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Review

Electronic fibers and textiles: Recent progress and perspective

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SUMMARY

Wearable electronics are receiving increasing attention with the advances of human society and technologies. Among various types of wearable electronics, electronic fibers/textiles, which integrate the comfort and appearance of conventional fibers/textiles with the functions of electronic devices, are expected to play important roles in remote health monitoring, disease diagnosis/treatment, and human-machine interface. This article aims to review the recent advances in electronic fibers/textiles, thus providing a comprehensive guiding reference for future work. First, we review the selection of functional materials and fabrication strategies of fiber-shaped electronic devices with emphasis on the newly developed functional materials and technologies. Their applications in sensing, light emitting, energy harvest, and energy storage are discussed. Then, the fabrication strategies and applications of electronic textiles are summarized. Furthermore, the integration of multifunctional electronic textiles and their applications are summarized. Finally, we discuss the existing challenges and propose the future development of electronic fibers/textiles.

INTRODUCTION

Recently, development of flexible and wearable electronics has been gradually prominent in our daily life (Park et al., 2018; Trung and Lee, 2016). Ideal wearable electronics possess characteristics of flexibility, light weight, easy to bind with human skin, and tolerating mechanical deformation, to satisfy the requirements of comfort and avoid interfering with normal activities of humans (Zeng et al., 2014). However, traditional electronics with high performance are mostly made of bulky and rigid inorganic materials, such as silicon or gallium arsenide, which are used for fabrication of complex planar circuits (Fan et al., 2008; Kim et al., 2009). The mechanical mismatch between rigid electronics and human skin has immensely prevented electronic devices from conformably attaching on the human body. Therefore, electronic devices are gradually developing toward flexibility and miniaturization to fulfill the requirements of wearing, and have developed from three dimensional (3D) rigid devices to low-dimensional and lightweight flexible devices. Electronics in forms of fibers and textiles, with advantages of good flexibility, light weight, breathability, and easiness of integration with traditional clothes, are one of the ideal form of wearables (Chatterjee et al., 2019).

Although fibers have been used in human lives for thousands of years, the history of developing functional and intelligent fibers is not long. Before the emergence of flexible and wearable electronics, optical fibers and metal fibers were the representative functional fibers (Kao and Hockham, 1966; Wardclose and Partidge, 1990). Recently, with the progress of material science and nanotechnology, wearable electronic fibers/textiles, including 1D fiber-shaped electronic devices (electronic fibers) and 2D/3D electronic textiles, which combine the flexibility and excellent mechanical properties of fibers/textiles with the functionality and intelligence of electronic components, are attracting enormous interest. Electronic fibers/textiles can inherit the advantages of light weight, flexibility, air permeability, and a certain degree of ductility of traditional fibers/textiles while possessing electronic functions. Currently, 1D fiber-shaped electronics have been widely studied and used in sensing (Mattmann et al., 2008), light emitting (O'Connor et al., 2007), energy harvesting (Qin et al., 2008), and energy storage (Yang et al., 2013b; Zhang et al., 2016b). At the same time, some works have explored the integration of electronic fibers into functional textiles. Combining electronic fibers/textiles with human skin can potentially build an intelligent system, which combines and coordinates the functions of response, perception, communication, energy harvesting, energy storage, and data processing (Shi et al., 2020). With further efforts, electronic fibers/textiles may be integrated with biological nerves, muscles, and ligaments in the future to endow us with more functions.

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Table 1. Summary of 1D electronic fibers including the conductive materials, fabrication strategies, electrical conductivity, stretchability, and applications reported in the literature

Conductive material	Preparation method	Conductivity /S m^{-1}	Strength /MPa	Stretchability /%	Application	Reference
Metals						
Ag/NWs/Ag NPs	Chemical incorporation	2.45	2.8	900	Strain sensor	(Lee et al., 2015)
Liquid metal (EGaIn)/CBs	Thermal drawing + Dip coating	1	4.2	500	Optical fiber Strain sensor	(Qu et al., 2018)
Cu microwires	Helically convolving	0.0005	–	70	Electrode	(He et al., 2017)
Ag NWs	Wet spinning	142.05	18.9	786	Conductive wire	(Lu et al., 2018)
Cu NWs	Dip coating	0.5	–	100	Electrical heater	(Cheng et al., 2016)
Functional polymers						
Polypyrrole	Dip coating	–	–	100	Thermal sensor	(He et al., 2016)
PEDOT	Dip coating	0.0167	100	20	Strain sensor	(Eom et al., 2017)
Conductive hydrogel	Wet spinning	0.02	5.6	1180	–	(Zhang et al., 2018b)
Organohydrogel	Wet spinning	0.765	0.2	400	Strain sensor	(Song et al., 2020)
Ionically conductive fluid	Multicore–shell printing	0.00050	–	700	Strain sensor	(Frutiger et al., 2015)
Carbon materials						
SWCNTs	Twisting SWCNT	4.40	110	285	Strain sensor	(Shang et al., 2012)
MWCNTs	Wrapping MWCNT on a rubber fiber	0.038	–	1320	Strain sensor	(Lee et al., 2015c)
MWCNTs	Wet spinning	0.001	–	300	Strain sensor	(Tang et al., 2018)
Graphene	CVD	25,000	40	7.1	Strain sensor	(Wang et al., 2015)
rGO	Twisting rGO film	6000	23	40	Thermal sensor	(Wang et al., 2017)
rGO	Dip coating	0.136	29	656	Strain sensor	(Cheng et al., 2015)

MWCNT, multiwall carbon nanotube; SWCNT, single-wall carbon nanotube.

Although great progress has been made in the fields of electronic fibers/textiles, most of the reported results are still far from practical applications owing to technical hindrances and challenges. The challenges mainly come from aspects such as flexible conductive materials, manufacturing techniques, functionalities, data security, testing methods, and standards for wearable technology. Currently, there still is a lack of comprehensive review papers that cover the material selections for electronic fiber/textiles, the designing of functions and corresponding applications, and the integration of multifunctional textiles, which is exactly the purpose of this review (Figure 1). In this review, the material selections and fabrications of electronic fibers are first introduced, with emphasis on the newly developed functional materials and technologies. Second, fabrication methods and applications of electronic textiles are discussed. Third, integration strategies and applications of multifunctional electronic textiles are explicated. Finally, the persisting challenges, future opportunities, and trend of electronic fibers/textiles are discussed.

ELECTRONIC FIBERS: FABRICATION AND APPLICATIONS

Electrical conductivity is the prerequisite for fibers to be used as electronic fibers. Therefore, directly fabricating conductive fibers or endowing traditional fibers with conductivity is necessary. This section will focus on fiber-shaped electronics. First, the main types of the involved conductive components (such as metals, functional polymers, and carbon materials) and the strategies to make them into electronic fibers will be reviewed (Table 1). Then, the applications of the fiber-shaped electronic devices in sensing, light emitting, and energy harvesting and storage will be discussed.

Conductive materials

Metals

Metals usually have excellent conductivity and have played very important roles in traditional rigid and bulky devices. In recent years, traditional metal wires with high conductivity and strength have been used in fiber-shaped electronics. For example, lithium wires could be directly used as negative electrodes

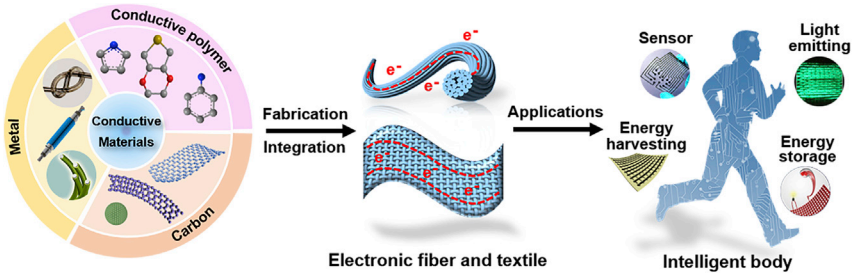

Figure 1. An overview showing the field of electronic fibers/textiles, including the conductive materials, the structures and properties, and their applications in wearable electronics for intelligent body. Reprinted with permission from (He et al., 2019). Copyright 2019, AAAS. Reprinted with permission from (Park et al., 2019). Copyright 2019, American Chemical Society. Reprinted with permission from (Zhang et al., 2019). Copyright 2019, Elsevier. Reprinted with permission from (Liu et al., 2015a). Copyright 2015, Nature Publishing Group.

in fibrous lithium-based batteries (Liu et al., 2017; Pan et al., 2018; Zhang et al., 2016a; Zhou et al., 2019). Platinum wires have been used as counter electrodes in fiber-shaped dye-sensitized solar cells (Gu et al., 2019; Pu et al., 2016). A newly developed thermally drawn technology, jointly stretching a variety of materials, including metals, insulators, and semiconductors, can regulate the diameter of fibers from micro- to nanoscale, achieving novel and complex structures with the required size (Figure 2A) (Leber et al., 2020). In the thermally drawn process, solid/liquid metals with low melting points can be used as the core layers, and thermoplastic polymers can be used as the cladding layers, which were flowed together in a laminar flow mode and thus the obtained fibers are continuous and do not agglomerate or break due to unstable capillarity (Du et al., 2020). It should be noted that the thermally drawn technique can only be used on materials fitting certain requirements, such as the viscosity of materials in different layers should match with each other and the cladding polymers must be thermoplastic.

Metal-based electronic fibers can also be prepared by coating metal nanomaterials on the surface of polymer fibers. The inner polymer fibers provide certain flexibility and stretchability for the electronic fibers and reduce the weight of the electronics. The outer metal coating layers provide the electron transport paths for electronic fibers. The metal nanomaterials can be assembled onto the fiber surface through atomic layer deposition, electrochemical deposition, and electrodeposition (ELD) methods (Jur et al., 2011; Lee et al., 2013). Among them, polymer-assisted metal deposition, a kind of ELD method, is very attractive because it does not require expensive equipment and can prepare conductive fibers at a large scale under ambient conditions. For instance, a thin layer of Ni with a thickness of 340 μm was deposited on the surface of cotton fibers (Figure 2B). To improve the electrochemical activity, reduced graphene oxide (rGO) was further electrochemically deposited (Liu et al., 2015a). Moreover, elastic fibers such as polyurethane (PU) fibers were selected as the inner layer of electrode fibers to prepare highly elastic electronic fibers (Li et al., 2017). However, the coating method also has its disadvantages. The binding force between the conductive layer and the polymer fiber layer is usually poor, and the conductive layer is prone to flake off induced by mechanical deformation, thus resulting in deterioration in stability.

Another strategy is introducing metal nanomaterials into light weight and flexible polymer matrixes through traditional spinning technology to prepare conductive hybrid/composite fibers. For instance, Ag nanowires (NWs) were mixed with poly(styrene-block-butadiene-block-styrene) (SBS), followed by obtaining Ag NWs-mixed SBS fibers through a simple wet spinning process. To further improve the electrical conductivity of the fiber, additional Ag NPs were directly coated on the surface of the composite fibers, obtaining elastic and conductive composite fibers (Figure 2C). The composite fibers showed superior initial electrical conductivity and elongation at break and exhibited strain-sensing behavior within a broad range of applied tensile strain. The fibers could be embedded into a smart glove for detecting human motions (Lee et al., 2015). However, the metal-polymer mixing strategy for fabricating fibers also has some limitations: 1) The percentage of metal nanomaterials in the composite fibers is limited, and the conductivity is not particularly ideal. Therefore, this kind of composite fibers are rarely used as conductive wires. 2) Metal nanomaterials with excessive sizes will cause poor dispersion in polymer matrix, leading to the blockage of the spinneret and low performance of the obtained composite fibers.

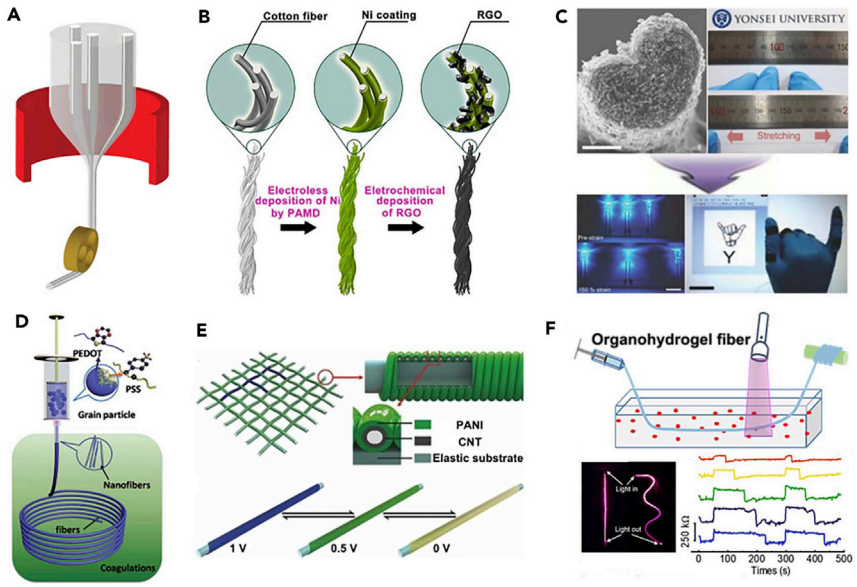

Figure 2. Metals and functional polymers for fabrication of electronic fibers

(A) Constant-scale and scale-down co-drawing strategy of flexible fiber probe. Reprinted with permission from Leber et al. (2020). Copyright 2020, Wiley-VCH.

(B) Fabrication of rGO/Ni-cotton yarn composite electrodes for FSCs. Reprinted with permission from Liu et al. (2015a). Copyright 2015, Nature Publishing Group.

(C) The fabrication process of highly stretchable conductive fibers reinforcing Ag nanowires for wearable electronics. Reprinted with permission from Lee et al. (2015). Copyright 2015, Wiley-VCH.

(D) PEDOT:PSS fiber prepared by the wet-spinning processes. Digital photograph and scanning electron microscopy image of PEDOT:PSS fiber and digital photographs of the fibers woven on the surface of cotton glove fabrics. Reprinted with permission from Yuan et al. (2016). Copyright 2016, The Royal Society of Chemistry.

(E) Structure and display function of the electrochromic FSC. Reprinted with permission from Chen et al. (2014). Copyright 2014, Wiley-VCH.

(F) Fabrication process of organohydrogel fibers and their multifunctional applications in electrodes, optical devices, and sensors. Reprinted with permission from Song et al. (2020). Copyright 2020, Wiley-VCH.

Functional polymers

Polymer fibers usually have excellent flexibility, but most of them are not conductive except for some electronically conductive polymers and emerging ionic conductive polymers. This section will mainly discuss the preparations and applications of electronic-conductive polymers and ionic conductive polymers.

Traditional electronic-conductive polymers, such as polypyrrole (PPy) (Li et al., 2019b), polyaniline (PANI) (Xie et al., 2014), poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) (Guo et al., 2016), and polythiophene (Ambade et al., 2016) have showed wide applications owing to their unique electronic properties. For example, PEDOT:PSS fibers with length of meters and excellent electrical properties were obtained in $CaCl_2$ aqueous solution (Figure 2D). The fibers can be used as the electrodes of all-solid-state fiber-shaped supercapacitors (FSCs). The FSCs show a high areal capacitance and areal energy density (Yuan et al., 2016). However, it is challenging to fabricate freestanding electronic fibers by employing bare electronic-conductive polymers owing to their poor mechanical properties. To address this problem, electronic-conductive polymers were usually coated onto commercial fibers or composited with other conductive fibers, such as carbon-based fibers (Figure 2E) (Chen et al., 2014). Besides, some electronic-conductive polymer fibers can change their colors in response to varying voltages, which have potential to be used as electrochromic fibrous devices.

In addition, ionic conductive polymers have attracted significant attention owing to their high stretchability, transparency, and superior conductivity and have been prepared in forms of hydrogel and fiber (Shuai et al., 2020). The current in ionic conductive polymers is transported by means of the migration of free ions in water, thus endowing the ionic conductive polymers with a smaller change in resistance under

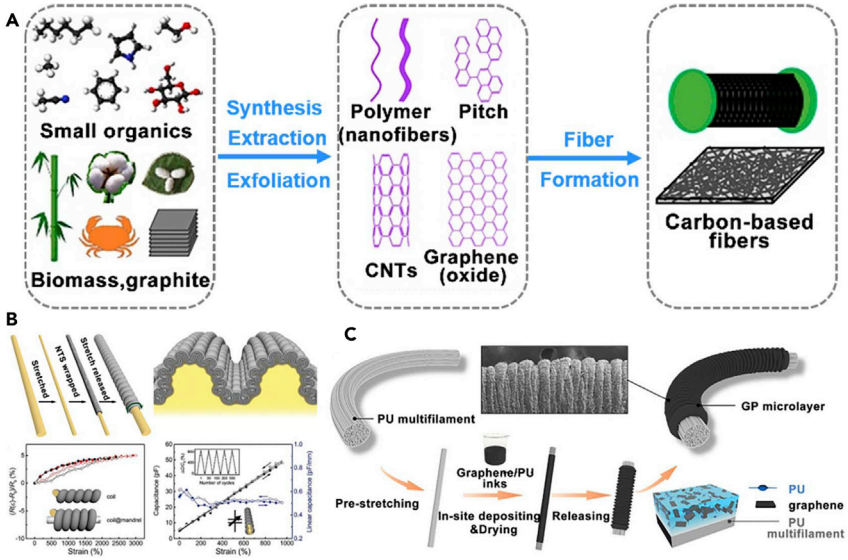

Figure 3. Carbon-based nanomaterials as active materials or conductive additives for flexible and wearable electronic devices

(A) Carbon sources, synthesis methods, and formations of carbon-based fibers. Reprinted with permission from Chen et al. (2020b). Copyright 2020, American Chemical Society.

(B) Hierarchically buckled sheath-core CNT/PU fibers for super-elastic electronics, sensors, and muscles. Reprinted with permission from Liu et al. (2015b). Copyright 2015, AAAS.

(C) Schematic diagram of preparing the bionic, super-elastic, and conductive PU filaments with worm-shaped graphene microlayer. Reprinted with permission from Sun et al. (2019). Copyright 2019, American Chemical Society.

deformation compared with electronic conductors. Currently, ionic conductive fibers are mainly prepared through tubular templated method and wet spinning. Compared with the tubular templated method, wet spinning is more efficient for preparing continuous fibers. However, the incompatibility of the slow polymerization process with the fast and dynamic spinning process under stretching force usually results in poor spinnability, limiting the continuous preparations of ionic conductive fibers. In addition, ionic conductive fibers have drawback of evaporation/freezing of water under excessively high/low temperature, resulting in low efficiency. To solve these problems, it was reported that a kind of ionic conductive fiber was prepared continuously by wet spinning through a dual network strategy of ionic complexation and covalent hybrid cross-linking, followed by replacing water with a glycerol/water mixture (Song et al., 2020). As stretchable and optical electrodes, the ionic conductive fibers could collect bioelectrical signals and be used in phototherapy (Figure 2F).

Carbon materials

Carbon materials with 0D, 1D, and 2D structures have been widely used in flexible electronic fibers/textiles, owing to their outstanding conductivity ($\approx 10^4$ S cm^{-1}), high strength, large specific surface area, and relatively low mass density (Hirsch, 2010). Among them, carbon fibers (CFs), carbon nanotube (CNT) fibers, and graphene fibers (GFs) have been widely used as conductive materials for preparing electronic fibers and will be discussed in this section (Figure 3A).

CFs, a kind of carbon materials with fibrous morphology and carbon content of above 95%, are usually obtained from carbonizing/graphitizing polymer fibers. They have excellent mechanical properties, light weight, certain conductivity, and environmental stability. According to the precursors, CFs can be divided into polyacrylonitrile (PAN)-based CFs, pitch-based CFs, and viscose-based CFs. For instance, PAN fibers were first produced by polymerization of acrylonitrile and wet spinning, followed by stabilizing at the temperature of 200–300°C. Finally, CFs were obtained through carbonization/graphitization process in the temperature range of 1,000–2,800°C (Lee et al., 2001). However, owing to their compact structure, high brittleness, and small specific surface area, CFs were usually only suitable for conductive substrates or wires but not suitable for active materials in sensors and other electronics (Rahaman et al., 2007).

CNTs, another representative of 1D carbon nanomaterials, show a series of excellent characteristics, such as light weight, high strength, tunable electrical conductivity, and good chemical stability. CNT fibers, the 1D macroassembly of CNTs, can partly inherit the shape and properties of CNTs at the microscopic scale (Cheng et al., 1998). At present, the main preparation methods for CNT fibers are wet spinning and dry spinning (array spinning, direct vapor deposition, and film winding). The structure and performance of CNT fibers are strongly dependent on the spinning methods. For example, good orientation of CNTs in a fiber will endow the fiber good flexibility, good electrical conductivity, and excellent mechanical properties. Thus, the CNT fibers can be bent, twisted, knotted, and woven without affecting their mechanical properties (Jang et al., 2020).

GFs, using microscopic 2D graphene sheets as building blocks, are also considered as potential materials for electronic fibers (Xue et al., 2017). To prepare GF-based electronic fibers, it is necessary to first realize the preparation of macroscopic GFs with good flexibility, high mechanical strength, and excellent electrical conductivity. There are four main methods for preparing GFs, including wet spinning, scrolling fibers from films, 3D printing, and confined hydrothermal method (Xu et al., 2020; Zhang et al., 2020c). Compared with other methods, wet spinning has prevailed in the fabrication methods of GFs and has been extended to the production of composite or hybrid GFs, in a manner of continuity and scale, but there is still a lot of room for the improvement of the orientation and mechanical properties of the prepared GFs.

In addition, the above carbonaceous fibers can be used as substrates to *in situ* grow or coat conductive polymers, such as PEDOT:PSS (Qu et al., 2016), PPy (Huang et al., 2015), or some inorganic nanomaterials (MnO_2 [Huang et al., 2015], MoS_2 [Liang et al., 2017]), to obtain functional composite fibers. Meanwhile, carbon nanomaterials can also be made into composites with polymer fibers by coating or dipping methods, to fabricate hybrid/composite fibers (Meng et al., 2015). Among various types of composite polymers, stretchable and conductive fibers prepared by wrapping CNTs (Liu et al., 2015b) or graphene (Sun et al., 2019) oriented in the fiber direction on pre-stretched rubber polymer fibers exhibit ultrahigh tensile ability, wide reversible response range for strain, and long-term durability (Figures 3B and 3C). However, similarly, the carbon nanomaterials in these composite fibers also show problems of easy aggregation and desquamation.

Fiber-shaped electronic devices and their applications

Sensing devices

Sensing electronics can convert external stimuli, such as mechanical deformation, environment chemicals, and changes in temperature or humidity into electronic signal, to obtain the related information. According to the difference of the work mechanisms, sensing electronics can be divided into physical sensors, chemical sensors, and electrophysiological sensors. Compared with traditional bulky electronic sensors, fiber-shaped sensors exhibit better conformability with the body and are easily integrated into commercial textiles (Cheng et al., 2017; Zhou et al., 2017). Over the past decades, fiber-shaped sensors have been proven not only in concept but also in practical applications ranging from basic healthcare monitoring to clinical assessment of disease status (Cho et al., 2019; Li et al., 2020a).

When physical sensors are subjected to mechanical deformation or environmental stimulation, their microstructures or inherent conductivity will change, which can be translated into resistance/capacitance or voltage/current. Traditionally flexible sensors and even ultra-thin sensors can reduce the sense of touch to some extent when they are attached to human body, resulting in deviation of the measured results, unable to truly reflect the natural feeling of the skin. Recently, flexible fiber-shaped strain/stress sensors are widely studied and have become the most widely developed sensors owing to their applications in physiological signal monitoring (such as heart rate, blood pressure, and respiratory rate) (Lee et al., 2020a). For example, to reduce the sensory interference, an FSC flexible pressure sensor with high sensitivity has been fabricated using the electrospinning method (Lee et al., 2020b), which can accurately monitor finger pressure without detectable influence on human sensation (Figure 4A). Electronic fibers can also work as temperature sensors because they may show linear or nonlinear changes in electrical resistivity under varying temperatures. Fiber-shaped electronics were prepared by integrating a printed fiber-shaped temperature sensor (FTS) and a printed asymmetric FSC through a simple 3D printing method (Zhao et al., 2018). The FSC could provide stable output power to the FTS, and the temperature responsivity of the FTS is 1.95% $°C^{-1}$ (Figure 4B). Besides, some conductive fibers also exhibit changes in electrical resistivity when exposed to different atmospheric humidity conditions, which can be used as humidity sensors. An inflight fiber

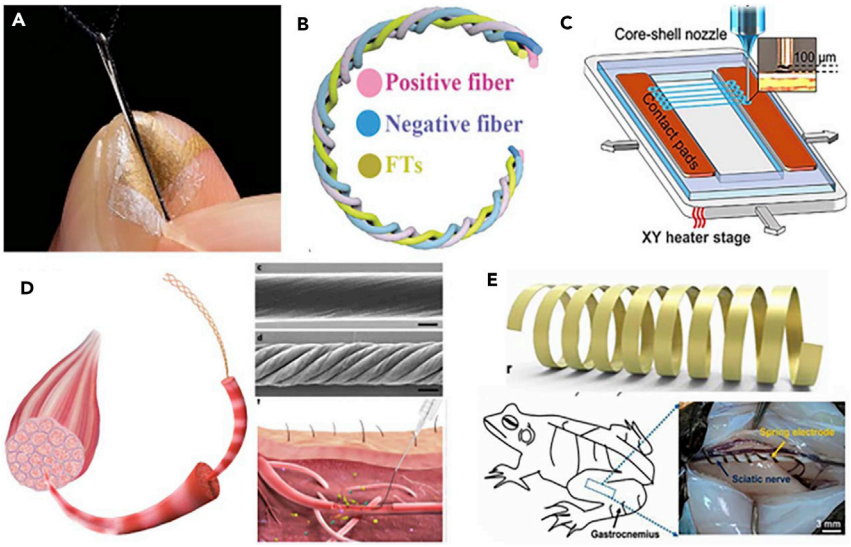

Figure 4. Fiber-shaped electronic devices for wearable sensors

(A) Nanomesh pressure sensor for monitoring finger manipulation without sensory interference. Reprinted with permission from Lee et al. (2020b). Copyright 2020, AAAS.

(B) Weavable tunicate cellulose/CNT fibers for high-performance wearable sensors. Reprinted with permission from Cho et al. (2019). Copyright 2019, American Chemical Society.

(C) Inflight fiber printing toward array and 3D optoelectronic and sensing architectures. Reprinted with permission from Wang et al. (2020c). Copyright 2020, AAAS.

(D) Functionalized helical fiber bundles of CNTs as electrochemical sensors for long-term *in vivo* monitoring of multiple disease biomarkers. Reprinted with permission from Wang et al. (2020b). Copyright 2020, Nature Publishing Group.

(E) GO/SA microribbons composed of directionally self-assembled nanoflakes employing 3D printing as highly stretchable ionic neural electrodes. Reprinted with permission from Zhang et al. (2020b). Copyright 2020, National Academy of Sciences.

printing method that integrates conductive fiber preparation and fiber-to-circuit connection to fabricate PEDOT:PSS fibers has been reported (Figure 4C). The PEDOT:PSS fibers, working as noncontact and portable respiratory sensors, can collect both the distribution and direction of exhaled gas (Wang et al., 2020c). Although electronic fibers can easily realize sensing ability, poor selectivity and anti-interference ability are still huge challenges. For example, most of humidity sensors are very sensitive to temperature. Many strain sensors also respond to pressure. Moreover, some conductive fibers/textiles show serious hysteresis, which seriously affects the accuracy and response time.

In addition to monitoring physical signals, continuous monitoring of chemical/biological parameters such as electrolytes, metabolites, and other biomarkers in body fluids is also important to obtain complete information of an individual's health at the molecular level. Hence, fibrous chemical/electrophysiological sensors have been developed. Chemical sensors can selectively convert the identities and concentrations of various chemicals into electrical signals.

The fibrous chemical/electrophysiological sensors can be prepared through coating active materials on the surface of conductive fibers. A coaxial fiber sensor prepared by coating different functional materials on the surface of a conductive CNT fiber could simultaneously realize real-time monitoring of five physiological signals (such as glucose, Na^+, K^+, Ca^{2+}, and pH) and maintain structural integrity and detection ability under repeated deformation (bending and twisting) (Wang et al., 2018). Besides, fibrous electrodes can be obtained by *in situ* polymerization of conducting polymers or polyelectrolyte-based coating with CNTs on the surface of commercial nonconductive yarns (such as cotton [Shim et al., 2008], nylon [Wang et al., 2016b]) for detecting the content of glucose or metal ions in body fluid. For example, a fiber-shaped electrochemical transistor (FECT) was fabricated by coating polypyrrole NWs and PVA-co-PE nanofibers on a nylon fiber. The channel current of the FECT depended on the concentration of metal ions, enabling the fiber to work as a chemical sensor (Wang et al., 2016b). In addition, conductive fibers obtained by carbonizing commercial fibers could also be used as the current collector or work electrode of sensing devices for physiological signal detection and energy harvesting (Wu et al., 2020).

Recently, fiber-shaped electrophysiological sensors implanted into living organisms to monitor health signals in real time have also been reported. Conventionally electrophysiological electrodes are usually made of rigid materials (metal or metal oxide), which result in a mechanical and geometric mismatch between electrodes and the soft, dynamic biological tissues. Recently, it has been reported that functionalized multi-walled CNTs twisted into helical fiber bundles by mimicking the hierarchical structure of muscles can monitor a variety of disease biomarkers *in vivo* (Figure 4D) (Wang et al., 2020b). Peripheral nerve signal collection and electrical stimulation also have important clinical application value in the treatment of neuropathic diseases. A helical ionic neural electrode with ultrahigh stretchability up to 1,000% and excellent nanoscale ionic transport properties was prepared by a direct-ink writing method, which showed excellent compatibility with soft and dynamic biological tissues (Figure 4E) (Zhang et al., 2020b). However, although great progress has been achieved, fibrous chemical/electrophysiological sensors are still facing challenges, such as easily drifted output signals, requiring calibration before using each time, unstable for long-term storage and use, limiting their practical applications.

Light-emitting electronics

As a kind of functional electronic fibers, luminescent electronic fibers have also received extensive attention and played an important role in transportation, security, anti-counterfeiting, clothing, and aviation (Lee et al., 2020a; Wu et al., 2018). Fiber-shaped light-emitting electronics can be seamlessly integrated with textiles, enabling applications in textile display, sensing, and camouflage. Fiber-shaped perovskite solar cells (PSCs), polymer light-emitting electrochemical cells (PLECs), organic light-emitting diodes (OLEDs) driven by direct current and alternating current electroluminescent (ACEL) devices have been reported (Kwon et al., 2020).

Fiber-shaped PSCs have attracted more and more attention owing to their better flexibility than silicon-based photovoltaic solar cells and higher energy conversion efficiency than organic photovoltaic cells. For instance, fiber-shaped PSCs can be obtained by depositing perovskite materials on the surface of spring-like modified titanium wires (Figure 5A) (Deng et al., 2015). Besides being used in PSCs, metal wires for PLECs have also been reported. The fiber-shaped PLECs have a coaxial structure consisting of a ZnO-modified stainless steel wire in the core as the cathode and a CNT film in the sheath as the anode, with an electroluminescent polymer layer sandwiched between the cathode and the anode (Figure 5B) (Zhang et al., 2015). Besides, fibrous OLEDs were prepared by coating PEDOT:PSS, ZnO, polyethylenimine, super yellow, MoO_3, and Al layers in sequence on the surface of commercial PET fibers (Figure 5C) (Kwon et al., 2018). In addition to using commercial nonconductive polymer fibers, conductive fibers can be directly used for coating functional materials. For example, perovskite-CNT light-emitting fibers were obtained by integrating CNT fibers with organic-inorganic emissive composite layers through an all-solution-processed method (Figure 5D) (Jamali et al., 2020). However, the distribution of the active materials on/along the fibers and the solvent compatibility in the dipping process remain a challenge. To address these issues, the outer electroluminescent layer and two internal parallel gels were extruded simultaneously by a one-step extrusion process to obtain super-stretchable electroluminescent fiber (Figure 5E) (Zhang et al., 2018). In addition, 1D ACEL fibers could be assembled by simultaneously extruding different functional materials using multicore-shell printing heads by 3D printing (Figure 5F). By assembling functional 1D devices into highly precise and complex 3D macrostructures, the fiber-shaped ACEL could be used for phototherapy, imaging bioelectronics, and wearable electronic textiles (Liu et al., 2020). However, this multicore-shell printing method requires each of printing inks possessing similar rheological behaviors in order to ensure the simultaneous flow of different materials, which increase the difficulty for preparing fiber-shaped ACEL devices. In addition, the high working voltage also limits the practical applications of fiber-shaped ACEL devices.

Energy-harvesting devices

Mechanical and thermal energy are pervasively available, especially from human motions and bodies (Huang et al., 2020). Energy-harvesting devices in fiber shape can be woven into yarns or fabrics to build large-scale wearable electronic systems, which can harvest energy from human motions and bodies to power wearable electronic devices (Pu et al., 2018). At present, there are mainly three kinds of energy-harvesting devices based on piezoelectricity, triboelectricity, and thermoelectricity, respectively, which will be discussed in this section.

The working mechanism of piezoelectric nanogenerators (PENGs) is that the mechanical energy in the environment makes the piezoelectric material deform, causing the potential difference on the different surfaces of the material due to the piezoelectric effect, thus realizing the transformation from mechanical energy to

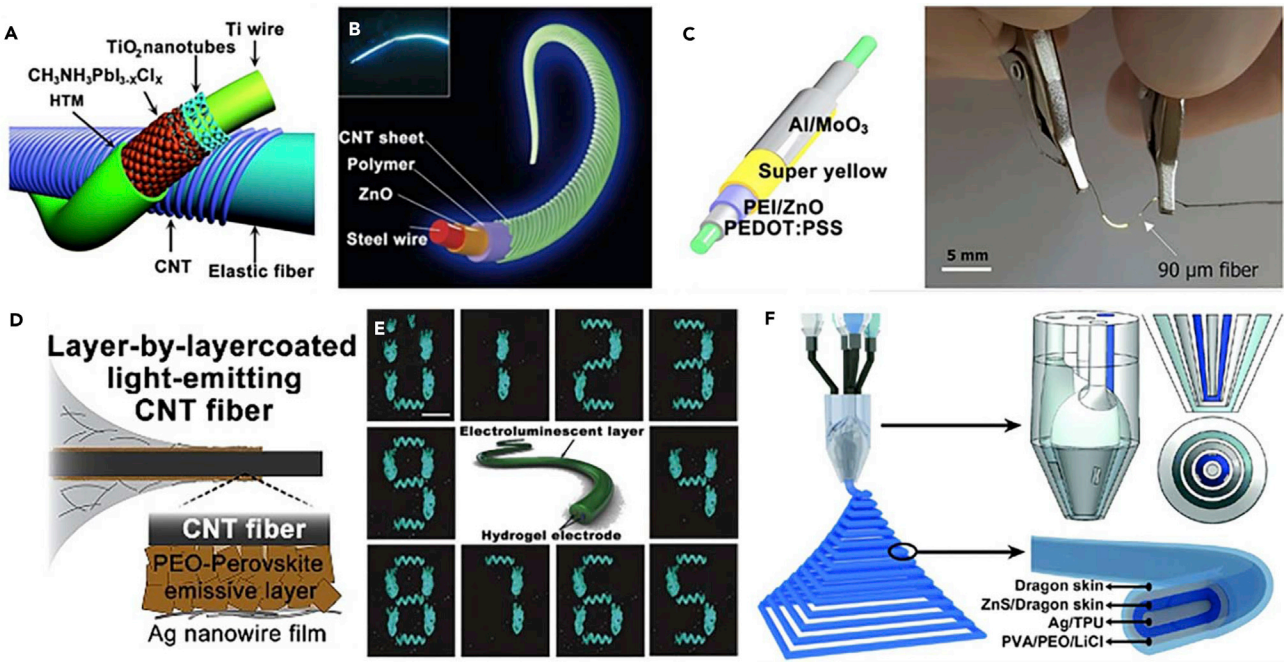

Figure 5. Fibrous electronics for flexible light-emitting devices.

(A) Schematic illustration of an elastic perovskite solar cells fiber. Reprinted with permission from Deng et al. (2015). Copyright 2015, The Royal Society of Chemistry.

(B) Schematic illustration of a PLEC fiber. Reprinted with permission from Zhang et al. (2015). Copyright 2015, Nature Publishing Group.

(C) Schematic illustration of a fiber-shaped OLED and photograph of the OLED as a flexible light-emitting device. Reprinted with permission from Kwon et al. (2018). Copyright 2018, American Chemical Society.

(D) Fabrication process for the coaxially coated light-emitting carbon nanotube fiber by a layer-by-layer method. Reprinted with permission from Jamali et al. (2020). Copyright 2020, American Chemical Society.

(E) Super-stretchable electroluminescent fibers as textile display for electronic and brain-interfaced communications. Reprinted with permission from Zhang et al. (2018). Copyright 2018, Wiley-VCH.

(F) Schematic illustration showing a multicore-shell print head and the printed 1D stretchable ACEL device. Reprinted with permission from Liu et al. (2020). Copyright 2020, The Royal Society of Chemistry.

electrical energy (Figure 6A) (Huang et al., 2020). Polymer fibers, which are flexible and chemically inert, can be easily constructed into fiber-based PENGs. However, polymer-based PENGs usually have low dielectric constants and require a high electric field to polarize, limiting their applications (Fan et al., 2016). In contrast, inorganic piezoelectric materials, such as barium titanate (Liao et al., 2017), cadmium sulfide (Mohanta and Sarkar, 2020), and zinc oxide (Gao et al., 2009; Yang et al., 2009) have excellent piezoelectric effects. However, their brittleness and rigidity limit their applications in flexible and wearable electronics. To address this problem, inorganic piezoelectric materials are nanostructured or mixed with polymers to construct fiber-shaped PENG devices (Figure 6D) (Jella et al., 2019). These devices exhibited high piezoelectric performance, showing excellent ability to harvest mechanical energy from human motions.

Compared with that of PENGs, the working mechanism of triboelectric nanogenerators (TENGs) is that the combined effect of contact electrification and electrostatic induction harvests the mechanical energy from the environment and human motions, which have been applied in charging mobile phone batteries as direct power sources and powering self-powered active sensors (Figure 6B) (Wu and Wang, 2016). At present, a variety of commercial organic materials (such as nylon [Zhang et al., 2020a], cotton [Jeong et al., 2019], silk [Dudem et al., 2020], perfluoroalkoxy [Hinchet et al., 2019], and PVDF [Fang et al., 2011]) and inorganic materials (MoS_2 [Xue et al., 2016], TiO_2 [Lin et al., 2013], and Si [Yang et al., 2013a]) have been used to prepare fiber-shaped TENGs with excellent performances. Commonly, fiber-shaped TENGs are designed as coaxial or core-shell structures. Depending on the operation mode of fiber-shaped TENGs, they can be further divided into single electrode mode ones and vertical contact separation mode ones. Compared with the TENGs with single electrode mode, those with vertical contact separation mode usually have higher electrical output and better stretchability (Dong et al., 2020b). Kim et al. reported a textile-based

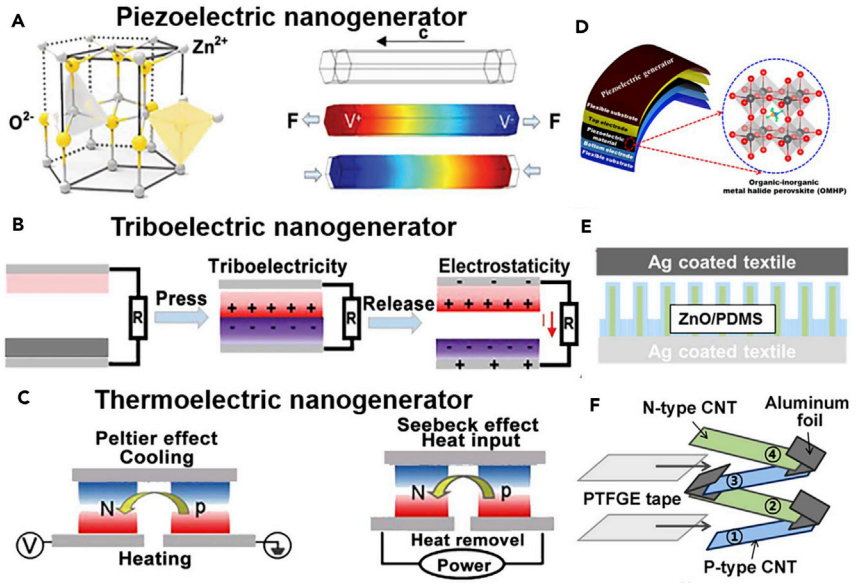

Figure 6. Fiber-shaped devices for flexible and wearable energy management

(A–C) The mechanism of piezoelectric (A), triboelectric (B), and thermoelectric (C) nanogenerators, respectively. Reprinted with permission from Huang et al. (2020). Copyright 2020, Wiley-VCH.

(D) Schematic illustration of a flexible piezoelectric nanogenerator based on organic-inorganic metal halide perovskite (OMHP) materials and their polymer composites. Reprinted with permission from Jella et al. (2019). Copyright 2019, Elsevier.

(E) Schematic illustration of a TENG. Reprinted with permission from Seung et al. (2015). Copyright 2015, American Chemical Society.

(F) Schematic illustration of the assembly process of TEGs composed of organic thermoelectric polymers and CNTs. Reprinted with permission from Kim et al. (2014). Copyright 2014, American Chemical Society.

TENG fabricated by stacking a Ag-coated textile and a nanopatterned PDMS-coated textile, which can power LEDs, a liquid crystal display, and a remote control (Seung et al., 2015). Moreover, hybrid nanogenerators that integrated PENG with TENG together, which can harvest more mechanical energy through energy accumulation, have been reported (Han et al., 2013; Hansen et al., 2010). The key issue in the design of hybrid nanogenerators is the integration methods and how to combine different energy harvesting modes. In a hybrid nanogenerator fabricated on a coaxial carbon fiber, the instantaneous power density generated by PENG and TENG could achieve 10.2 and 42.6 mW m^{-2}, respectively (Li et al., 2014). The presence of PENG is a complement for TENG, which can still harvest energy when the TENG does not work in certain situations.

Except for mechanical motions, human body can continuously provide thermal energy up to 20 mW cm^{-2} (Hyland et al., 2016; Proto et al., 2017). The thermal energy can be converted into electrical energy by thermoelectric nanogenerators (TEGs) (Figure 6C). Thermoelectric materials mainly contain metal sulfide (Wan et al., 2015), BiTe alloy (Harman et al., 2002), and metal silicide (Gayner and Kar, 2016), but their brittleness and rigidity hinder their applications in flexible fiber-based TEGs. Besides, organic TMs, such as polyaniline (Bhadra et al., 2009), PEDOT:PSS (Fan et al., 2018), and poly(2,7-carbazole) (Aïch et al., 2009), have been shown to be suitable for assembling flexible TENG devices, but their low Seebeck coefficient results in poor thermoelectric merit. To improve their thermoelectric properties, the conductivity of these polymers can be enhanced through doping, desorbing or mixing with high conductive carbon/metal materials (Zeier et al., 2016). Organic thermoelectric polymers can be also combined with rGO (Sevinçli and Cuniberti, 2010) or CNTs (Figure 6F) (Kim et al., 2014) to improve the electrical conductivity thus to enhance the thermoelectric performance of the obtained TEGs.

Energy storage devices

However, although the output voltage of fiber/textile-based nanogenerators has been significantly improved, especially the output voltage has been beyond 1,000 V, the most reported output current is

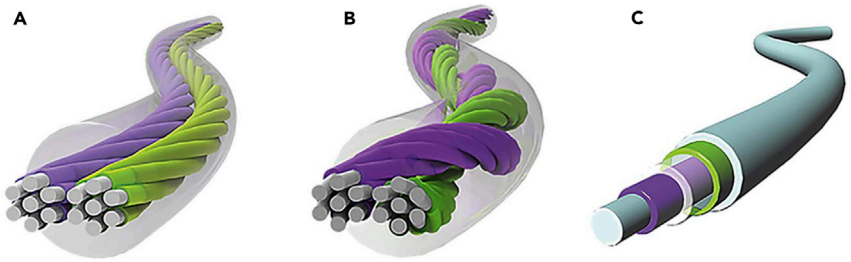

Figure 7. Fiber-shaped devices for flexible and wearable energy storage devices

(A–C) Schematic representation for three configured methods with parallel structure (A), twisted structure (B), and coaxial structure (C) for fiber-shaped batteries. Reprinted with permission from Mo et al. (2020). Copyright 2020, Wiley-VCH.

only several to hundreds of microamperes, which is still the biggest hindrance at present. It is still a great challenge to enhance the output current of nanogenerators. The development of advanced weaving technology, such as the connection or integration of multiple fiber devices in series through 3D weaving, may be an effective way to address the above issues.

With the continuous expansion of wearable electronics market, flexible energy storage devices in various forms have attracted more and more attention. Among them, fiber-shaped energy storage devices, such as SCs and batteries, display excellent flexibility, ductility, portability and deformation adaptability and are very suitable for applying in the field of wearable electronics.

FSCs, being different from the traditional 2D planar SCs, show a unique 1D structure. The FSCs not only exhibit the advantages of high-power density and long cycling stability but also can meet the requirements of miniaturization, integration, and flexibility of wearable devices (Zhai et al., 2020). Owing to the fact that SCs store energy by the formed double electrode layer between the electrodes and the electrolytes, the designing of the structure plays a vital role in the improvement of electrochemical performance. Currently, there are mainly three kinds of structures (parallel, twisted, and coaxial structure) for FSCs. The FSCs with parallel structure can be made by closing positive and negative electrodes in parallel with a separator or polymer gel electrolyte layer, which are similar to conventional planar SCs (Figure 7A) (Mo et al., 2020). However, extra substrates (flat substrates or plastic packaging shells) are required to encapsulate the parallel FSCs. In addition, the capacitance and energy density are largely restricted by the limited interface between the electrolyte and electrodes. Besides, two fibrous electrodes can also be twined or twisted together, followed by separating with a separator or gel electrolyte, forming FSCs with a twisted structure (Figure 7B). Compared with the parallel structure, the twisted structure could increase the interface surface, thus improving the electrochemical performances of FSCs. However, the interface area of the FSCs with twisted structure is still small. Moreover, FSCs with parallel/twisted structure may be physically separated from each other in the process of bending, which may cause high internal resistance, thus reducing the electrochemical performance. To address these problems, FSCs with coaxial structures were designed and prepared to enhance the electrochemical performance. FSCs with coaxial structures were prepared with an outer electrode layer, a core fiber electrode, and a polymer gel electrolyte between them through layer-by-layer (LbL) assembling (Figure 7C). The FSCs with increased interface and coaxial structures exhibit improved electrochemical properties. However, the precisely assembling process on the fiber with large length-diameter ratio is technically difficult.

In addition, fiber-shaped lithium-ion batteries (FLIBs), as a kind of fiber-shaped energy storage devices, were reported almost 10 years ago and soon attracted the interest of researchers (Kwon et al., 2012; Ren et al., 2013). To date, fiber-shaped lithium-sulfur batteries, sodium-ion/sulfur batteries, aqueous Zn-ion batteries, and metal-air batteries with high electrochemical performances have also been designed and developed (Mo et al., 2020). Compared with planar batteries, the designing and fabrication of fiber-shaped batteries (FBs) have some prerequisites. The essential components (electrodes, electrolytes, and separators) and fiber-shaped structures must be compatible. In the processes of work and deformation, the FBs devices should avoid the short circuiting and leakage of the electrolytes. The safety, convenience, and durability of FBs are also the main development directions for their practical applications in the future. Recently, FBs have been combined with sensors, light-emitting devices, and SCs and have been demonstrated in multifunctional integration systems (Sun et al., 2017). An integrated system can have high energy

and power density or self-powered function by converting environmental energy (mechanical energy and thermal energy) and also have the ability to respond to environmental stimuli. However, the process to configure such an integrated system is usually complex and requires an in-depth understanding of the working mechanisms of different functional parts, as well as precise structure design of different components.

ELECTRONIC TEXTILES: FABRICATION AND APPLICATIONS

Electronic textiles, which may possess multiple functions by integrating various functional fibers, are considered as one of the ideal forms of wearable equipment. There are mainly four ways to prepare electronic textiles: 1) direct weaving of electronic fibers into fabrics; 2) integration of fiber-shaped electronic devices into commercial fabrics; 3) coating conductive materials on commercial fabrics; 4) carbonization of commercial fabrics into conductive fabrics.

Direct weaving of electronic fibers into fabrics

Based on excellent flexibility and electrical properties of electronic fibers, it is easy to imagine that electronic fibers can be directly woven into fabrics, to give full play to the advantages of electronic fibers, thus obtaining electronic textiles with various functions (Ding et al., 2020). For instance, a triboelectric-induced electroluminescent textile, composed of ZnS:Cu/PDMS composite fibers (warp yarns) and PTFE fibers (weft yarns), were woven with a simple plain woven structure (Figure 8A). The electronic textiles could realize the integration of luminescent devices with self-powered systems and be further made into intelligent cloths (Park et al., 2019). Besides, all-textile pressure sensors can be knitted using conductive yarns and commercial nylon yarns together in a full cardigan stitch by a machine knitting method, exhibiting high-pressure sensitivity (7.84 mV Pa^{-1}) and fast response (20 ms) (Figure 8E) (Fan et al., 2020). The textile-based sensors can also be independently woven into neck bands, wristbands, socks, and gloves to monitor the arterial pulse of different body sites. In addition, energy storage textiles could be fabricated based on energy storage fibers. A zinc-air battery with textile structure was prepared using zinc wires as the cathodes and Co_3O_4/N-doped rGO-coated CFs as the anodes (Figure 8C). The energy storage textiles can successfully power an LED watch or even charge a mobile phone (Li et al., 2018b). Compared with the above conventional 2D structures, 3D woven structures, which have advantages of structure integrity, dimensional stability, high protection ability, and warmth retention, have also been used for flexible electronics (Dong et al., 2020a; Li et al., 2020b).

Even so, there are still some challenges limiting the development of directly weaving electronic fibers into electronic textiles. The mechanical properties of many electronic fibers are not strong enough to satisfy the requirements of the automatic integration processes. Some electronic fibers are easy to be damaged during the process of weaving. Besides, the fabrication approaches of electronic fibers are still limited and the fabrication efficiency is low, making it difficult to prepare large-area electronic textiles. Thus, there is still a long way to go before the practical application of electronics textiles.

Integration of fiber-shaped electronic devices into commercial fabrics

Weaving fiber-shaped electronics into commercial fabrics is also one of the methods to construct textile-based electronic devices. The method can partly avoid the problem of poor mechanical properties of fiber-shaped electronics and ensure long-term stability of conductive textiles in processes of stretching and other deformation. This method has been applied in the fabrication of textiles with sensing, light emitting, energy harvesting, and storage functions. Besides the direct woven method, machine embroidery, screen-printing, and 3D printing have also been used to fabricate electronic fibers on commercial textiles. The advantage of these methods for constructing electronic textiles is that electronic devices can be patterned through designed procedures. Embroidery is a general approach for fabricating various decorative patterns embroidered by yarns on textiles. For example, conductive silk yarns were integrated in different locations on a cloth by an embroidery machine, obtaining patterned smart textiles (Figure 8D). The obtained smart textiles could be used to monitor human motions, showing the potential of electronic textiles in the fields of healthcare monitoring and human-machine interfaces (Ye et al., 2019). Besides employing the screen-printing method, CNTs/PU inks were printed on nylon textiles to obtain patterned conductive textiles with water resistance for self-powered touch/gesture tribo-sensors (Figure 8E) (Cao et al., 2018). Besides, core-sheath fiber-based conductive patterns were directly printed on textiles by 3D printing

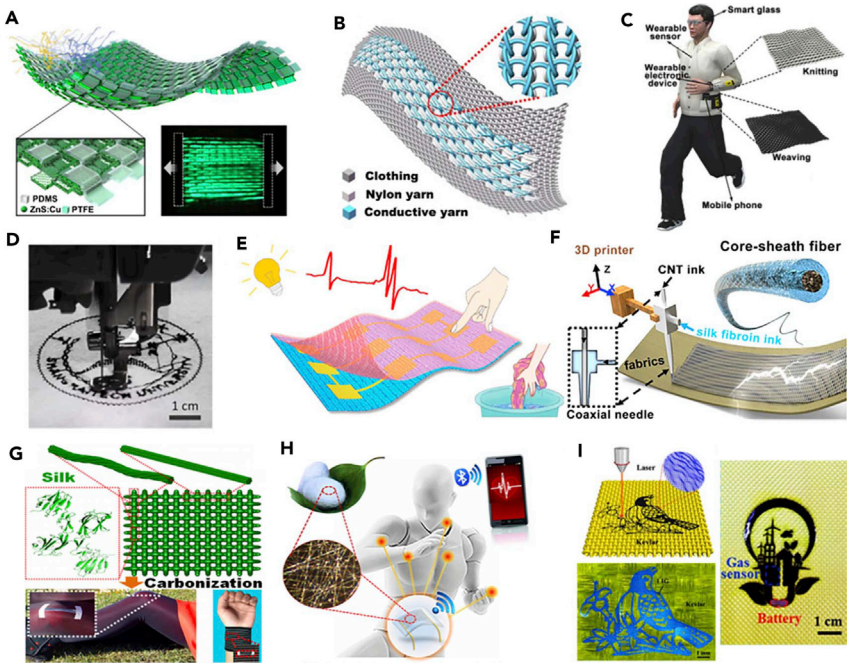

Figure 8. Fabrication and applications of electronic textiles

(A) Motion-driven electroluminescence textile that was woven using the ZnS:Cu-embedded PDMS composite fibers and PTFE fibers. Reprinted with permission from Park et al. (2019). Copyright 2019, American Chemical Society.

(B) Machine-knitted washable sensor array textile for monitoring epidermal physiological signal. Reprinted with permission from Fan et al. (2020). Copyright 2020, AAAS.

(C) Schematic illustration of energy storage textiles for powering wearable sensor and charging the mobile phone. Reprinted with permission from Li et al. (2018b). Copyright 2018, Wiley-VCH.

(D) Photograph of the conductive silk yarn knit into a logo pattern on a cloth by an embroidery machine. Reprinted with permission from Ye et al. (2019). Copyright 2019, Elsevier.

(E) Screen-printed washable electronic textiles as self-powered touch/gesture tribo-sensors for intelligent human-machine interaction. Reprinted with permission from Cao et al. (2018). Copyright 2018, American Chemical Society.

(F) 3D printed smart patterns for multifunctional energy-management electronic textiles. Reprinted with permission from Zhang et al. (2019). Copyright 2019, Elsevier.

(G) Carbonized commercial silk textile for wearable strain sensors. Reprinted with permission from Wang et al. (2016a). Copyright 2016, Wiley-VCH.

(H) Carbonized electrospun silk nanofiber membrane for transparent and sensitive electronic skin. Reprinted with permission from Wang et al. (2017b). Copyright 2017, Wiley-VCH.

(I) Direct laser writing of Janus graphene/Kevlar textile for intelligent protective clothing. Reprinted with permission from Wang et al. (2020a). Copyright 2020, American Chemical Society.

(Figure 8F) (Zhang et al., 2019). The direct printing of various custom designed functional patterns can contribute to the production of personalized electronic textiles.

Coating conductive materials on commercial fabrics

Compared with the above methods, it is a simple and low-cost approach to fabricate electronic textiles by directly coating conductive materials on the surface of commercial fabrics (Du et al., 2016; Liu et al., 2008; Shim et al., 2008). Commercial fabrics can be immersed into the dispersion containing conductive materials for a certain time, and then conductive textiles can be obtained after drying. The electronic textiles obtained by this approach can retain the inherent flexibility of commercial fabrics (Chatterjee et al., 2019; Ehrmann and Blachowicz, 2019). Recently, various conductive nanomaterials, such as Ag (Hwang et al., 2020; Wu et al., 2016), Mxene (An et al., 2020; Li et al., 2019a), CNTs (Shim et al., 2008), graphene (Du et al., 2016), PEDOT:PSS (Choi et al., 2017), and PPy (Villanueva et al., 2019) have been used to prepare electronic textiles. In the process of coating, the properties of the solvents and conductive materials will influence the conductivity of the electronic textiles (Yang et al., 2018). While choosing the solvents, the wettability of fabrics in the dispersion should be considered to ensure the continuous coating of

conductive materials on the surface of fabrics. In addition, the viscosity and boiling point of the solvent should be low to facilitate the uniform coating and the rapid drying of the fabrics (Noel et al., 2017). In brief, the coating strategy has advantages of low cost and potential of mass production, while the dispersion and the process should be carefully designed in order to ensure the uniform coating of conductive materials on the fabrics.

Carbonization of commercial fabrics into conductive fabrics

Except for commercial CF cloths and metal meshes, conductive textiles can be prepared through carbonization of a variety of commercial fabrics (cotton [Zhang et al., 2017], silk [Lu et al., 2020; Wang et al., 2017b], and Kevlar [Wang et al., 2020a]) using high-temperature treatment or directly laser writing. The prepared conductive textiles have advantages of large scale, low cost, and environmental benignity and can be widely used for fabrication of flexible and wearable devices. During the carbonization process, the macromolecules in the fibers are decomposed and some part of the carbon atoms are reorganized and recrystallized, forming partly graphitized carbon structures with certain conductivity, while the original macro-structure of the textiles is maintained. The original woven structures play an important role in achieving high-performance electronic functions. For example, carbonized silk cloths with plain woven structures encapsulated in elastic polydimethylsiloxane (PDMS) films can work as wearable strain sensors, which have integrated advantages of super-stretchability and wide sensing range (Figure 8G) (Wang et al., 2016a). In contrast, sensors made of silk georgette-derived carbon textiles have higher sensitivity and ultra-low detection limit but a relatively smaller sensing range than that made of plain woven silk (Wang et al., 2017a). In addition to conductive textiles derived from commercial fabrics, flexible carbon nanofiber membranes obtained through carbonizing electrospun nanofiber membranes have also been used in wearable sensors (Figure 8H) (Wang et al., 2017b). Recently, a laser writing approach has been used to realize *in situ* fabrication of conductive patterns on commercial fabrics, which facilitates the design of electronic textiles with personalized patterns (Figure 8I) (Wang et al., 2020a).

However, the carbonization approaches also have some limitations in fabricating conductive textiles. The obtained materials usually have low graphitization degree and high defects, which result in low electrical conductivity. Moreover, the excellent mechanical performance of the original textiles is mostly lost after the carbonization process and the obtained textiles are usually fragile and easy to break.

INTEGRATION TOWARD MULTIFUNCTIONAL ELECTRONIC TEXTILES

Integration is essential in order to prepare electronic devices with multiple desired functions that can fulfill requirements of practical applications (Shi et al., 2020). Electronic devices with the same function or different functions can be achieved integrated to achieve a functional system. The integration of multifunctional electronic devices not only reduces the complexity of external circuits but also makes devices more portable and efficient to manage. For instance, FSCs with high output voltage have been prepared and fabricated by mimicking the ordered structure of discharge cells in electric eel (Figure 9A). A stretchable polymer fiber was used as the substrate for FSCs, and the series connection of adjacent single FSCs was realized through the design of shared electrodes (Shi et al., 2020). Besides, coaxial FSCs could be integrated with a photodetector to form a smart ring that display a stable optical response to white light (Figure 9B) (Li et al., 2018a).

Although the integration of FSCs with other electronics has been proved to be feasible in a 1D wearable integrated system, an external power source is still needed to charge to the FSCs. Recently, in order to substitute the external power source, multifunctional and coaxial energy fibers integrated functions of energy harvesting and energy storage have been developed. The energy fibers could power devices in a sustainable and continuous way without external power sources (Figure 9C) (Han et al., 2021). Similarly, electronic textiles with integrated functions can be constructed. TENG textiles were prepared using non-conductive polyamide (PA) yarns as warps, and conductive PA/Ag yarns and PA yarns as wefts alternately (Figure 9D). The direct current generated by the triboelectric effect could charge the FSC yarns, realizing the integration of energy collection and energy storage functions (Chen et al., 2020a). Besides, the resist-dyeing-analogous method is one of the common dyeing techniques in traditional textile industry. TENG and SCs were integrated on commercial knitted fabrics through the resist-dyeing-analogous method (Figure 9E). The obtained electronic textiles could power small electronic devices intermittently without additional energy supply from outside (Cong et al., 2020). However, the resist-dyeing-analogous method for the patterned conductive textiles is only suitable for hydrophobic textiles but not for hydrophilic textile substrates.

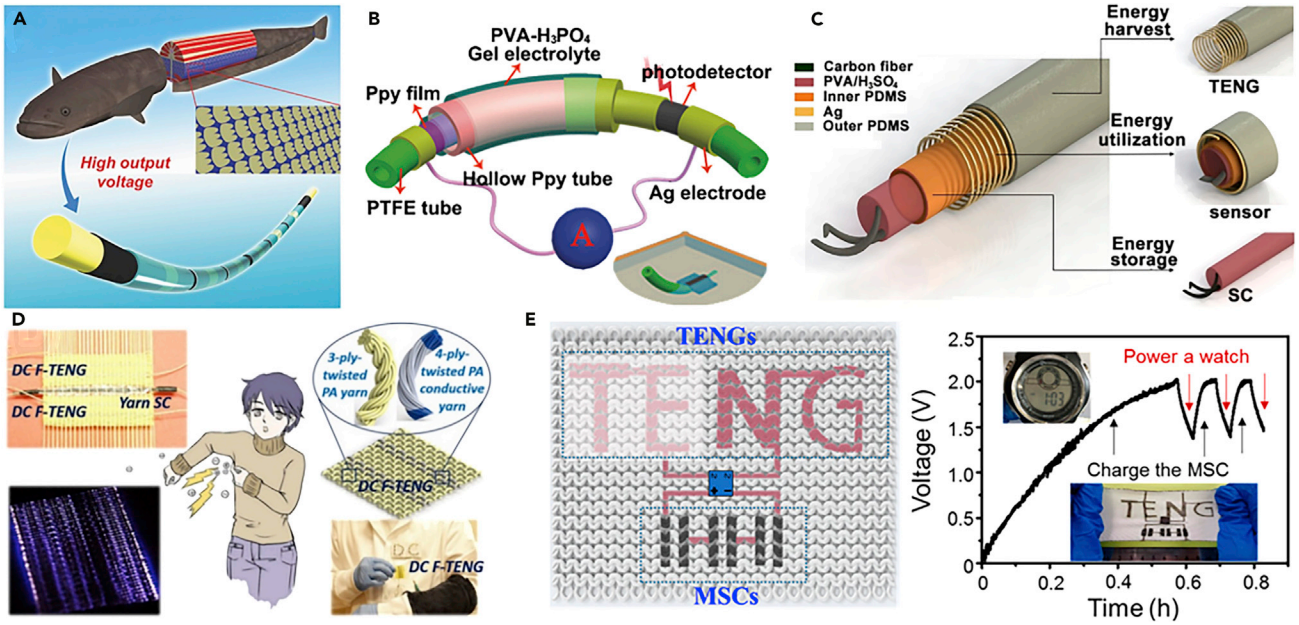

Figure 9. Integration of multifunctional electronic textiles and their applications

(A) In-series fiber-shaped electrochemical capacitors with high output voltages mimicking electric eels. Reprinted with permission from Sun et al. (2016). Copyright 2016, Wiley-VCH.

(B) Coaxial wire FSCs integrated with $CuInS_2$ photodetector for a wearable integrated system. Reprinted with permission from Li et al. (2018a). Copyright 2018, Wiley-VCH.

(C) Structures of fibers with functions of energy harvesting, storage, and utilization. Reprinted with permission from Han et al. (2021). Copyright 2021, American Chemical Society.

(D) Integration of direct current fabric TENG and solid-state FSCs for bio-motion energy harvest and storage. Reprinted with permission from Chen et al. (2020a). Copyright 2020, American Chemical Society.

(E) Self-charging power textile integrated with TENGs and FSCs. Reprinted with permission from Cong et al. (2020). Copyright 2020, American Chemical Society.

FUTURE AND PROSPECTS

As reviewed above, electronic fibers/textiles exhibit great potentials and have become one of the most promising branches of flexible electronics. In this review, we systematically reviewed the recent advances in electronic fibers/textiles in terms of the involved conductive materials, fabrication strategies, applications, and multifunctional integration. Although tremendous accomplishments in functional diversity of electronic fibers/textiles have been demonstrated, challenges that hinder the practical applications of electronic fibers/textiles still remain.

First, compared with traditional bulk or thin-film devices, electronic fibers/textiles exhibit relatively poor performances. The diameters of electronic fibers are usually so small that the electrical conductivities of electronic fibers are usually relatively lower than those of bulk or thin-film electrodes. Although various strategies, such as introducing more conductive materials or designing device structures, have been reported to enhance the performances of electronic fibers/textiles, a balance between their electrical and mechanical properties has not been really achieved. In addition, cycling stability and washability of electronic fibers/textiles also need to be improved. For example, conductive materials on the surface of electronic fibers/textiles especially that prepared by dipping or coating, are easy to peel off during the processes of repeated deformation and washing. Therefore, further efforts are necessary to make electronic fibers/textiles to be washable and stable while showing the desired electrical performance.

Second, in order to fully realize commercial application potentials of electronic fibers/textiles, it is essential to develop efficient technologies to produce flexible, breathable, and large-scale electronic fibers while ensuring that the performances of the electronics meet the requirements of practical applications. At present, electronic fibers are mainly woven into electronic textiles by hand at the laboratory scale. To promote the large-scale fabrication, it is necessary to develop new and efficient machine weaving technologies to

fabricate electronic textiles. Besides, the integration of multi-functions in electronic fibers/textiles is one of the big challenges due to the interference between different functions. Moreover, in addition to the functions discussed above, including sensing, energy harvesting, and energy storage, the integration of fiber/textile-based circuits, information acquisition parts, personal data security function, and computing parts almost has not been explored.

Third, it is difficult to compare the performances of electronic fibers/textiles owing to the lack of uniform technical and testing standards at present. The calculating methods of parameters for electronic fibers/textiles are not consistent in different reports, so it is difficult to compare between different functions or even the same function. Furthermore, the ability to sustain bending, stretching, and twisting of electronic fibers/textiles is an important property for evaluating the flexibility of devices, but there is no uniform evaluation standards so far. Finally, the study of electronic fibers/textiles belongs to interdisciplinary research, requiring the joint efforts of scientists in various fields. Such interdisciplinary cooperation will increase the possibility of commercialization of electronic fibers/textiles, which will speed up the application of flexible and wearable electronics in human health, digitalization, and intelligence.

In summary, electronic fibers/textiles, as a new form of flexible electronics, have great potential in smart wearable fields. In future, electronic fibers/textiles with integrated characteristics of unique structures and various functions are expected to blend into our life, similar to traditional fibers/textiles. They will not only meet the needs of wears daily but also serve the emerging fields of personalized health/medical treatment and human-machine interface, which will innovate the way of our lives. Although some exciting progress has been achieved in various aspects, lots of challenges remain. We believe that, with the continuous efforts of researchers from different fields, the design, functions, and performances of electronic fibers/textiles will be further improved, thus promoting the further development of electronic fibers/textiles toward a bright future.

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AUTHOR CONTRIBUTIONS

Yong Zhang drafted the manuscript under the supervision of Yingying Zhang. H.W., H.L., and S.L. participated in the writing of some parts. All the authors commented on and revised the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

Aïch, R.B., Blouin, N., Bouchard, A., and Leclerc, M. (2009). Electrical and thermoelectric properties of poly(2,7-carbazole) derivatives. Chem. Mater. *21*, 751–757.

Ambade, R.B., Ambade, S.B., Salunkhe, R.R., Malgras, V., Jin, S.-H., Yamauchi, Y., and Lee, S.-H. (2016). Flexible-wire shaped all-solid-state supercapacitors based on facile electropolymerization of polythiophene with ultra-high energy density. J. Mater. Chem. A *4*, 7406–7415.

An, J., Ma, Y., He, M., Yan, J., Zhang, C., Li, X., Shen, P., Luo, S., and Gao, Y. (2020). A wearable and highly sensitive textile-based pressure sensor with Ti3C2Tx nanosheets. Sens. Actuators A *311*, 112081.

Bhadra, S., Khastgir, D., Singha, N.K., and Lee, J.H. (2009). Progress in preparation, processing and applications of polyaniline. Prog. Polym. Sci. *34*, 783–810.

Cao, R., Pu, X., Du, X., Yang, W., Wang, J., Guo, H., Zhao, S., Yuan, Z., Zhang, C., Li, C., et al. (2018). Screen-printed washable electronic textiles as self-powered touch/gesture tribosensors for intelligent human-machine interaction. ACS Nano *12*, 5190–5196.

Chatterjee, K., Tabor, J., and Ghosh, T.K. (2019). Electrically conductive coatings for fiber-based E-textiles. Fibers *7*, 51.

Chen, C., Guo, H., Chen, L., Wang, Y.-C., Pu, X., Yu, W., Wang, F., Du, Z., and Wang, Z.L. (2020a). Direct current fabric triboelectric nanogenerator for biomotion energy harvesting. ACS Nano *14*, 4585–4594.

Chen, S., Qiu, L., and Cheng, H.-M. (2020b). Carbon-based fibers for advanced electrochemical energy storage devices. Chem. Rev. *120*, 2811–2878.

Chen, X., Lin, H., Deng, J., Zhang, Y., Sun, X., Chen, P., Fang, X., Zhang, Z., Guan, G., and Peng, H. (2014). Electrochromic fiber-shaped supercapacitors. Adv. Mater. *26*, 8126–8132.

Cheng, H.M., Li, F., Su, G., Pan, H.Y., He, L.L., Sun, X., and Dresselhaus, M.S. (1998). Large-scale and low-cost synthesis of single-walled carbon nanotubes by the catalytic pyrolysis of hydrocarbons. Appl. Phys. Lett. *72*, 3282–3284.

Cheng, Y., Wang, R., Sun, J., and Gao, L. (2015). A stretchable and highly sensitive graphene-based fiber for sensing tensile strain, bending, and torsion. Adv. Mater. *27*, 7365–7371.

Cheng, Y., Wang, R., Zhai, H., and Sun, J. (2017). Stretchable electronic skin based on silver nanowire composite fiber electrodes for sensing pressure, proximity, and multidirectional strain. Nanoscale *9*, 3834–3842.

Cheng, Y., Zhang, H., Wang, R., Wang, X., Zhai, H., Wang, T., Jin, Q., and Sun, J. (2016). Highly stretchable and conductive copper nanowire based fibers with hierarchical structure for wearable heaters. ACS Appl. Mater. Inter. *8*, 32925–32933.

Cho, S.-Y., Yu, H., Choi, J., Kang, H., Park, S., Jang, J.-S., Hong, H.-J., Kim, I.-D., Lee, S.-K., Jeong, H.S., et al. (2019). Continuous meter-scale synthesis of weavable tunicate cellulose/carbon nanotube fibers for high-performance wearable sensors. ACS Nano *13*, 9332–9341.

Choi, C.M., Kwon, S.N., and Na, S.-I. (2017). Conductive PEDOT:PSS-coated poly-paraphenylene terephthalamide thread for highly durable electronic textiles. J. Ind. Eng. Chem. *50*, 155–161.

Cong, Z., Guo, W., Guo, Z., Chen, Y., Liu, M., Hou, T., Pu, X., Hu, W., and Wang, Z.L. (2020). Stretchable coplanar self-charging power textile with resist-dyeing triboelectric nanogenerators and microsupercapacitors. ACS Nano *14*, 5590–5599.

Deng, J., Qiu, L., Lu, X., Yang, Z., Guan, G., Zhang, Z., and Peng, H. (2015). Elastic perovskite solar cells. J. Mater. Chem. A *3*, 21070–21076.

Ding, T., Chan, K.H., Zhou, Y., Wang, X.-Q., Cheng, Y., Li, T., and Ho, G.W. (2020). Scalable thermoelectric fibers for multifunctional textile-electronics. Nat. Commun. *11*, 6006.

Dong, K., Peng, X., An, J., Wang, A.C., Luo, J., Sun, B., Wang, J., and Wang, Z.L. (2020a). Shape adaptable and highly resilient 3D braided triboelectric nanogenerators as E-textiles for power and sensing. Nat. Commun. *11*, 2868.

Dong, K., Peng, X., and Wang, Z.L. (2020b). Fiber/fabric-based piezoelectric and triboelectric nanogenerators for flexible/stretchable and wearable electronics and artificial intelligence. Adv. Mater. *32*, 1902549.

Du, D., Li, P., and Ouyang, J. (2016). Graphene coated nonwoven fabrics as wearable sensors. J. Mater. Chem. C *4*, 3224–3230.

Du, M., Huang, L., Zheng, J., Xi, Y., Dai, Y., Zhang, W., Yan, W., Tao, G., Qiu, J., So, K.-F., et al. (2020). Flexible fiber probe for efficient neural stimulation and detection. Adv. Sci. *7*, 2001410.

Dudem, B., Dharmasena, R.D.I.G., Graham, S.A., Leem, J.W., Patnam, H., Mule, A.R., Silva, S.R.P., and Yu, J.S. (2020). Exploring the theoretical and experimental optimization of high-performance triboelectric nanogenerators using microarchitectured silk cocoon films. Nano Energy *74*, 104882.

Ehrmann, A., and Blachowicz, T. (2019). Recent coating materials for textile-based solar cells. Aims Mater. Sci. *6*, 234–251.

Fan, F.R., Tang, W., and Wang, Z.L. (2016). Flexible nanogenerators for energy harvesting and self-powered electronics. Adv. Mater. *28*, 4283–4305.

Fan, W., He, Q., Meng, K., Tan, X., Zhou, Z., Zhang, G., Yang, J., and Wang, Z.L. (2020). Machine-knitted washable sensor array textile for precise epidermal physiological signal monitoring. Sci. Adv. *6*, eaay2840.

Eom, J., Jaisutti, R., Lee, H., Lee, W., Heo, J.-S., Lee, J.-Y., Park, S.K., and Kim, Y.-H. (2017). Highly sensitive textile strain sensors and wireless user-interface devices using all-polymeric conducting fibers. ACS Appl. Mater. Inter. *9*, 10190–10197.

Fan, Z., Du, D., Guan, X., and Ouyang, J. (2018). Polymer films with ultrahigh thermoelectric properties arising from significant seebeck coefficient enhancement by ion accumulation on surface. Nano Energy *51*, 481–488.

Fan, Z., Ho, J.C., Jacobson, Z.A., Yerushalmi, R., Alley, R.L., Razavi, H., and Javey, A. (2008). Wafer-scale assembly of highly ordered semiconductor nanowire arrays by contact printing. Nano Lett. *8*, 20–25.

Fang, J., Wang, X.G., and Lin, T. (2011). Electrical power generator from randomly oriented electrospun poly(vinylidene fluoride) nanofibre membranes. J. Mater. Chem. *21*, 11088–11091.

Frutiger, A., Muth, J.T., Vogt, D.M., Mengüç, Y., Campo, A., Valentine, A.D., Walsh, C.J., and Lewis, J.A. (2015). Capacitive soft strain sensors via multicore–shell fiber printing. Adv. Mater. *27*, 2440–2446.

Gao, Z., Zhou, J., Gu, Y., Fei, P., Hao, Y., Bao, G., and Wang, Z.L. (2009). Effects of piezoelectric potential on the transport characteristics of metal-ZnO nanowire-metal field effect transistor. J. Appl. Phys. *105*, 113707.

Gayner, C., and Kar, K.K. (2016). Recent advances in thermoelectric materials. Prog. Mater. Sci. *83*, 330–382.

Gu, X.Y., Chen, E.Z., Ma, M.Y., Yang, Z.Y., Bai, J.L., Chen, L.L., Sun, G.Z., Zhang, Z.X., Pan, X.J., Zhou, J.Y., et al. (2019). Effect of TiO_2-rGO heterojunction on electron collection efficiency and mechanical properties of fiber-shaped dye-sensitized solar cells. J. Phys. D Appl. Phys. *52*, 095502.

Guo, Y., Otley, M.T., Li, M.F., Zhang, X.Z., Sinha, S.K., Treich, G.M., and Sotzing, G.A. (2016). PEDOT:PSS "wires" printed on textile for wearable electronics. ACS Appl. Mater. Interfaces *8*, 26998–27005.

Han, J., Xu, C., Zhang, J., Xu, N., Xiong, Y., Cao, X., Liang, Y., Zheng, L., Sun, J., Zhai, J., et al. (2021). Multifunctional coaxial energy fiber toward energy harvesting, storage, and utilization. ACS Nano *15*, 1597–1607.

Han, M., Zhang, X.-S., Meng, B., Liu, W., Tang, W., Sun, X., Wang, W., and Zhang, H. (2013). R-shaped hybrid nanogenerator with enhanced piezoelectricity. ACS Nano *7*, 8554–8560.

Hansen, B.J., Liu, Y., Yang, R., and Wang, Z.L. (2010). Hybrid nanogenerator for concurrently harvesting biomechanical and biochemical energy. ACS Nano *4*, 3647–3652.

Harman, T.C., Taylor, P.J., Walsh, M.P., and LaForge, B.E. (2002). Quantum dot superlattice thermoelectric materials and devices. Science *297*, 2229–2232.

He, Y., Gui, Q., Liao, S., Jia, H., and Wang, Y. (2016). Coiled fiber-shaped stretchable thermal sensors for wearable electronics. Adv. Mater. Technol. *1*, 1600170.

He, W., Wang, C., Wang, H., Jian, M., Lu, W., Liang, X., Zhang, X., Yang, F., and Zhang, Y. (2019). Integrated textile sensor patch for real-time and multiplex sweat analysis. Sci. Adv. *5*, eaax0649.

He, X., Zi, Y., Guo, H., Zheng, H., Xi, Y., Wu, C., Wang, J., Zhang, W., Lu, C., and Wang, Z. (2017). A highly stretchable fiber-based triboelectric nanogenerator for self-powered wearable electronics. Adv. Funct. Mater. *27*, 1604378.

Hinchet, R., Yoon, H.-J., Ryu, H., Kim, M.-K., Choi, E.-K., Kim, D.-S., and Kim, S.-W. (2019). Transcutaneous ultrasound energy harvesting using capacitive triboelectric technology. Science *365*, 491.

Hirsch, A. (2010). The era of carbon allotropes. Nat. Mater. *9*, 868–871.

Huang, L., Lin, S., Xu, Z., Zhou, H., Duan, J., Hu, B., and Zhou, J. (2020). Fiber-based energy conversion devices for human-body energy harvesting. Adv. Mater. *32*, 1902034.

Huang, Y., Hu, H., Huang, Y., Zhu, M., Meng, W., Liu, C., Pei, Z., Hao, C., Wang, Z., and Zhi, C. (2015). From industrially weavable and knittable highly conductive yarns to large wearable energy storage textiles. ACS Nano *9*, 4766–4775.

Hwang, B., Lund, A., Tian, Y., Darabi, S., and Muller, C. (2020). Machine-washable conductive silk yarns with a composite coating of Ag nanowires and PEDOT:PSS. ACS Appl. Mater. Interfaces *12*, 27537–27544.

Hyland, M., Hunter, H., Liu, J., Veety, E., and Vashaee, D. (2016). Wearable thermoelectric generators for human body heat harvesting. Appl. Energy *182*, 518–524.

Jamali, V., Niroui, F., Taylor, L.W., Dewey, O.S., Koscher, B.A., Pasquali, M., and Alivisatos, A.P. (2020). Perovskite-carbon nanotube light-emitting fibers. Nano Lett. *20*, 3178–3184.

Jang, Y., Kim, S.M., Spinks, G.M., and Kim, S.J. (2020). Carbon nanotube yarn for fiber-shaped electrical sensors, actuators, and energy storage for smart systems. Adv. Mater. *32*, 1902670.

Jella, V., Ippili, S., Eom, J.-H., Pammi, S.V.N., Jung, J.-S., Tran, V.-D., Nguyen, V.H., Kirakosyan, A., Yun, S., Kim, D., et al. (2019). A comprehensive review of flexible piezoelectric generators based on organic-inorganic metal halide perovskites. Nano Energy *57*, 74–93.

Jeong, J., Kwon, J.H., Lim, K., Biswas, S., Tibaldi, A., Lee, S., Oh, H.J., Kim, J.H., Ko, J., Lee, D.W., et al. (2019). Comparative study of triboelectric nanogenerators with differently woven cotton textiles for wearable electronics. Polymers *11*, 7.

Jur, J.S., Sweet, W.J., III, Oldham, C.J., and Parsons, G.N. (2011). Atomic layer deposition of conductive coatings on cotton, paper, and synthetic fibers: conductivity analysis and functional chemical sensing using "all-fiber" capacitors. Adv. Funct. Mater. *21*, 1993–2002.

Kao, K.C., and Hockham, G.A. (1966). Dielectric-fibre surface waveguides for optical frequencies. Proc. Inst. Electr. Engineers *113*, 1151.

Kim, D.-H., Kim, Y.-S., Amsden, J., Panilaitis, B., Kaplan, D.L., Omenetto, F.G., Zakin, M.R., and

Rogers, J.A. (2009). Silicon electronics on silk as a path to bioresorbable, implantable devices. Appl. Phys. Lett. *95*, 133701.

Kim, S.L., Choi, K., Tazebay, A., and Yu, C. (2014). Flexible power fabrics made of carbon nanotubes for harvesting thermoelectricity. ACS Nano *8*, 2377–2386.

Kwon, S., Hwang, Y.H., Nam, M., Chae, H., Lee, H.S., Jeon, Y., Lee, S., Kim, C.Y., Choi, S., Jeong, E.G., et al. (2020). Recent progress of fiber shaped lighting devices for smart display applications-a fibertronic perspective. Adv. Mater. *32*, e1903488.

Kwon, S., Kim, H., Choi, S., Jeong, E.G., Kim, D., Lee, S., Lee, H.S., Seo, Y.C., and Choi, K.C. (2018). Weavable and highly efficient organic light-emitting fibers for wearable electronics: a scalable, low-temperature process. Nano Lett. *18*, 347–356.

Kwon, Y.H., Woo, S.-W., Jung, H.-R., Yu, H.K., Kim, K., Oh, B.H., Ahn, S., Lee, S.-Y., Song, S.-W., Cho, J., et al. (2012). Cable-type flexible lithium ion battery based on hollow multi-helix electrodes. Adv. Mater. *24*, 5192–5197.

Leber, A., Dong, C., Chandran, R., Das Gupta, T., Bartolomei, N., and Sorin, F. (2020). Soft and stretchable liquid metal transmission lines as distributed probes of multimodal deformations. Nat. Electron. *3*, 316–326.

Lee, H.M., Choi, S.-Y., Jung, A., and Ko, S.H. (2013). Highly conductive aluminum textile and paper for flexible and wearable electronics. Angew. Chem. Int. Ed. *52*, 7718–7723.

Lee, J., Llerena Zambrano, B., Woo, J., Yoon, K., and Lee, T. (2020a). Recent advances in 1D stretchable electrodes and devices for textile and wearable electronics: materials, fabrications, and applications. Adv. Mater. *32*, 1902532.

Lee, J.K., An, K.W., Ju, J.B., Cho, B.W., Cho, W.I., Park, D., and Yun, K.S. (2001). Electrochemical properties of PAN-based carbon fibers as anodes for rechargeable lithium ion batteries. Carbon *39*, 1299–1305.

Lee, S., Franklin, S., Hassani, F.A., Yokota, T., Nayeem, M.O.G., Wang, Y., Leib, R., Cheng, G., Franklin, D.W., and Someya, T. (2020b). Nanomesh pressure sensor for monitoring finger manipulation without sensory interference. Science *370*, 966–970.

Lee, S., Shin, S., Lee, S., Seo, J., Lee, J., Son, S., Cho, H.J., Algadi, H., Al-Sayari, S., Kim, D.E., et al. (2015). Ag nanowire reinforced highly stretchable conductive fibers for wearable electronics. Adv. Funct. Mater. *25*, 3114–3121.

Li, L., Lou, Z., Chen, D., Han, W., and Shen, G. (2018a). Hollow polypyrrole sleeve based coaxial fiber supercapacitors for wearable integrated photosensing system. Adv. Mater. Technol. *3*, 1800115.

Li, S., Zhang, Y., Wang, Y., Xia, K., Yin, Z., Wang, H., Zhang, M., Liang, X., Lu, H., Zhu, M., et al. (2020a). Physical sensors for skin-inspired electronics. InfoMat *2*, 184–211.

Li, T., Chen, L., Yang, X., Chen, X., Zhang, Z., Zhao, T., Li, X., and Zhang, J. (2019a). A flexible pressure sensor based on an MXene-textile network structure. J. Mater. Chem. C *7*, 1022–1027.

Li, X., Lin, Z.-H., Cheng, G., Wen, X., Liu, Y., Niu, S., and Wang, Z.L. (2014). 3D fiber-based hybrid nanogenerator for energy harvesting and as a self-powered pressure sensor. ACS Nano *8*, 10674–10681.

Li, X., Sun, C., Cai, Z., and Ge, F. (2019b). High-performance all-solid-state supercapacitor derived from PPy coated carbonized silk fabric. Appl. Surf. Sci. *473*, 967–975.

Li, X.T., Hua, T., and Xu, B.G. (2017). Electromechanical properties of a yarn strain sensor with graphene-sheath/polyurethane-core. Carbon *118*, 686–698.

Li, Y., Xiong, J.Q., Lv, J., Chen, J., Gao, D.C., Zhang, X.X., and Lee, P.S. (2020b). Mechanically interlocked stretchable nanofibers for multifunctional wearable triboelectric nanogenerator. Nano Energy *78*, 10.

Li, Y., Zhong, C., Liu, J., Zeng, X., Qu, S., Han, X., Deng, Y., Hu, W., and Lu, J. (2018b). Atomically thin mesoporous Co_3O_4 layers strongly coupled with N-rGO nanosheets as high-performance bifunctional catalysts for 1D knittable zinc–air batteries. Adv. Mater. *30*, 1703657.

Liang, J., Zhu, G., Wang, C., Wang, Y., Zhu, H., Hu, Y., Lv, H., Chen, R., Ma, L., Chen, T., et al. (2017). MoS2-Based all-purpose fibrous electrode and self-powering energy fiber for efficient energy harvesting and storage. Adv. Energy Mater. *7*, 1601208.

Liao, W.-Q., Tang, Y.-Y., Li, P.-F., You, Y.-M., and Xiong, R.-G. (2017). Large piezoelectric effect in a lead-free molecular ferroelectric thin film. J. Am. Chem. Soc. *139*, 18071–18077.

Lin, Z.H., Xie, Y.N., Yang, Y., Wang, S.H., Zhu, G., and Wang, Z.L. (2013). Enhanced triboelectric nanogenerators and triboelectric nanosensor using chemically modified TiO_2 nanomaterials. ACS Nano *7*, 4554–4560.

Liu, D., Ren, J., Wang, J., Xing, W., Qian, Q., Chen, H., and Zhou, N. (2020). Customizable and stretchable fibre-shaped electroluminescent devices via mulitcore-shell direct ink writing. J. Mater. Chem. C *8*, 15092–15098.

Liu, L., Yu, Y., Yan, C., Li, K., and Zheng, Z. (2015a). Wearable energy-dense and power-dense supercapacitor yarns enabled by scalable graphene–metallic textile composite electrodes. Nat. Commun. *6*, 7260.

Liu, R., Liu, Y., Chen, J., Kang, Q., Wang, L., Zhou, W., Huang, Z., Lin, X., Li, Y., Li, P., et al. (2017). Flexible wire-shaped lithium-sulfur batteries with fibrous cathodes assembled via capillary action. Nano Energy *33*, 325–333.

Liu, Y., Wang, X., Qi, K., and Xin, J.H. (2008). Functionalization of cotton with carbon nanotubes. J. Mater. Chem. *18*, 3454–3460.

Liu, Z.F., Fang, S., Moura, F.A., Ding, J.N., Jiang, N., Di, J., Zhang, M., Lepró, X., Galvão, D.S., Haines, C.S., et al. (2015b). Hierarchically buckled sheath-core fibers for superelastic electronics, sensors, and muscles. Science *349*, 400–404.

Lu, Y., Jiang, J., Yoon, S., Kim, K.-S., Kim, J.-H., Park, S., Kim, S.-H., and Piao, L. (2018). High-performance stretchable conductive composite fibers from surface-modified silver nanowires and thermoplastic polyurethane by wet spinning. ACS Appl. Mater. Inter. *10*, 2093–2104.

Lu, W., Yu, P., Jian, M., Wang, H., Wang, H., Liang, X., and Zhang, Y. (2020). Molybdenum disulfide nanosheets aligned vertically on carbonized silk fabric as smart textile for wearable pressure-sensing and energy devices. ACS Appl. Mater. Interfaces *12*, 11825–11832.

Mattmann, C., Clemens, F., and Tröster, G. (2008). Sensor for measuring strain in textile. Sensors *8*, 3719–3732.

Meng, F., Lu, W., Li, Q., Byun, J.-H., Oh, Y., and Chou, T.-W. (2015). Graphene-based fibers: a review. Adv. Mater. *27*, 5113–5131.

Mo, F., Liang, G., Huang, Z., Li, H., Wang, D., and Zhi, C. (2020). An overview of fiber-shaped batteries with a focus on multifunctionality, scalability, and technical difficulties. Adv. Mater. *32*, 1902151.

Mohanta, M.K., and Sarkar, A.D. (2020). Tweaking the physics of interfaces between monolayers of buckled cadmium sulfide for a superhigh piezoelectricity, excitonic solar cell efficiency, and thermoelectricity. ACS Appl. Mater. Interfaces *12*, 18123–18137.

Noel, N.K., Habisreutinger, S.N., Wenger, B., Klug, M.T., Hörantner, M.T., Johnston, M.B., Nicholas, R.J., Moore, D.T., and Snaith, H.J. (2017). A low viscosity, low boiling point, clean solvent system for the rapid crystallisation of highly specular perovskite films. Energy Environ. Sci. *10*, 145–152.

O'Connor, B., An, K.H., Zhao, Y., Pipe, K.P., and Shtein, M. (2007). Fiber shaped light emitting device. Adv. Mater. *19*, 3897–3900.

Pan, J., Li, H., Sun, H., Zhang, Y., Wang, L., Liao, M., Sun, X., and Peng, H. (2018). A lithium-air battery stably working at high temperature with high rate performance. Small *14*, 1703454.

Park, H.-J., Kim, S., Lee, J.H., Kim, H.T., Seung, W., Son, Y., Kim, T.Y., Khan, U., Park, N.-M., and Kim, S.-W. (2019). Self-powered motion-driven triboelectric electroluminescence textile system. ACS Appl. Mater. Interfaces *11*, 5200–5207.

Park, S., Heo, S.W., Lee, W., Inoue, D., Jiang, Z., Yu, K., Jinno, H., Hashizume, D., Sekino, M., Yokota, T., et al. (2018). Self-powered ultra-flexible electronics via nano-grating-patterned organic photovoltaics. Nature *561*, 516–521.

Proto, A., Penhaker, M., Conforto, S., and Schmid, M. (2017). Nanogenerators for human body energy harvesting. Trends Biotechnol. *35*, 610–624.

Pu, X., Hu, W., and Wang, Z.L. (2018). Toward wearable self-charging power systems: the integration of energy-harvesting and storage devices. Small *14*, 1702817.

Pu, X., Song, W.X., Liu, M.M., Sun, C.W., Du, C.H., Jiang, C.Y., Huang, X., Zou, D.C., Hu, W.G., and Wang, Z.L. (2016). Wearable power-textiles by integrating fabric triboelectric nanogenerators

and fiber-shaped dye-sensitized solar cells. Adv. Energy Mater. *6*, 9.

Qin, Y., Wang, X., and Wang, Z.L. (2008). Microfibre-nanowire hybrid structure for energy scavenging. Nature *451*, 809–813.

Qu, G., Cheng, J., Li, X., Yuan, D., Chen, P., Chen, X., Wang, B., and Peng, H. (2016). A fiber supercapacitor with high energy density based on hollow graphene/conducting polymer fiber electrode. Adv. Mater. *28*, 3646–3652.

Qu, Y., Nguyen-Dang, T., Page, A.G., Yan, W., Das Gupta, T., Rotaru, G.M., Rossi, R.M., Favrod, V.D., Bartolomei, N., and Sorin, F. (2018). Superelastic multimaterial electronic and photonic fibers and devices via thermal drawing. Adv. Mater. *30*, 1707251.

Rahaman, M.S.A., Ismail, A.F., and Mustafa, A. (2007). A review of heat treatment on polyacrylonitrile fiber. Polym. Degrad. Stabil. *92*, 1421–1432.

Ren, J., Li, L., Chen, C., Chen, X., Cai, Z., Qiu, L., Wang, Y., Zhu, X., and Peng, H. (2013). Twisting carbon nanotube fibers for both wire-shaped micro-supercapacitor and micro-battery. Adv. Mater. *25*, 1155–1159.

Seung, W., Gupta, M.K., Lee, K.Y., Shin, K.-S., Lee, J.-H., Kim, T.Y., Kim, S., Lin, J., Kim, J.H., and Kim, S.-W. (2015). Nanopatterned textile-based wearable triboelectric nanogenerator. ACS Nano *9*, 3501–3509.

Sevinçli, H., and Cuniberti, G. (2010). Enhanced thermoelectric figure of merit in edge-disordered zigzag graphene nanoribbons. Phys. Rev. B *81*, 113401.

Shang, Y., He, X., Li, Y., Zhang, L., Li, Z., Ji, C., Shi, E., Li, P., Zhu, K., Peng, Q., Wang, C., Zhang, X., Wang, R., Wei, J., Wang, K., Zhu, H., Wu, D., and Cao, A. (2012). Super-stretchable spring-like carbon nanotube ropes. Adv. Mater. *24*, 2896–2900.

Shi, J., Liu, S., Zhang, L., Yang, B., Shu, L., Yang, Y., Ren, M., Wang, Y., Chen, J., Chen, W., et al. (2020). Smart textile-integrated microelectronic systems for wearable applications. Adv. Mater. *32*, 1901958.

Shim, B.S., Chen, W., Doty, C., Xu, C., and Kotov, N.A. (2008). Smart electronic yarns and wearable fabrics for human biomonitoring made by carbon nanotube coating with polyelectrolytes. Nano Lett. *8*, 4151–4157.

Shuai, L., Guo, Z.H., Zhang, P., Wan, J., Pu, X., and Wang, Z.L. (2020). Stretchable, self-healing, conductive hydrogel fibers for strain sensing and triboelectric energy-harvesting smart textiles. Nano Energy *78*, 105389.

Song, J., Chen, S., Sun, L., Guo, Y., Zhang, L., Wang, S., Xuan, H., Guan, Q., and You, Z. (2020). Mechanically and electronically robust transparent organohydrogel fibers. Adv. Mater. *32*, 1906994.

Sun, F., Tian, M., Sun, X., Xu, T., Liu, X., Zhu, S., Zhang, X., and Qu, L. (2019). Stretchable conductive fibers of ultrahigh tensile strain and stable conductance enabled by a worm-shaped graphene microlayer. Nano Lett. *19*, 6592–6599.

Sun, H., Fu, X., Xie, S., Jiang, Y., and Peng, H. (2016). Electrochemical capacitors with high output voltages that mimic electric eels. Adv. Mater. *28*, 2070–2076.

Sun, H., Zhang, Y., Zhang, J., Sun, X., and Peng, H. (2017). Energy harvesting and storage in 1D devices. Nat. Rev. Mater. *2*, 17023.

Tang, Z., Jia, S., Wang, F., Bian, C., Chen, Y., Wang, Y., and Li, B. (2018). Highly stretchable core–sheath fibers via wet-spinning for wearable strain sensors. ACS Appl. Mater. Inter. *10*, 6624–6635.

Trung, T.Q., and Lee, N.-E. (2016). Flexible and stretchable physical sensor integrated platforms for wearable human-activity monitoringand personal healthcare. Adv. Mater. *28*, 4338–4372.

Villanueva, R., Ganta, D., and Guzman, C. (2019). Mechanical, in-situ electrical and thermal properties of wearable conductive textile yarn coated with polypyrrole/carbon black composite. Mater. Res. Express *6*, 016307.

Wan, C., Gu, X., Dang, F., Itoh, T., Wang, Y., Sasaki, H., Kondo, M., Koga, K., Yabuki, K., Snyder, G.J., et al. (2015). Flexible n-type thermoelectric materials by organic intercalation of layered transition metal dichalcogenide TiS_2. Nat. Mater. *14*, 622–627.

Wang, C., Xia, K., Jian, M., Wang, H., Zhang, M., and Zhang, Y. (2017a). Carbonized silk georgette as an ultrasensitive wearable strain sensor for full-range human activity monitoring. J. Mater. Chem. C *5*, 7604–7611.

Wang, C.Y., Li, X., Gao, E.L., Jian, M.Q., Xia, K.L., Wang, Q., Xu, Z.P., Ren, T.L., and Zhang, Y.Y. (2016a). Carbonized silk fabric for ultrastretchable, highly sensitive, and wearable strain sensors. Adv. Mater. *28*, 6640.

Wang, X., Qiu, Y., Cao, W., and Hu, P. (2015). Highly stretchable and conductive core–sheath chemical vapor deposition graphene fibers and their applications in safe strain sensors. Chem. Mater. *27*, 6969–6975.

Wang, H., Wang, H., Wang, Y., Su, X., Wang, C., Zhang, M., Jian, M., Xia, K., Liang, X., Lu, H., et al. (2020a). Laser writing of Janus graphene/Kevlar textile for intelligent protective clothing. ACS Nano *14*, 3219–3226.

Wang, L., Wang, L., Zhang, Y., Pan, J., Li, S., Sun, X., Zhang, B., and Peng, H. (2018). Weaving sensing fibers into electrochemical fabric for real-time health monitoring. Adv. Funct. Mater. *28*, 1804456.

Wang, L., Xie, S., Wang, Z., Liu, F., Yang, Y., Tang, C., Wu, X., Liu, P., Li, Y., Saiyin, H., et al. (2020b). Functionalized helical fibre bundles of carbon nanotubes as electrochemical sensors for long-term in vivo monitoring of multiple disease biomarkers. Nat. Biol. Eng. *4*, 159–171.

Wang, Q., Jian, M., Wang, C., and Zhang, Y. (2017b). Carbonized silk nanofiber membrane for transparent and sensitive electronic skin. Adv. Funct. Mater. *27*, 1605657.

Wang, W., Ouaras, K., Rutz, A.L., Li, X., Gerigk, M., Naegele, T.E., Malliaras, G.G., and Huang, Y.Y.S. (2020c). Inflight fiber printing toward array and 3D optoelectronic and sensing architectures. Sci. Adv. *6*, eaba0931.

Wang, R., Xu, Z., Zhuang, J., Liu, Z., Peng, L., Li, Z., Liu, Y., Gao, W., and Gao, C. (2017). Highly stretchable graphene fibers with ultrafast electrothermal response for low-voltage wearable heaters. Adv. Electron. Mater. *3*, 1600425.

Wang, Y., Zhou, Z., Qing, X., Zhong, W., Liu, Q., Wang, W., Li, M., Liu, K., and Wang, D. (2016b). Ion sensors based on novel fiber organic electrochemical transistors for lead ion detection. Anal. Bioanal. Chem. *408*, 5779–5787.

Wardclose, C.M., and Partidge, P.G. (1990). A fiber coating process for advanced metal-matrix composites. J. Mater. Sci. *25*, 4315–4323.

Wu, C., Kim, T.W., Li, F., and Guo, T. (2016). Wearable electricity generators fabricated utilizing transparent electronic textiles based on polyester/Ag nanowires/graphene core-shell nanocomposites. ACS Nano *10*, 6449–6457.

Wu, R., Ma, L., Patil, A., Meng, Z., Liu, S., Hou, C., Zhang, Y., Yu, W., Guo, W., and Liu, X.Y. (2020). Graphene decorated carbonized cellulose fabric for physiological signal monitoring and energy harvesting. J. Mater. Chem. A *8*, 12665–12673.

Wu, W., and Wang, Z.L. (2016). Piezotronics and piezo-phototronics for adaptive electronics and optoelectronics. Nat. Rev. Mater. *1*, 16031.

Wu, Z., Li, P., Zhang, Y., and Zheng, Z. (2018). Flexible and stretchable perovskite solar cells: device design and development methods. Small Methods *2*, 1800031.

Xie, Y.Z., Liu, Y., Zhao, Y.D., Tsang, Y.H., Lau, S.P., Huang, H.T., and Chai, Y. (2014). Stretchable all-solid-state supercapacitor with wavy shaped polyaniline/graphene electrode. J. Mater. Chem. A *2*, 9142–9149.

Xu, T., Zhang, Z., and Qu, L. (2020). Graphene-based fibers: recent advances in preparation and application. Adv. Mater. *32*, 1901979.

Xue, F., Chen, L., Wang, L., Pang, Y., Chen, J., Zhang, C., and Wang, Z.L. (2016). MoS2 tribotronic transistor for smart tactile switch. Adv. Funct. Mater. *26*, 2104–2109.

Xue, Q., Sun, J., Huang, Y., Zhu, M., Pei, Z., Li, H., Wang, Y., Li, N., Zhang, H., and Zhi, C. (2017). Recent progress on flexible and wearable supercapacitors. Small *13*, 1701827.

Yang, M., Pan, J., Xu, A., Luo, L., Cheng, D., Cai, G., Wang, J., Tang, B., and Wang, X. (2018). Conductive cotton fabrics for motion sensing and heating applications. Polymers *10*, 568.

Yang, R., Qin, Y., Dai, L., and Wang, Z.L. (2009). Power generation with laterally packaged piezoelectric fine wires. Nat. Nanotechnol. *4*, 34–39.

Yang, Y., Zhang, H.L., Liu, Y., Lin, Z.H., Lee, S., Lin, Z.Y., Wong, C.P., and Wang, Z.L. (2013a). Silicon-based hybrid energy cell for self-powered electrodegradation and personal electronics. ACS Nano *7*, 2808–2813.

Yang, Z., Deng, J., Chen, X., Ren, J., and Peng, H. (2013b). A highly stretchable, fiber-shaped

supercapacitor. Angew. Chem. Int. Ed. *52*, 13453–13457.

Ye, C., Ren, J., Wang, Y., Zhang, W., Qian, C., Han, J., Zhang, C., Jin, K., Buehler, M.J., Kaplan, D.L., et al. (2019). Design and fabrication of silk templated electronic yarns and applications in multifunctional textiles. Matter *1*, 1411–1425.

Yuan, D., Li, B., Cheng, J., Guan, Q., Wang, Z., Ni, W., Li, C., Liu, H., and Wang, B. (2016). Twisted yarns for fiber-shaped supercapacitors based on wetspun PEDOT:PSS fibers from aqueous coagulation. J. Mater. Chem. A *4*, 11616–11624.

Zeier, W.G., Schmitt, J., Hautier, G., Aydemir, U., Gibbs, Z.M., Felser, C., and Snyder, G.J. (2016). Engineering half-heusler thermoelectric materials using Zintl chemistry. Nat. Rev. Mater. *1*, 16032.

Zeng, W., Shu, L., Li, Q., Chen, S., Wang, F., and Tao, X.M. (2014). Fiber-based wearable electronics: a review of materials, fabrication, devices, and applications. Adv. Mater. *26*, 5310–5336.

Zhai, S., Karahan, H.E., Wang, C., Pei, Z., Wei, L., and Chen, Y. (2020). 1D supercapacitors for emerging electronics: current status and future directions. Adv. Mater. *32*, 1902387.

Zhang, L., Su, C., Cui, X., Li, P., Wang, Z., Gu, L., and Tang, Z. (2020a). Free-standing triboelectric layer-based full fabric wearable nanogenerator for efficient mechanical energy harvesting. ACS Appl. Electron. Mater. *2*, 3366–3372.

Zhang, M., Guo, R., Chen, K., Wang, Y., Niu, J., Guo, Y., Zhang, Y., Yin, Z., Xia, K., Zhou, B., et al. (2020b). Microribbons composed of directionally self-assembled nanoflakes as highly stretchable ionic neural electrodes. Proc. Natl. Acad. Sci. U S A *117*, 14667–14675.

Zhang, M., Wang, Y., Jian, M., Wang, C., Liang, X., Niu, J., and Zhang, Y. (2020c). Spontaneous alignment of graphene oxide in hydrogel during 3D printing for multistimuli-responsive actuation. Adv. Sci. *7*, 1903048.

Zhang, M., Zhao, M., Jian, M., Wang, C., Yu, A., Yin, Z., Liang, X., Wang, H., Xia, K., Liang, X., et al. (2019). Printable smart pattern for multifunctional energy-management E-textile. Matter *1*, 168–179.

Zhang, M.C., Wang, C.Y., Wang, H.M., Jian, M.Q., Hao, X.Y., and Zhang, Y.Y. (2017). Carbonized cotton fabric for high-performance wearable strain sensors. Adv. Funct. Mater. *27*, 7.

Zhang, Y., Wang, L., Guo, Z.Y., Xu, Y.F., Wang, Y.G., and Peng, H.S. (2016a). High-performance lithium-air battery with a coaxial-fiber architecture. Angew. Chem. Int. Ed. *55*, 4487–4491.

Zhang, Y., Zhao, Y., Ren, J., Weng, W., and Peng, H. (2016b). Advances in wearable fiber-shaped lithium-ion batteries. Adv. Mater. *28*, 4524–4531.

Zhang, Z., Cui, L., Shi, X., Tian, X., Wang, D., Gu, C., Chen, E., Cheng, X., Xu, Y., Hu, Y., et al. (2018). Textile display for electronic and brain-interfaced communications. Adv. Mater. *30*, 1800323.

Zhang, Z., Guo, K., Li, Y., Li, X., Guan, G., Li, H., Luo, Y., Zhao, F., Zhang, Q., Wei, B., et al. (2015). A colour-tunable, weavable fibre-shaped polymer light-emitting electrochemical cell. Nat. Photonic. *9*, 233–238.

Zhao, J., Zhang, Y., Huang, Y., Xie, J., Zhao, X., Li, C., Qu, J., Zhang, Q., Sun, J., He, B., et al. (2018). 3D printing fiber electrodes for an all-fiber integrated electronic device via hybridization of an asymmetric supercapacitor and a temperature sensor. Adv. Sci. *5*, 1801114.

Zhou, J., Li, X., Yang, C., Li, Y., Guo, K., Cheng, J., Yuan, D., Song, C., Lu, J., and Wang, B. (2019). A quasi-solid-state flexible fiber-shaped Li-CO_2 battery with low overpotential and high energy efficiency. Adv. Mater. *31*, 1804439.

Zhou, Y., He, J., Wang, H., Qi, K., Nan, N., You, X., Shao, W., Wang, L., Ding, B., and Cui, S. (2017). Highly sensitive, self-powered and wearable electronic skin based on pressure-sensitive nanofiber woven fabric sensor. Sci. Rep. *7*, 12949.