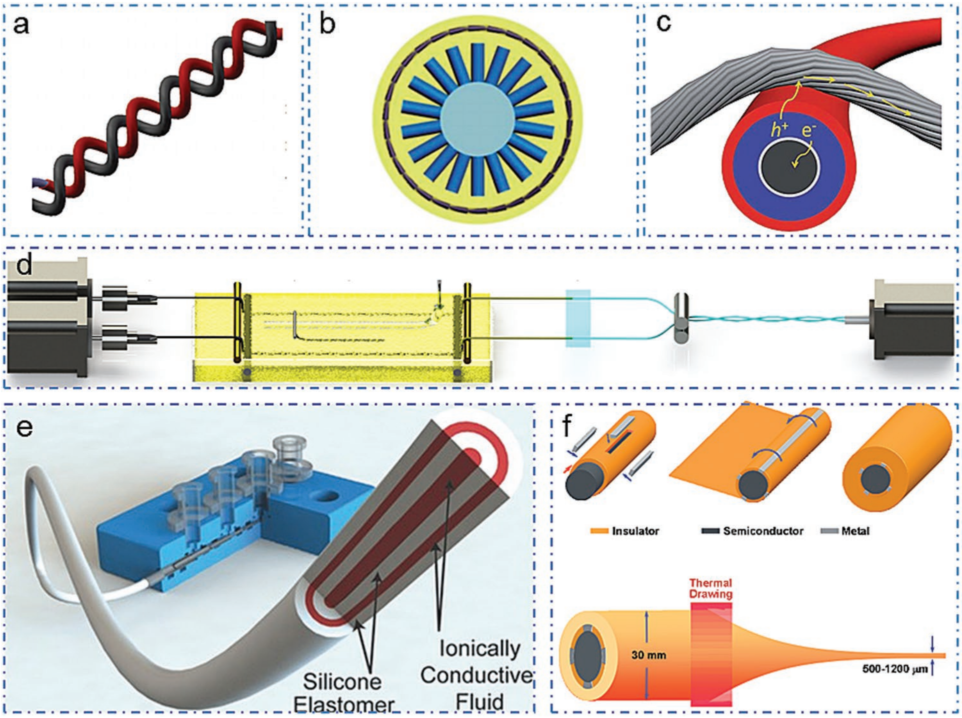

Figure 6. a–c) Fiber-shaped electronic devices with twisting, coaxial, and interlaced structures, respectively. a) Reproduced with permission.[88e] Copyright 2012, Wiley-VCH. b) Reproduced with permission.[145] Copyright 2014, Royal Society of Chemistry. c) Reproduced with permission.[11b] Copyright 2018, Royal Society of Chemistry. d–f) Large-scale fabrication methods for synchronous deposition, spinning, and thermal drawing, respectively. d) Reproduced with permission.[69] Copyright 2015, Wiley-VCH. e) Reproduced with permission.[150] Copyright 2015, Wiley-VCH. f) Reproduced with permission.[152] Copyright 2006, Wiley-VCH.

3.2. Large-Scale Fabrication of Fiber-Shaped Electronic Devices

At present, various fiber-shaped electronic devices with twisting, coaxial, or interlaced structures have been extensively investigated mainly at the lab scale. The commercialization of these fiber devices is limited by the challenging fabrication processes including the preparation of fiber substrates, the introduction of active materials, the infiltration of electrolytes, the assembly, and encapsulation. These complicated treatments and time-consuming procedures seriously hinder the applications of fiber electronics. Although the state-of-the-art techniques developed for planar electronic devices are not easily transferred to the fabrication of fiber-shaped devices, they do offer useful information for the preparation and application of long, thin, and flexible fiber devices.[148]

Several strategies have been developed to realize the continuous production of fiber devices. A synchronous deposition strategy had been designed to continuously fabricate fiber-shaped supercapacitors by integrating the above discrete fabrication steps into a continuous process (Figure 6d). In this method, a constant potential was applied on the as-prepared CNT fiber to establish a synchronous electrochemical deposition system. During this process, graphene oxide sheets were coated on the CNT fiber and reduced to graphene, forming a graphene-coated CNT composite fiber. Subsequently, two composited fibers were drawn into the gel electrolyte to ensure the fiber electrodes free of short-circuit when they were twisted tightly with a rotating motor. This synchronous deposition strategy was also extendable and transferable to a variety of active materials such as MnO_2, PANI, and PPy. Furthermore, this method was compatible to different fiber substrates such as carbon fibers, metal wires, and metal-coated synthetic fibers, to fabricate various fiber-shaped supercapacitors.[69]

A significant improvement has been made through a coaxial wet spinning of graphene with the polyelectrolyte-protecting layer for the continuous preparation of composite fibers, which were used directly as fiber electrodes to construct fiber-shaped supercapacitors.[74] Such a coaxial co-spinning method provided a useful strategy for the direct preparation of fiber-shaped electronics. Then, a general multichannel spinning method was proposed to continuously fabricate coaxial fiber-shaped supercapacitors through designing a special spinneret with coaxial three-channel structure. During the wet-spinning process, the electrode inks and gel electrolytes were simultaneously extruded into the coagulation bath. The gel electrolyte was quickly solidified to stabilize the inner and outer electrodes and meanwhile functioned as a separator. The diameter, thickness, and uniformity of electrode or electrolyte layers can be precisely adjusted by changing the electrolyte concentration and the extrusion speed.[149] Furthermore, this multichannel spinning method can be upgraded to construct more complex fiber-shaped electronic devices such as the capacitive soft strain sensor. Four alternate layers consisted of nonvolatile ionic fluid and silicone elastomer were co-extruded in concentric configuration using a designed printhead consisted of four cylindrical nozzles aligned coaxially (Figure 6e). The alternate nozzle designs and print parameters can be used to vary the relative thickness of each layer of the fiber sensor, enabling customized sensor properties.[150]

As an advanced manufacturing technology, 3D printing has recently attracted interests due to its high manufacturing efficiency, integrated construction, scalability, and complexity capability. 3D extrusion printing has been widely used in conventional electronic devices, such as batteries, capacitors, and sensors, which can also be employed to design and fabricate fiber-shaped electronic devices. A quasi-solid-state fiber-shaped LIB has been constructed by using the extrusion-based direct-write 3D printing method.[151] The rheological properties of the polymer-based cathode/anode inks were critical factors in this extrusion 3D printing method, and they should be carefully tuned to ensure smooth printing and good solidification. The as-prepared cathode/anode inks were ejected into the ethanol coagulation and wrapped by PVDF fibrous gel. However, the fabrication of the all-fiber LIBs needed to apply the printed positive fiber, negative fiber, and polymer-based gel electrolyte into a heat-shrinkable tube in the Ar-filled glove box, followed by injecting liquid electrolyte. It may be difficult to scale up the above fabrication to satisfy the real application.

Thermal drawing is a significant fiber-processing technique originally used to make optical fiber, and it can also be used for polymers and other conducting and semiconducting materials.[152] Recently, thermal drawing is extended as a new strategy for the fiber-shaped electronic devices with multiple functionalities. In this method, all of the functional materials are first assembled into a single, macroscopic, cylindrical rod in prescribed architectures, followed by directly co-drawing to produce the fiber-shaped devices. For instance, through the thin-film rolling method, a multimaterial macroscopic preform was prepared by assembling the polymer shell and metal electrode around a semiconducting glass rod. Then the preform was thermally consolidated and drawn to mesoscale fiber, which can work as a functional thermal sensing device by connecting metal electrodes to an external circuit (Figure 6f). The thermal drawing method has special requirements for the component materials. First, the component should be glassy to support the drawing stress and maintain the structural regularity. Second, the components which bear the drawing stress showed softening or melting points above the drawing temperatures. Third, the different components should exhibit good adhesion/wetting in the viscous and solid states without delamination.

3.3. Encapsulation

Inorganic or organic functional materials in fiber-shaped electronic devices are extremely easy to react with water and oxygen, resulting in device failures. In order to effectively protect and prolong the service life of fiber-shaped electronic devices, it is necessary to pack them effectively, i.e., adding a package layer outside the functional materials so that it could prevent water and oxygen from intruding into the devices and corroding them.

Different fiber-shaped electronic devices have different sensitivities to water and oxygen, and the encapsulation effects of packing materials are also different. Water vapor transmission rate (WVTR) and oxygen transmission rate (OTR) are usually used to characterize the performance of packaging materials. For the normal use of the fiber electronic devices in daily, which means the service life of the devices exceeds 1000 h and storage life exceeds 5000 h, the WVTR of fiber-shaped energy storage devices should be less than 0.01 g m^{-2} day^{-1}; for the more sensitive fiber-shaped OLEDs, it should be less than 0.000001 g m^{-2} day^{-1}.[153]

Fiber-shaped electronic devices need not only water and oxygen insulating performance, but also high flexibility, so flexible packaging materials must be used for fiber electronic devices. Compared with traditional rigid packaging materials such as metals and ceramics, polymer packaging materials have the characteristics of high flexibility, easy processing, and low cost, so they have been widely used as packaging materials in food and pharmaceutical industries. Common polymer packaging materials include PE, polypropylene (PP), poly(vinylidene chloride) (PVDC), PEN, and PI. However, the WVTR of the above polymers ranged from 0.1 and 100 g m^{-2} day^{-1}, which cannot meet the actual packaging requirements of fiber-shaped electronic devices.[154]

Polymer/inorganic nanocomposites can effectively reduce the WVTR of polymers also with high flexibility via blending,[155] intercalating,[156] in situ polymerization,[157] or sol–gel reaction.[158] The WVTR of the new composites can be effectively decreased to 0.01–0.1 g m^{-2} day^{-1}. The addition of flaky nanoparticles can further not only cut down the volume fraction of polymer matrix in the system to reduce the solubility of permeable molecules, but also prolong the permeation path of water molecules to reduce the diffusion rate of permeable molecules and improve the packaging performance.[43] However, it remains difficult for the nanoparticles to be uniformly dispersed and highly oriented, and they often aggregate during preparation. It is also difficult to prepare polymer packaging materials with high transparency, which cannot meet the needs of fiber-shaped optoelectronic devices.

By using physical vapor deposition (PVD) and CVD techniques, metals and ceramics are deposited on the surface of polymers. The lowest WVTR can achieve <0.000001 g m^{-2} day^{-1} while maintaining good light transmittance.[159] However, the equipment used in these methods is extremely expensive; the process is time-consuming; and the process is relatively complex. Due to the deposition process occurs on the polymer surface, the deposition temperature required must be lower than the thermal deformation temperature of the polymer substrate, which results in less compact deposition layer and more pinhole defects with reduced packaging effect. For this reason, denser and more uniform layers were deposited by plasma technology to assist low-temperature deposition process.[160]

Fiber-shaped electronic devices are frequently subjected to tension, compression, and shearing during use. However, the inorganic packaging layer obtained by vapor deposition is prone to crack, which becomes a new path of vapor diffusion and reduces the packaging performance.[161] Therefore, the organic/inorganic multilayer composite structure had been prepared, in which the organic layer was used as the buffer layer to delay the cracking of the inorganic layer under frequent external forces, which effectively prolonged the penetration path so as to further improve the packaging performance.[153]

Currently, the flexible packaging materials for fiber-shaped electronic devices have been rarely explored and are still at the infancy. Thermal tubes are typically used for encapsulation at the lab study, and the resulting fiber-shaped electronic devices are thus limited to centimeters in length, which is not applicable for the industry production.[162] Considering the high curvatures of fiber-shaped electronic devices, which are totally different from their planar counterparts, it is urgent to develop new packaging technologies specifically for the fiber shape.

4. Electronic Textiles

Electronic textiles with various functionalities distributed all over the fabric such as energy harvesting and storage, sensing, and displaying, which could be considered as the ultimate form of wearable electronics. Until now, there are three different ways to integrate electronics into textiles: i) embedment of simple electronic devices on fabric substrate; ii) fabrication of flexible electronic devices based on fabric substrate; iii) integration of fiber-shaped electronic devices into fabric. From a viewpoint of practical applications, the third strategy has been mostly explored and will be mainly discussed here.

4.1. Fabrication of Electronic Textiles

Compared with the commercial electronic devices, fiber-shaped electronic devices are soft and deformable, and the structure of textile can be designed into various patterns with high integration degrees. The current processing technologies fail to adapt to the fabrication of the electronic textile. To this end, it is necessary to develop suitable processing technologies to construct electronic textiles, which mainly involve the integration of fiber devices, the construction of conductive tracks, and the interconnection between devices and circuits. Fortunately, to certain degrees, the traditional textile technologies, e.g., weaving, knitting, and embroidering, have been proposed and demonstrated as effective strategies. Some modifications on the above textile technologies may further enhance the efficiency for a large-scale production.

4.1.1. Integration of Fiber-Shaped Electronic Devices into Textiles

In the early work, the integration of fiber-shaped electronic devices was achieved mainly through manual weaving in the laboratory, as a demonstration of the conceptual fabrics. Subsequently, in order to improve the processing efficiency, the semiautomatic and fully automatic processing technologies have been implemented. To date, there are two main strategies for integrating fiber-shaped electronic devices into textiles. The first strategy is to make complete fiber-shaped electronic devices and then integrate them into textiles through traditional textile technologies. The other is to weave cathode and anode fiber electrodes with an interlaced structure to construct textile-type electronic devices.

The first strategy is simple and applicable for a variety of fiber-shaped electronic devices such as solar cells,[89e] lithium-ion batteries,[163] sensors,[35] and light-emitting devices.[114c] For example, fiber-shaped aqueous lithium-ion batteries were woven into power textiles (**Figure 7**a). The operating voltage can be enhanced from 2.5 V for a single fiber-shaped lithium-ion

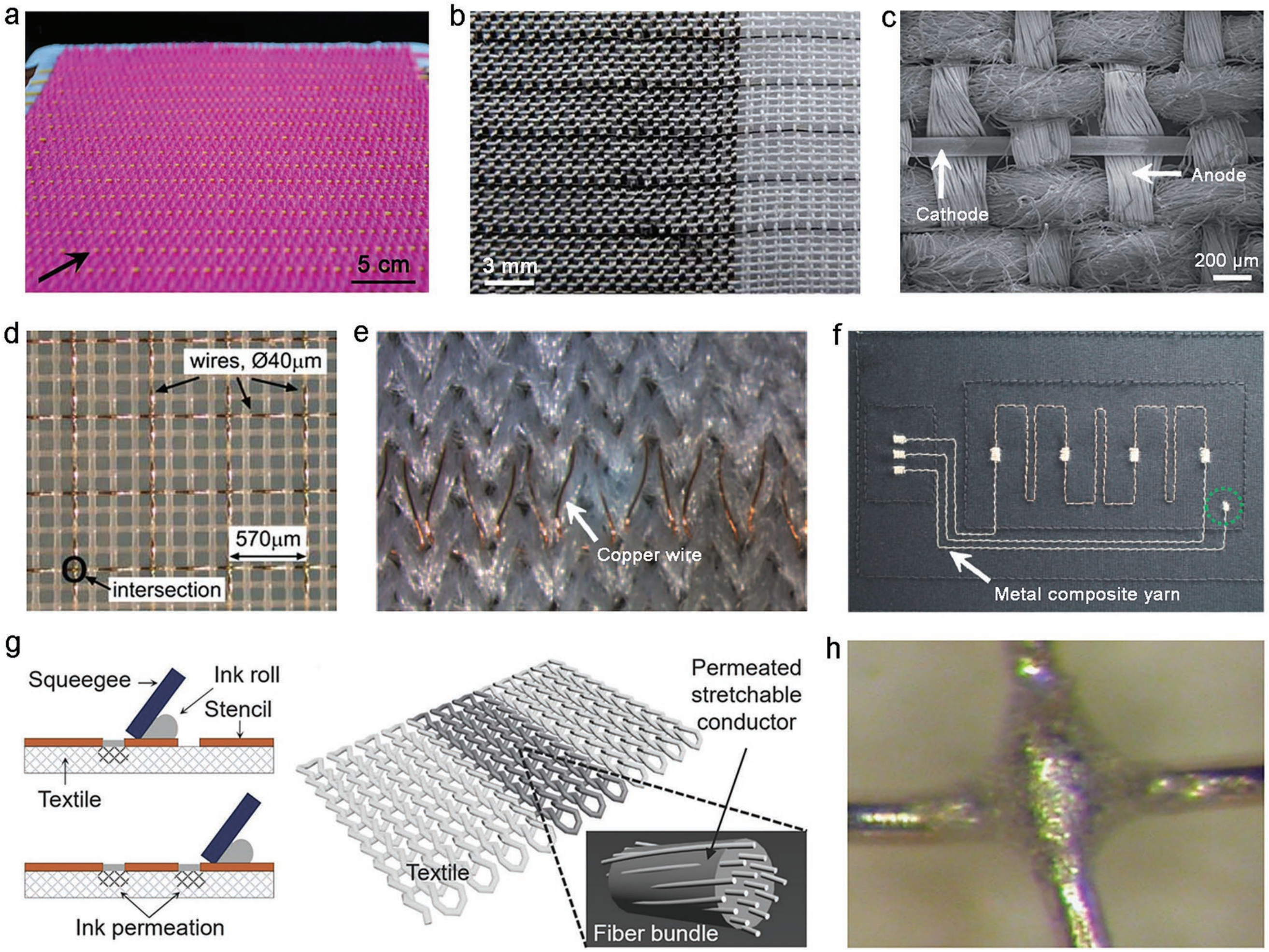

Figure 7. a) Energy-storage textile woven with fiber-shaped aqueous lithium-ion batteries. The black arrow indicates the battery. Reproduced with permission.[163] Copyright 2016, Royal Society of Chemistry. b,c) Photograph and SEM image of photovoltaic textile woven with intersection of cathode and anode fibers. b,c) Reproduced with permission.[11b] Copyright 2018, Royal Society of Chemistry. d–g) Conductive tracks constructed in/on textile by weaving (d), knitting (e), embroidering (f) of conductive yarns, and g) patterning of conductive inks. d) Reproduced with permission.[164] Copyright 2007, IEEE. e) Reproduced with permission.[165] Copyright 2011, SAGE Publications. f) Reproduced with permission.[166] Copyright 2017, SAGE Publications. g) Reproduced with permission.[167] Copyright 2017, Wiley-VCH. h) Two crossing wires connected by conductive adhesive. Reproduced with permission.[174a] Copyright 2004, IMAPS.

battery to 5, 7.5, and 10 V after connection of two, there, and four ones in parallel.[163] However, it is challenging to effectively connect a large amount of fiber electrodes of the constructed fiber-shaped electronic devices.

Unlike the first strategy, the second strategy with an interlaced structure may be used mainly to fabricate solar cell textiles, in which the warp and weft yarns serve as the anode and modified cathode, respectively (Figure 7b,c).[11b] A polymer solar cell textile at the applicable scale of meters can be fabricated by using an industrial loom. Different weaving parameters such as thickness and interval of the anode fibers were systematically studied and concluded that too thick anode fibers and too large an interval would decrease the photovoltaic performance of the polymer solar cell textile. Moreover, the polymer solar cell textile can be designed into modules connected in series or parallel to change the output voltage or current.[11b] For this strategy, however, the encapsulation remains a big challenge. If the whole textile was encapsulated, some characteristics of the textile such as air permeability and moisture permeability would be lost. More efforts are needed to solve the above problem to really realize a continuous production based on this interlaced strategy.

It should be noted that the mechanical properties of many fiber-shaped electronic devices are lower than required for automatic integration processes. Some fiber-shaped electronic devices are also easily damaged during the weaving processes. As a result, the integration can only be made by hand processing, which can significantly increase the cost of the application. This may be acceptable in early small-scale applications, but it needs to be taken into account for the further study aiming at large-scale applications. This issue has been often overlooked in the past years.

4.1.2. Construction of Conductive Tracks into Textiles

Conductive tracks are a necessary part of electronic textiles to interconnect different electronic components such as batteries, sensors, and displays. There are four ways to fabricate conductive tracks in/on textiles including weaving,[164] knitting,[165] embroidering of conductive yarns,[166] and patterning of conductive inks[167] (Figure 7d–g). The weaving and knitting processes form an interconnected conductive network during textile manufacturing process, whereas embroidering and patterning processes take place at the later stage of finished fabric.

To fabricate conductive tracks during weaving process, the conductive yarns are usually woven in a regular grid pattern, which were distributed in only weft or warp direction, or at localized positions. In the past few decades, a variety of weaving processes to fabricate conductive tracks have been demonstrated.[168] A textile circuit was made by interlacing polyester yarns and steel/copper yarns into textiles, in which the routing of electrical signals was achieved by the formation of effective electrical interconnect.[169] However, capacitive and inductive crosstalk is usually aggravated by long parallel conductive yarns in a woven circuit. Later, the crosstalk can be significantly reduced by using coaxial and twisted pairs of copper yarns rather than bare copper yarns or insulated conductive yarns.[169] A similar textile named PETEX was also woven with polyester monofilaments and isolated copper wires (Figure 7d).[164] Although the circuit structure is simple by using a weaving process, it can only be wired vertically, which significantly reduced the freedom of the circuit routing.

In comparison to woven fabric, the knitted fabric is much more elastic due to its 3D looped configuration. Therefore, a stretchable conductive track with a more complex arbitrary route can be created by using a knitting process. A stretchable conductive track was demonstrated by using a superfine insulating metal conductor wire co-knitted into a fabric (Figure 7e).[165] The knitted track exhibited consistent electrical resistance between 44.0 and 45.0 Ω for 5000 cycles with an average strain of 46%.

Embroidery has also been used as one of the simple methods for conductive track fabrication. It is processed on the finished fabric and can be modified or removed at any time, which provides a great freedom for the design of conductive tracks. For instance, an embroidering process was made by combining the commercial embroidering process and computer-aided design.[170] The conductive track pattern can be precisely designed by sewing conductive yarns on textile substrates. However, appropriate strains are needed to allow needle manipulation of the yarn at relatively high speeds in the sewing machine, while the mechanical properties of the conductive yarns are generally lower than conventional yarns. To this end, composite yarns that containing a mixture of conductive and nonconductive fibers were introduced to show good machine sewability.[171] A metal composite yarn for circuit patterning was also prepared by using a computer numeric control embroidery machine (Figure 7f).[166] However, the embroidery conductive track is not intrinsically stretchable if the conductive yarn is not stretchable.

Patterning conductive materials on fabric substrates is another way to fabricate conductive tracks in a textile. Numerous mature methods such as screen printing and inkjet printing can be employed to achieve the fabrication processes.[172] However, achieving high electrical properties of printed tracks in fabrics is a great challenge. On the one hand, the porosity and roughness of the fabric substrate complicate the printing of a continuous and smooth layer of conductive materials. On the other hand, the strain endured by the fabric substrate is fully transmitted to the printed materials, which induces crack or delamination in conductive tracks. Recently, a mechanically and electrically robust conductive track was realized by designing a textile-permeable conductive ink (Figure 7g).[167] Due to the optimal morphology of textile bundles and conductive inks, the printed tracks showed an initial sheet resistance of 0.06 Ω sq^{-1} and could be stretched by up to 450%.

4.1.3. Connection Technologies

The reliable connection between the electronic components and conductive tracks is indispensable on textile electronics. Many approaches have been developed to achieve a reliable connection such as physical soldering/welding,[170] mechanical gripping,[173] and chemical bonding.[164,174]

The physical soldering/welding process is commonly used for connection of the electronic components on rigid circuit board. In a typical soldering process, two metal leads are joined together by melting a filler metal into the joint, while the welding process lacks the filler metal and works directly by melting the two metal leads. For instance, a micro-spotwelding rig was introduced to connect stainless steel yarn to the leads of a chip.[170] Although a high conductivity could be realized with a soldered/welded connection, it is too stiff and brittle for textile applications. It is noteworthy that the brittle connections might be tolerable if it is designed in certain places on body that do not move often.

In situations where soldering/welding cannot be applied due to heat and brittleness, connections can be made using mechanical gripping such as crimping, stapling, and embroidery.[173,175] However, the connection fabricated by crimping and stapling is also inflexible, which might lead to a break in the connection when the textile is wrinkling. A flexible conductive yarn could be embroidered to directly connect other components, while the electrical contact is unreliable.[171]

The chemical bonding by using conductive adhesives is also used extensively for making electrical connections in electronic textiles. The conductive adhesive can be used to connect the electronic component in textile circuits (Figure 7h).[174a] It has the advantages of relatively simple manufacturing method and structure. However, the environmental conditions, e.g., humidity and temperature, have a large impact on the connection quality. These problems may be restrained by covering the connection with an encapsulation layer.

4.2. Functional Integration of Electronic Textiles

The complete function of electronic textiles requires the cooperation of numerous electronic components. However, the functional integration of electronic components in textiles has shown very limited commercial success so far. On the one hand, the electrical connections among fiber-shaped electronic devices are more complex compared with their

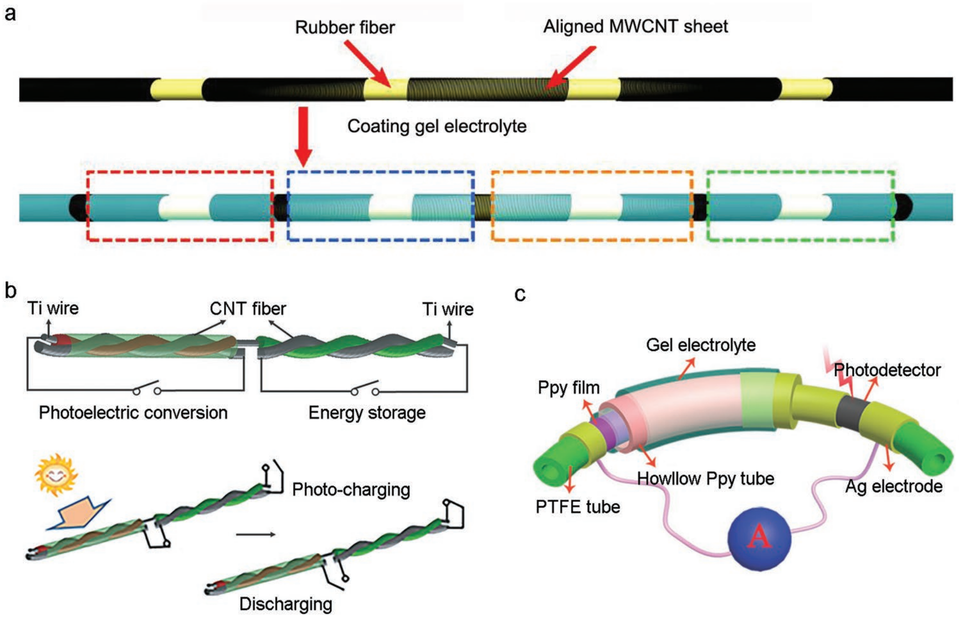

Figure 8. a) Schematic illustration of an in-series fiber-shaped supercapacitor. Reproduced with permission.[176] Copyright 2016, Wiley-VCH. b,c) Schematic illustration of an integrated solar cell–supercapacitor system and integrated supercapacitor–photodetector system. b) Reproduced with permission.[88e] Copyright 2012, Wiley-VCH. c) Reproduced with permission.[178] Copyright 2018, Wiley-VCH.

planar counterparts. On the other hand, smart systems that perform data acquiring, analysis, and transmission require reliability and high computational performances, which lag much behind applications. To this end, many strategies are developed for implementing functional integration of electronic textiles.

4.2.1. Integration on Single Fiber-Shaped Electronic Devices

The integration of numerous components in one fiber-shaped electronic device that can not only reduce the complexity of the external circuits, but also allow more convenient and efficiently managed devices. Taking the fiber-shaped supercapacitor as an example, the traditional assembly with leads suffers from many disadvantages, such as complex connection processes, extra weight, and more fragile connecting points, which are not favored for electronic textiles. Inspired by the electrolyte structure in electric eels, building units were designed on one fiber with an in-series connection, which prevented the use of external conducting wires with high efficiency (**Figure** 8a).[176] The integrated supercapacitor offered output voltages up to 1000 V, and it also showed high flexibility and stretchability.

The integration of energy-harvesting and storage devices in one fiber can convert environmental energy into electricity and simultaneously store it. For example, an integrated energy wire was designed with one part functioning like DSSC and the other part functioning like supercapacitor (Figure 8b).[88e] In a typical fabrication process, photoactivity and electrochemically active materials with appropriate electrolytes were coated on the left and right parts of a titania-modified titanium wire that was used as a common electrode, and two aligned multi-walled carbon nanotube (MWCNT) fiber electrodes were then twisted with both parts to produce the integrated device. Under light illumination, the DSSC part can directly charge the supercapacitor part to 0.6 V within seconds.[88e] In addition to the series architecture, the integrated device can also be designed in core–shell architecture with the DSSC part at the shell and the supercapacitor part at the core.[177]

The energy storage devices can also be integrated with functional electronic devices such as sensors to fabricate self-powering systems. A self-powering photodetecting system was made by constructing a $CuInS_2$-based photodetector and coaxial supercapacitor on the same fiber substrate (Figure 8c).[178] The photodetector part powered by the supercapacitor part showed the same high photoresponse compared with the use of external power source. It also demonstrated high flexibility with almost unchanged photoresponse under different bending states. Given that some materials such as graphene, metal oxides, and conducting polymer are both electrocapacitive and light sensitive, it is effective to make the integration of energy storage and photodetection easy by using the same electrode. For instance, a fiber-shaped asymmetric supercapacitor, integrated with optoelectronic detection, was constructed by using titanium wire/Co_3O_4 nanowires as a positive electrode and carbon fibers/graphene as a negative electrode.[179] When the supercapacitor was charged to 1.5 V, the leakage currents showed obvious photoresponse when the graphene or Co_3O_4 electrode was exposed to white light.

4.2.2. Integration on Textiles

Ideally, all the electronic components of an electronic textile are in the form of fibers, and their mutual integration enables the complete function of the electronic textile. However, some fiber-shaped

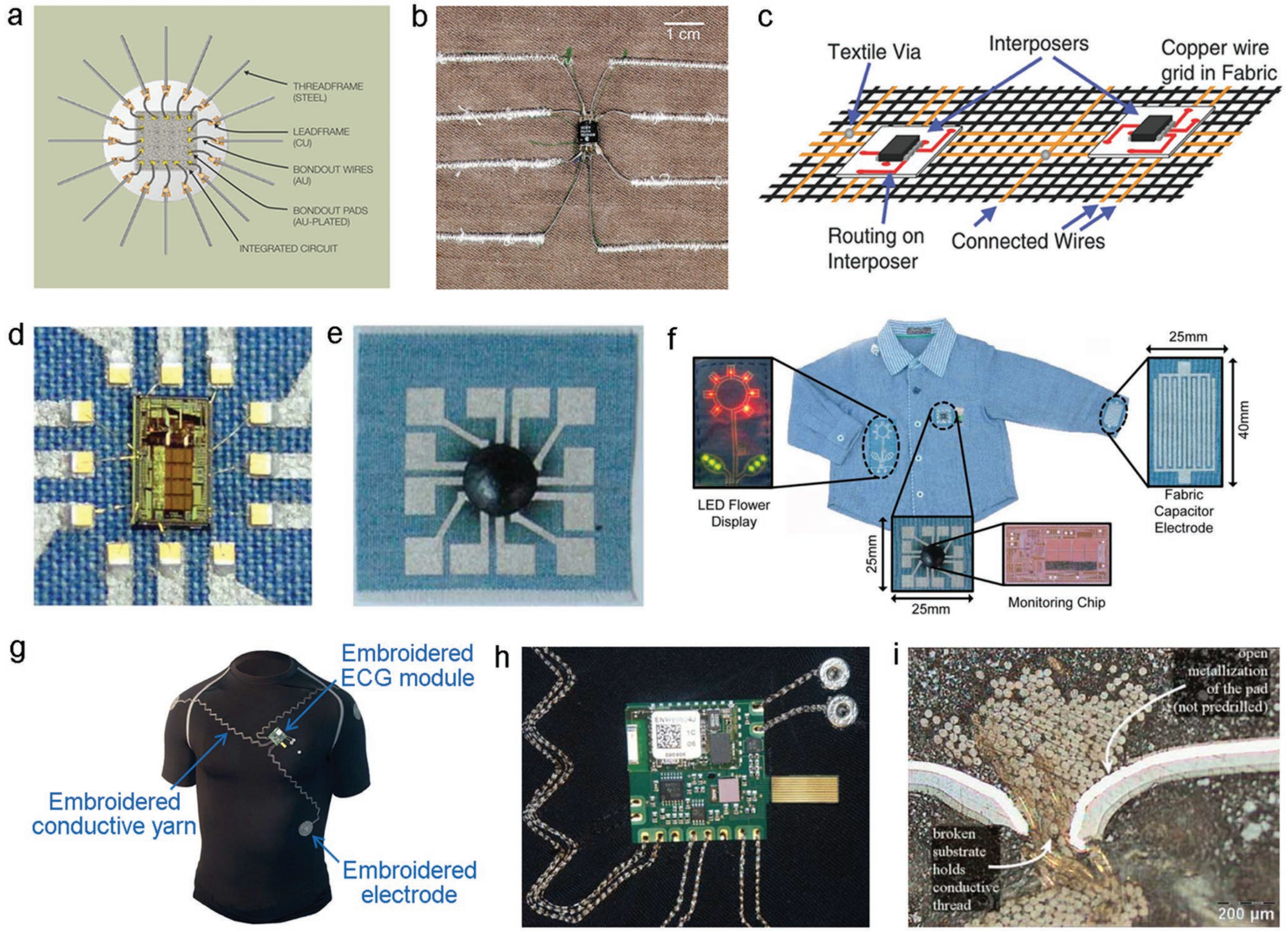

Figure 9. a,b) PTCC construction and PTCC prototype couched onto fabric substrate, respectively. a,b) Reproduced with permission.[170] Copyright 2000, IBM. c) Electronic circuit on fabric using interposers. Reproduced with permission.[164] Copyright 2007, IEEE. d,e) Electronic-component bonding and packaging on a P-FCB, respectively. f) System integration on P-FCB with capacitive sensor, chip, and LED display. d–f) Reproduced with permission.[181] Copyright 2010, IEEE. g,h) An ECG shirt and embroidered ECG module, respectively. g,h) Reproduced with permission.[182] Copyright 2006, IEEE. i) Embroidered conductive yarn held by the gap. Reproduced with permission.[171] Copyright 2005, IEEE.

electronic components, e.g., transistor and memory,[180] are still in its infancy and are far from practical applications. Therefore, at the present stage, some commercial silicon-based electronic components are integrated into the fabric to realize the electronic functions such as data recording and processing.

Different integration strategies between electronic component and textile were developed. The discrete integration of electronic components on textile is a typical strategy, in which the discrete rigid components distributed on the textile surface avoid large stiff areas and allow natural deformations such as wrinkling.[168a] For instance, a plastic threaded chip carrier (PTCC) technology was designed to integrate the silicon chip on textile.[170] The silicon chip was first fixed in the middle of the chip carrier and electrically connected to the PTCC copper pads by fine gold wires. The PTCC pads were then punched through conductive yarns and connected to the textile circuit (**Figure 9**a,b).[170] Locher and Troster developed an interposer concept that adapted the pitch mismatch between electrical components and fabric, hence allowing the integration of arbitrary components (Figure 9c).[164] Planar-fashionable circuit board (P-FCB) was constructed by a screen-printed process on the textile directly to form the patterned electrodes (lead frame) for the integration of the electronic components with textile (Figure 9d,e).[181] Different electronic components, e.g., system-on-a-chip, chip capacitors, resistors, and LEDs, can be bonded directly on the textile lead frame (Figure 9f). Liquid molding epoxy was then coated on the chip after bonding process, which provided robust protection against stretching.[181]

The integration of flexible electronic module on textile is another strategy. Soldering electronic module directly to conductive tracks on fabric is a simple method, but it shows poor reliability due to the rigid and brittle solder. Embroidery can also be used to integrate electronic module on textile, in which the conductive yarns are embroidered to create electrical interconnection with the electronic module. As an example, a fully integrated ECG shirt was made from embroidered electrical interconnections with conductive yarns and miniaturized flexible electronics (Figure 9g–i).[171,182] They showed that the reliability of the electrical contact can be further improved by mold encapsulation.

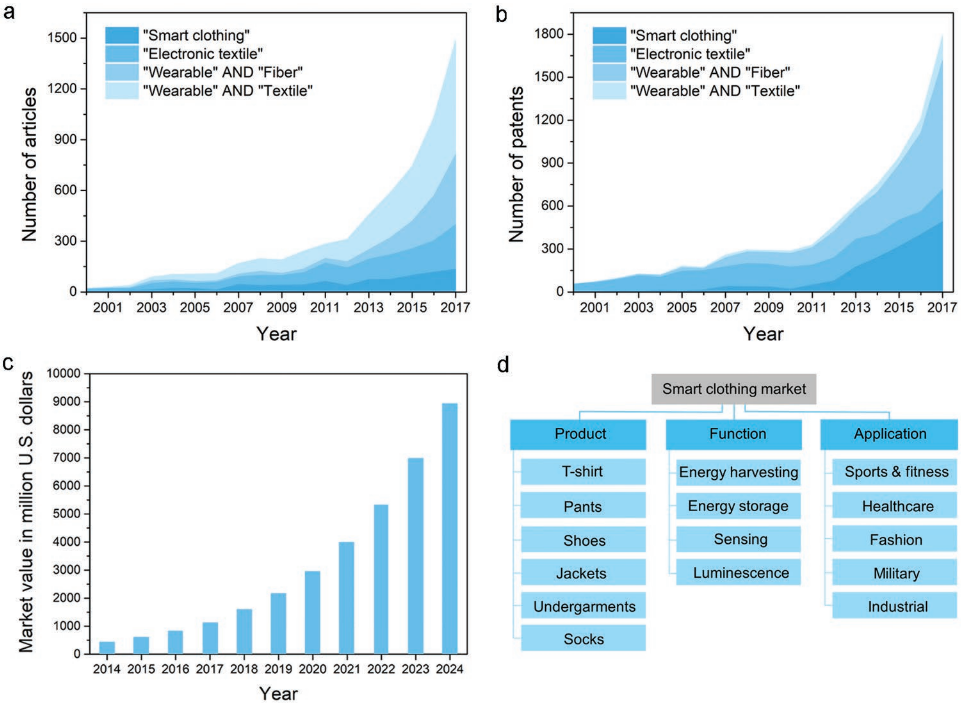

Figure 10. a) Number of articles published per year for different topics (source: Web of Science database). b) Number of patents registered per year for different topics (source: Derwent Innovations Index database). c) Forecast of global smart-clothing market value adapted from Ameri Research Inc. reports.[183] d) Segmentation of the smart clothing market.

For commercialization, standard snap fasteners are widely used, and allow repetitive manual connecting and removing of the electronic devices. Brands like BodyPlus developed a range of smart garments for real-time health monitoring, in which only the textile electrodes were washable, and the electrode module can be removed under washing or changing the supporting garment.

5. Evolutionary Trends

To evaluate the rapid growth of research on fiber and textile electronics, and the emergence of promising applications related to fiber and textile electronics, evolutionary trends in the relevant field are analyzed. The research trend by scientific community can be appraised through the number of articles published per year, here based on Web of Science database. Various subjects in connection with fiber and textile electronics, e.g., "smart clothing," "electronic textile," "wearable" AND "fiber," "wearable" AND "textile," were investigated and are presented in **Figure 10**a. It can be conclude that the number of relevant publications on fiber and textile electronics has been increasing remarkably since 2010. The number of relevant patents registered per year was also investigated, which shows a relatively consistent trend (Figure 10b).

Meanwhile, the economic impact and market trend of fiber and textile electronics are analyzed. The smart clothing market is a major application area for fiber and textile electronics, which has been growing remarkably in recent years. In 2015, the global smart clothing market was valued at \$674.8 million, and Ameri Research Inc. predicted that it would reach \$8.98 billion by 2024, growing at a compound annual growth rate (CAGR) of over 33% from 2017 to 2024 (Figure 10c).[183] Business Wire also forecast that the total shipments of smart clothing would grow from 968 000 units in 2015 to 24.8 million units in 2021.[184] At present, the smart clothing products on the market mainly include smart T-shirt, pants, shoes, jackets, undergarments, and socks. Based on the function, they are categorized as energy harvesting, energy storage, sensing, and luminescence, which are used in various applications such as sports and fitness, healthcare, fashion, military, and industrial production (Figure 10d). However, compared with the other wearable products such as smart watches and wristbands, smart clothing only has a very small market share with about 1%. The major restraint for the smart clothing market is the high cost of production. Moreover, technical problems such as power storage, sensor accuracy, heat dissipation, security, washability, and comfort are all factors in the commercialization challenge. In spite of this, the future market of the smart clothing is still exciting, because clothing is the most indispensable part of our life. In 2015, the global clothing market is a whopping \$1.3 trillion and will reach \$1.5 trillion in 2020.[185] It can be imaged that with advances in fiber and textile electronics, there will be an unprecedented market expansion.

6. Future and Prospects

In the past decade, the emerging fiber and textile electronics has become the most promising branch of modern electronics and has drawn considerable research and commercial interest. Although significant progress has been made in the field, currently available commercial products are very few. Thereinto, fiber-shaped sensors represent one main type of the few devices that are available for practical applications. However, they are simply used for signal monitoring, and more sensing functions are expected in the near future. For most fiber-shaped devices, there are still many challenges and technological gaps hindering their practical applications.

Compared with conventional rigid or thin-film devices, the fiber-shaped electronic devices show relatively poor performances. The fiber electrodes are usually so thin that the electrical conductivities are lower than those of plane electrodes, which will seriously reduce the performance of the fiber-shaped electronic devices. Although several attempts have been demonstrated by introducing highly conductive materials and optimizing device structures, a balance between mechanical and electrical properties is required. Hence, novel materials for fiber-shaped electronics are highly desired to improve the device performance. Moreover, the lifetime of fiber-shaped electronic devices needs to be improved. On the one hand, the active materials are easily peeled off the electrode or even the electrodes break during the repeated deformation processes. To this end, optimized device structures with stretchability have been widely studied to ensure that the devices can adapt to shear deformation during use. Unfortunately, the stretchability is often achieved at the expense of electrical performance due to the introduction of inactive elastomeric polymers that increase the volume and weight of the device. On the other hand, most fiber-shaped electronic devices are sensitive to oxygen and water, which leads to a rapid deterioration in performance. However, the current mainstream encapsulation materials and technology fail to meet the requirement of fiber electronic devices with highly curvilinear surface. Therefore, it is extremely important and urgent to find new and efficient encapsulation materials and methods for the fabrication of fiber-shaped electronic devices.

To fully realize the commercial potential of fiber and textile electronics, the development of large-scale production techniques is essential but still difficult to achieve. It is challenging to find a continuous preparation process to produce a stable interfacial bonding between the active material and the flexible substrate or among other components. Most reported devices are prepared by hand at a lab scale, and only a few attempts have been made for continuous preparation. Meanwhile, the performances of fiber-shaped electronic device greatly decrease when they are fabricated at a large scale. This decrease is induced by the relatively low electrical conductivity of fiber electrodes. The electrical resistance increases remarkably from centimeters to meters.

The electronic textile is the most important application for the fiber-shaped electronic devices. To this end, it is vital to develop efficient processing techniques to integrate different fiber electronic devices into textiles with a better and more comfortable human/textile interface design. Moreover, reliable connecting technique and integrated circuit are desired to achieve the high integration of electronic textile. However, only a few studies are available, and the human/textile interface is not taken into consideration. In addition, the functional integration of fiber devices is important for reaching a broader range of applications. For instance, the integration of supercapacitor and sensor in one fiber can enable the ability to monitor environmental changes without the use of an external power source. Although the integration of different functions of fibers has been widely demonstrated, the mismatch in material, structure, and fabrication requirement among the different kinds of devices remains a critical barrier for practical applications.

Apart from the problems mentioned above, safety issues are important for practical applications. Some fiber-shaped electronic devices such as batteries often require the use of flammable and toxic organic electrolytes, and they suffer from risks of fires and explosions induced by short-circuit during deformation. Stable and environmentally friendly aqueous or even gel aqueous electrolytes are preferred instead of liquid organic electrolytes in fiber-shaped electronic devices, while their electrochemical performance needs to be improved. Another security issue concerns the security of personal data. With greater market penetration, the wearable sensors are expected to generate huge volumes of personal data, where leaking of sensitive information can have deleterious effects. Therefore, date protection has become one of the most crucial factors for the application. Furthermore, for wearable applications, other issues such as comfortability and washability also need to be considered.

What is more, it is often difficult to compare the reported performance of fiber-shaped electronic devices because of the lack of appropriately evaluation systems. In the literature, the performance metrics are expressed in different forms according to different units. Taking the fiber-shaped supercapacitor as an example, we may find a variety of parameters such as gravimetric/volumetric/areal/linear capacitance/energy density/power density, and the mass/volume/area may be calculated from active materials, electrodes, or whole devices. It is confusing to compare the different systems. Furthermore, the characteristics of flexibility such as bending, twisting, stretching, and other tolerance are unique indicators of flexible electronic devices, but there are no unified evaluation systems for fiber-shaped electronic devices at present. Therefore, the evaluation methods and testing protocols of fiber-shaped devices are necessary to be standardized.

The application of fiber and textile electronics require the joint efforts of professionals in many different fields, such as material scientists, chemists, physicists, textile scientists, bioengineers, electrical engineers, mechatronics engineers, and software engineers. This multidisciplinary collaboration will increase the possibility of a successful example, which will offer countless opportunities to improve our life.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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