Recent advances in functional fiber electronics

Xiaopei Zhang | Huijuan Lin | Huan Shang | Jingsan Xu | Jixin Zhu | Wei Huang

1 Key Laboratory of Flexible Electronics and Institute of Advanced Materials, Jiangsu National Synergetic Innovation Center for Advanced Materials, Nanjing Tech University, Nanjing, P. R. China
2 School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology, Brisbane, Queensland, Australia
3 Frontiers Science Center for Flexible Electronics, Xi’an Institute of Flexible Electronics (IFE) and Xi’an Institute of Biomedical Materials & Engineering, Northwestern Polytechnical University (NPU), Xi’an, P. R. China

Correspondence
Dr. Jixin Zhu, PhD and Dr. Wei Huang, PhD, Key Laboratory of Flexible Electronics and Institute of Advanced Materials, Jiangsu National Synergetic Innovation Center for Advanced Materials, Nanjing Tech University, Nanjing, 211816, P. R. China.
Email: iamjxzhu@njtech.edu.cn; iamwhuang@njtech.edu.cn

Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 51872139, 51903121; Natural Science Foundation of Jiangsu Province, Grant/Award Number: BK20190683; Natural Science Foundation of Jiangsu Higher Education Institutions, Grant/Award Number: JSKJB150016; “Six Talent Peak” Project of Jiangsu Province, Grant/Award Numbers: XCL-043, XCL-018; Natural Science Basic Research Program of Shaanxi, Grant/Award Number: 2019JLM-28

Abstract
Rapid development of wearable electronics with various functionalities has stimulated the demand to construct functional fiber devices due to their merits of mechanical flexibility, weavability, miniaturization, and integrability. To this end, fiber components which can realize the functions of energy storage and conversion, actuating plus sensing have gained increasing concerns. Herein, we summarize the recent progress with respect to fiber material preparation, innovative structure design, and device performance in this review, also highlighting the possibility of integrated fiber electronics as an extension of application, the remaining challenges and future perspectives toward next-generation smart systems and to facilitate their commercialization.

KEYWORDS
actuator, energy storage device, fiber material, integration system, strain detection

1 | INTRODUCTION

The advent of smart electronics, including wearable Apple watches, flexible Samsung Galaxy X, smart Google Glass, and so forth, has exerted a profound impact in our life including healthcare, sports, and communications. With these rapid developments, extensive efforts have been inspired to explore novel fiber devices with high performance.1–7 In comparison to the traditional two-dimensional (2D) planar products, 1D fiber-shaped device has intriguing features of being flexible, lightweight, and miniaturized, presenting the possibility to be woven into flexible textile structures, therefore, ensuring the wearing comfortability and durability during practical usages. Apart from energy storage and conversion, fiber devices have been actively endowed with intelligent functions of self-healing, actuating, sensing, communicating, and self-powering nowadays.
For flexible/wearable electronic applications, conducting fibers featuring high electrical conductivity and structural flexibility offer the great promise as essential building blocks for constructing flexible devices. Recently, conductive fibers have been made from metal fibers/nanowires, carbon nanotube (CNT) fibers, graphene fibers. Specifically, CNT fibers comprising of aligned CNT bundles have been attracting great attention owing to their advantageous properties of good electrical conductivity, superior mechanical flexibility, light weight together with satisfactory chemical stability. Besides, they can be easily tailored with desired properties via engineering their microstructures or incorporating functional material into the fibers, which present broad applications in the field of supercapacitors, batteries, actuators, strain sensors, etc. To date, flexible fibers with novel functions, such as high stretchability and self-healing ability, are also highly desirable to withstand the various deformations of bending, twisting, stretching plus the damages during daily usages, thus, satisfying the requirements of practical needs.

Among the plentiful applications, flexible fiber-shaped supercapacitors and batteries are regarded as promising power supplies for flexible/wearable electronics ascribed to their high power capability and high energy density, respectively. These fiber-shaped energy storage devices have been successfully realized via the rational incorporation of electroactive components into fibers, followed by device assembly in configurations of parallel, twisted, and coaxial patterns. In addition, sensors and actuators are also indispensable parts for wearable devices as they can monitor environmental variations. In addition to single function, considerable efforts have been devoted to boost the realization of integration devices/systems which can be achieved by weaving/knitting different functional fibers into multifunctional textiles on the basis of textile technologies or integrating all functional components on single fiber allowing for the accomplishment of self-powered smart system.

In comparison to well-established manufacturing approaches to planar 2D architecture electronics, it is more challenging to develop fiber-shaped ones. Critical aspects, including structural engineering and device assembly, were explored to obtain fiber components with targeted functions. Recent reviews on flexible electronics have mainly focused on the material preparation and their corresponding applications. Here, this article presents a critical review of the current and significant progress in fiber-shaped electronic devices with a focus on fibrous materials, device configurations, and performance, also highlights the construction of multifunctionality and integration system (as depicted in Figure 1). Particularly, conductive fibers are first introduced including metallic nanomaterials, CNT fibers, and graphene fibers with their corresponding fabrication methods and mechanical/electrical properties. Then, representative examples for fiber-shaped electronic devices covering supercapacitors, batteries (metal-ion batteries and metal–air batteries), actuators, and sensors are illustrated. Furthermore, integration systems for the purpose of multifunctionality have been described. The remaining challenges and future opportunities toward fiber electronics are also presented for next-generation wearable electronic devices.

2 FIBER MATERIALS

Extensive efforts have been exerted to explore fiber materials, including metallic nanostructures, CNT fibers, and graphene fibers, with both high mechanical flexibility and electrical conductivity for the realization of wearable electronic devices.

Conductive fiber materials comprising of metallic nanowires are mainly prepared via the methods of immersion, dip coating, wet spinning. Lee et al. proposed an effective method to incorporate conductive Ag nanoparticles (AgNPs) into stretchable fibers with a multifilament structure, which involves two steps: (1) the polyurethane (PU)-based elastic fiber in multifilament structure was immersed in an ethanol solution containing 40 wt% AgCF$_3$COO$^{-}$ to effectively absorb Ag precursor induced by the ion-dipole interaction between CF$_3$COO$^{-}$
and -OH in the alcohol solvent. (2) Chemical reduction of the absorbed Ag⁺ in fibers to AgNPs by hydrazine hydrate (N₂H₄·4H₂O) and finally Ag nanoparticle-based fiber strain sensors were obtained. Sun et al.⁵⁷ produced silver nanowires (AgNWs) composite fibers derived from braid-like weaved yarn (BWY) through a dip coating method (Figure 2A). The BWY was cleaned by ethanol sonication and dried, followed by the dip coating in AgNWs ethanol solution. Various conductivities of yarns can be manipulated via tuning the dip-coating times. Afterwards, the BWY fibers covered with AgNWs were treated with H₂ plasma to remove residual insulating PVP and finally produce BWY-AgNWs conductive fibers. Another efficient approach is wet spinning to fabricate conductive fiber comprising of Ag particle, nAg-MWNTs, and polymer matrix in a fiber with approximately 100 μm diameter (Figure 2B), which can be tuned by altering the nozzle size of wet-spinning process setup. The coagulant of hexane has been demonstrated to offer the fiber with a maximum strain of 490% and a conductivity of 236 S/cm measured for 7.4 wt % Ag particles.⁵⁶ Baik et al.⁵⁵ also employed a wet-spinning strategy to synthesize stretchable and conductive Ag-PU fibers that used dispersion of Ag nanoflowers in the PU solution to form a spinnable dope and then extradited into
Carbon nanotubes (CNTs) are attractive for their high electrical conductivity, high mechanical strength, sufficient surface area, and self-supporting characteristics. Unlike widely used carbon fibers, CNT in fiber format has good structural flexibility that can be bent and knotted. So far, the preparation of CNT fibers can be mainly divided into two methods: wet spinning and dry spinning. Wet spinning is a conventional method to manufacture fibers. In 2000, Vigolo first assembled single-walled CNT fibers. In 2000, Vigolo first assembled single-walled CNT (SWCNT) fibers via injecting dispersion of nanotubes in surfactant solution (SDS) into polyvinyl alchol (PVA) coagulation bath. The morphology of the as-spun fibers can be controlled with diameters from several micrometers to 100 μm by varying the parameters of injection rate, flow speed, and the needle, or capillary tube size. Due to the existence of the absorbed polymer (PVA), better alignment can be achieved after rewetting the fiber in an appropriate solvent (eg, acetone, poor solvent for PVA) and stretching treatment, thus, improving the fiber Young’s modulus. When replacing PVA with a polyethyleneimine (PEI) coagulant and cationic surfactant, the CNT fibers were obtained with improved mechanical properties and electrical conductivity ascribed to the strong interfacial binding effect of PEI with the nanotubes. Even so, the residual polymers during the spinning process still limited the fiber conductivity, requiring complete removal upon thermal annealing but with the decreased mechanical properties of fibers. Neat SWCNT fiber without surfactant or polymer assistance can be further achieved from SWCNTs dispersion in superacids (102% sulfuric acid) to separate the nanotubes into individuals, and then coagulation in water by wet-spinning technique. Compared with wet-spinning technology, dry-spinning method avoids the use of surfactants and strong acids. CNT fibers can be readily prepared by spinning from aligned CNT arrays and directly spinning from a chemical vapor deposition (CVD) reaction. The former preparation process involves the drawing of CNT sheets from a spinnable CNTs array grown on a silicon wafer coated with iron catalyst by CVD process to obtain continuous CNT fibers. The fiber can be engineered with controlled diameter by tuning the width of the array. By a similar spinning method, Jiang et al. spun CNT fibers having length of centimeters from superaligned CNT array originated from van der Waals interactions between aligned nanotubes. Li et al. proposed a direct spinning from CVD using liquid ethanol as the carbon source and an iron catalyst, and hydrogen as carrier gas to load into the reaction zone at a temperature range of 1050-1200°C to form CNTs aerogel. The aerogel can be drawn directly from the hot zone to form CNT fibers (Figure 2C). This direct-spinning process can be expanded with other carbon sources, for example, the mixture of aromatic-hydrocarbons and oxygen-containing molecules. Then, Zhang et al. obtained CNT fiber by introducing twist during a dry-spinning process (Figure 2D) and made the resulting multiply fibers overtwisted into yarns, or knotted and knitted into complex shapes. Due to the high strength and flexibility, this type of CNT yarn can be constructed into macroscopic structures for versatile applications. Furthermore, the fiber can be converted to a spring shape, reaching the tensile strain up to 285%, which is much higher than the straight CNT fibers (the tensile strain at break is usually less than 10%) (Figure 2E). In addition, CNT fibers are also excellent electrical/thermal conductors. Compared with other flexible wires, they have a larger surface area, resistance to oxidation and corrosion. Therefore, by incorporating guest materials into CNT fibers, a flexible functional fiber can be manufactured. Benefitting from the unique structure and properties, the application of CNT fibers/yarns can be extended to a much broader area including sensors, actuators, artificial muscles, and supercapacitors.

Graphene, a 2D monolayer of sp² hybrid carbon atoms tightly bound to the honeycomb lattice, have excellent electrical properties, and widely used in energy storage materials. Integration of 2D graphene sheets into macroarchitected fibers, has translated the excellent performance of individual graphene into advanced fibers. Up to now, the main methods to manufacture graphene fibers include wet spinning, dry spinning, and electrospinning. Injection of graphene oxide (GO) sheets dispersions into a coagulation bath containing hexadecyltrimethyl ammonium bromide (CTAB) surfactant solution to form GO fibers through wet-spinning technology and then chemical reduction can finally produce graphene fibers with a mechanical strength of approximately 182 MPa and electronic conductivity of approximately 35 S/cm. The diameter of the as-spun fiber can be set by changing the nozzle size or the GO dispersion content. Xu et al. obtained graphene fibers with aligned GO sheets from giant GO liquid crystals (LCs) using divalent ions (eg, Ca²⁺, Cu²⁺) as coagulation bath through wet-drawing and chemical reduction (Figure 3A-C). The improved mechanical properties of graphene fibers are ascribed to the giant size of the graphene sheet, and its good orientation, demonstrating a record tensile strength (up to 0.5 GPa) for Ca²⁺-crosslinked graphene fibers. To further improve tensile modulus of GO fibers, Xiang et al.
proposed a method for continuous wet spinning of oriented GO fibers from high-concentration small flake GO (9 μm in diameter) LCs with stretching, yielding a high tensile modulus of 47 GPa. Various guest materials can be easily introduced into the graphene host, affording graphene-based composite fibers with new functionality or enhanced performance, which opens up the opportunities for exploring the potential applications. Through electrospinning technology, Matsumoto et al. also successfully twisted from poly(acrylonitrile) (PAN) containing GO nanoribbons and subsequent pyrolysis to produce graphene nanoribbon/carbon composite nanofiber yarns. The as-spun yarn exhibited a tensile strength of 382.4 MPa and an electrical conductivity of 165 S/cm, respectively, which can be explained by well-dispersed nanoribbons highly oriented along the fiber axis and carbonization treatment, promoting the formation of ordered graphitic structure. Better physical properties can be expected by optimization of GO nanoribbon fraction and carbonization conditions.

Hybrid fibers of 1D CNTs and 2D graphene sheets can display improved properties of electrical conductivity and mechanical flexibility that exceeded of single constituent component, efficiently reducing the π–π stacking interaction among graphene sheets. Chen et al. developed a hybrid carbon-based fiber in hierarchical structure comprising of nitrogen-doped RGO and acid-oxidized SWCNTs (Figure 3D and E). The resultant fiber possesses not only high packing density, but also abundant electron and ion transport pathways to realize a microsupercapacitor with satisfactory volumetric performance. By embedding graphene fibers with Fe3O4 nanoparticles as catalysts to grow CNT under CVD method, Chen et al. also used the CVD method combined with a poststretching approach to obtain the CNTs and graphene (GNS) hybrid multiple-thread yarns. The tensile strength and electrical conductivity of the achieved composite fiber are 300 MPa and 1000 S/cm, respectively, presenting the prospects for application in various fields. Researches of metal, graphene, or CNT-based fibers have received considerable attention as summarized in Table 1. Although metallic fibers possess quite high electrical conductivities, their rigid structure and high mass density are unsatisfactory for construction of flexible electronics. In contrast, CNT or graphene fibers are more suitable ascribed to their
| Fiber material                        | Preparation method                      | Mechanical properties                                | Electrical properties | Reference |
|--------------------------------------|-----------------------------------------|-----------------------------------------------------|-----------------------|-----------|
| Metal fiber                          |                                         |                                                     |                       |           |
| PU/AgNPs                             | Absorption and reduction                | Tensile strength: 9 MPa; Break elongation: 500%     | 20964 S/cm            | 9         |
| AgNWs/POE                            | Absorption                              | Tensile strength: 1 Pa; Break elongation: 550%      | 10 Ω/cm               | 10        |
| DCY-AgNW-PDMS                        | Dip coating                              | Tensile strength: 10.1 MPa; Break elongation: 560%  | 4018 S/cm             | 54        |
| nAg-MWNTs/PVDF-HFP                   | Wet spinning                            | Tensile strength: 1 Pa; Break elongation: 550%      | 17 460 S/cm           | 56        |
| PU/AgNWs                             | Using the capillary tube                | Tensile strength: 491 kPa; Break elongation: 26%    | 3.1 S/cm              | 72        |
| AuNWs/AuFilm                         | Dry spinning                            |                                                     | 75 S/cm               | 73        |
| CNT fiber                            |                                         |                                                     |                       |           |
| Core–sheath MWCNT fiber              | Coaxial wet-spinning                    | Tensile strength: 0.49 MPa; Break elongation: ~600% | ~0.01 S/cm            | 49        |
| CNT fiber/PDMS                       | Prestraining-buckling                   | Tensile strength: 0.82 ± 0.06 GPa; Break elongation: 4.65 ± 0.20% | 634 S/cm              | 74        |
| SWCNT/PVA                            | Wet spinning                            | Tensile strength: 1.16 GPa; Break elongation: 160%  | 0.001 S/cm            | 75        |
| CNT fiber                            | Fiber spinning                          | Tensile strength: 4.44 N tex⁻¹                       | 2270 S m⁻³/kg         | 76        |
| Graphene fiber                       |                                         |                                                     |                       |           |
| RGO fiber                            | Wet spinning                            | Tensile strength: 501.5 MPa; Break elongation: 6.7%  | 4.1 × 10⁴ S/cm        | 67        |
| CNT-graphene fiber                   | Using silica capillary column           | Tensile strength: 84 MPa; Break elongation: ~3%      | 102 S/cm              | 70        |
| Graphene fiber@PVA                   | CVD                                     | Tensile strength: 590 MPa; Break elongation: ~16%    | 96 S/cm               | 77        |
| RGO fiber                            | Dry film scrolling                      | Toughness: 17 J/m³                                   | 416 S/cm              | 78        |
| PDCY–RGO                             | Winding and dip coating                 | Tensile strength: 29.14 MPa; Break elongation: 676%  | 1.36 × 10⁻³ S/cm     | 79        |

AgNPs, Ag nanoparticles; AgNWs, Ag nanowires; AuNWs, gold nanowire; AuFilm, gold film; DCY, double-covered yarn; MWNTs, multiwalled carbon nanotube; PDCY: a double-covered yarn treated with air plasma; PDMS, poly(dimethylsiloxane); POE, polyolefin elastomer; PU, polyurethane; PVA: poly(vinyl alcohol); PVDF-HFP, poly(vinylidene fluoride-co-hexafluoropropylene).
features of being flexible, stretchable, and lightweight. Despite the great achievement mentioned above, it is still challenging to exploit novel fiber materials and fabrication technique for scale-up production and applications.

3 | FIBER ELECTRONICS

Recent development in fiber materials has inspired the research of fiber-shaped configuration successfully utilized in energy storage devices, wearable displays, smart actuators, sensors, and so forth. In this section, the construction of fiber electronic devices for energy storage and actuating/sensing applications and integrated systems will be discussed.

3.1 | Fiber energy storage devices

Nowadays, enormous efforts have been directed toward fiber-shaped energy storage devices, such as supercapacitors and rechargeable lithium-ion batteries (LIBs), to power portable and wearable electronics. These fiber devices are actively pursued with light weight, flexibility and miniaturization, to meet the requirements of wearable electronics. Commonly, flexible fiber-shaped supercapacitors/batteries can be categorized into parallel, twisted, and coaxial types (Figure 4). Among them, devices in a parallel structure are just simply assembled by coupling two fiber electrodes uniformly coated with gel electrolyte on a planar support to keep a space between them, without extra operation. Besides, multiple devices fabricated in parallel structures can be readily grouped in series or parallel to further increase the output potential or current for wider applications. Another effective design is to construct a flexible device by twisting two fiber-shaped electrodes via a rotation–translation setup. Compared with the parallel pattern, the twisted device is capable of self-standing without the assistance of polymer support (eg, PET, PDMS) and can adapt to various mechanical deformations when being woven into textiles for practical usage. Special care needs to be taken to avoid the introduction of extra series resistance. The above-mentioned parallel configuration suffered from relatively low specific power/energy density due to the use of flexible substrate support to introduce additional volume and weight. To overcome these shortcomings, a twisted supercapacitor was developed directly from relatively low specific power/energy density due to the use of flexible substrate support to introduce additional volume and weight. To overcome these shortcomings, a twisted supercapacitor was developed directly

3.1.1 | Fiber supercapacitors

Supercapacitors can be classified into electrochemical double-layer capacitors (EDLCs) and pseudocapacitors according to their energy storage mechanism. The capacitance of EDLCs comes from the accumulation of ions formed at the electrode-electrolyte interface. Differentially, the energy storage of pseudocapacitors relies on fast and reversible redox reactions on the surface of electroactive materials (eg, metal oxides and conducting polymers), therefore, delivering a considerably higher capacitance than the values of carbon-based EDLCs.

Carbon-based fiber materials, specifically CNT or graphene fiber, possess excellent electrical conductivity and good physical properties, endowing them great potential as electrodes for fiber supercapacitors. In addition to carbon materials, pseudocapacitive materials, such as transition metal oxides/hydroxides (popular examples including MnO2, RuO2, Co(OH)2), and conducting polymers (typical representatives, such as polyaniline [PANI] and polypyrrole [PPy]), were also combined with carbon-based fibers to realize high performance. Among the metal oxides, MnO2 possessing a high theoretical specific capacitance (1380 F/g), wide voltage window, and low cost, is regarded as the most promising electrode material. However, its poor electrical conductivity and inferior flexibility, makes it infeasible to weave into textiles. To overcome these limitations and to fully exploit the potential of fiber supercapacitors, a twisted hybrid fiber electrodes in parallel (Figure 5A). The fiber-shaped electrodes were made of MnO2 nanoparticles uniformly anchored to the oxidized CNT fibers (Figure 5B) which were parallel laid on PDMS film to form a buckled structure after a prestretching-releasing process. The resulting devices exhibited excellent specific capacitance (409.4 F/cm3 tested at a current density of 0.75 A/cm3 in LiCl-PVA gel electrolyte) and nearly no curve change compared with the original cyclic voltammetry (CV) plots measured under different conditions of deformations (stretching and folding), plus stable capacitance retention especially at a prestrain of up to 40% (Figure 5C).
employing a highly flexible Au-coated poly(methyl methacrylate) (PMMA) plastic wire and a Kevlar fiber substrate covered with ZnO nanowires (Figure 5D). First, the Kevlar fiber was twisted around the straight plastic wire fixed on a stage. Then, the gel electrolyte was coated onto two electrodes to separate them to avoid the short circuit. As observed in Figure 5E, the flexible plastic wire had a diameter of approximately 200 μm. A magnified SEM showed ZnO nanowires in hexagonal shape covered on the substrate uniformly. To further enhance the capacitance, the fiber supercapacitor operated in a gel PVA/H$_3$PO$_4$ electrolyte delivered a specific capacitance approaching approximately 2.4 mF/cm$^2$ under a scan rate of 100 mV/s after MnO$_2$ coating (Figure 5F). Notably, the twisted fiber electrodes had limited electrical contact to produce a high internal resistance and would be easily detached from each other when bent or knitted into textile structure. To solve the critical issues, a coaxial
Fiber supercapacitor was developed, where aligned CNT fiber served as an inner layer wrapped with CNT sheet outer layer coated with a gel electrolyte (Figure 5G). The cross-sectional view of as-fabricated device (Figure 5H) showed the distinct morphologies of CNTs in the inner and outer part which were distinguished by two concentric cycles, evidencing a coaxial structure. The CNT fiber can be modified with a diameter ranging from 6 to 40 μm by controlling the width of spinnable CNT arrays. CV profiles of the device were overlapped well and kept a rectangular shape at 50 mV/s increased to a high scan rate of 1000 mV/s, indicating a double-layer capacitor behavior and stable electrochemical performance under high charge-discharge rates. Additionally, the coaxial supercapacitor yielded a discharge specific capacitance of 59 F/g with no obvious capacitance loss over 11 000 long-term cycles, and operated stably when bent under a curvature range of 0-31.25 cm⁻¹ (Figure 5I) or stretched.

Two different electrodes can further form a hybrid supercapacitor to broaden operational voltage range for performance enhancement. For instance, a fiber-shaped asymmetric supercapacitor assembled from the hybrid fibers of MnO₂ nanosheets onto the PEDOT:PSS-coated CNT (MnO₂/PEDOT:PSS/CNT) fiber and ordered microporous carbon (OMC)/CNT as positive and negative electrodes can achieve the voltage window expanded to 1.8 V along with an energy density as high as approximately 11.3 mWh/cm³.

Supercapacitors with extra functions, such as seal-healing capability and stretchability, are actively pursued for their importance in smart and wearable electronics. Huang et al. designed self-healable yarn-based supercapacitor by wrapping magnetic electrodes with a self-healing polymer (carboxylated PU) shell. The stainless steel yarn grown with magnetic Fe₃O₄ particles and subsequently electrodeposited with PPy layer can heal the damage upon cutting and restore the mechanical and electrical properties, thus, restoring the capacitance, which was contributed to the synergetic effect of vast hydrogen bonds in carboxylated PU network and the magnetic interaction between the yarn electrodes. Another research applied reduced GO-based fiber springs coated with self-healing carboxylated PU shell, can also reconnect the broken electrodes with a capacitance retention of 54.2% after three cutting-healing cycles. Apart from seal-healing property, Peng and coworkers developed stretchable fiber supercapacitor by sequentially wrapping CNT sheets on an elastic rubber fiber as inner and outer electrodes. Due to the combined advantages of elastic fiber and aligned CNT, the fabricated device exhibited high stretchability and electrical conductivity, which can be easily stretched after 100 cycles with a strain level of 75% without obvious structure degradation and capacitance fade. Although the use of elastic fibers endows the fiber devices with excellent stretchability, it adds extra volume and weight of the device, resulting in the limited capacitance and energy density for the entire device. To realize the fiber supercapacitor without the support of rubber fiber, Zhang et al. proposed a stretchable fiber supercapacitor with spring-like CNT fiber electrodes comprising of twisted CNT fibers with coiled loops. Upon stretching, the coil structured loops started to elongate while maintaining the CNTs in high alignment. After releasing, the spring fiber recovered to its initial coiled shape. To construct stretchable fiber supercapacitor, two fiber springs were placed in parallel with a coating layer of gel electrolyte to avoid short circuits. When stretched to 100% for 100 cycles, the specific capacitance of stretchable fiber supercapacitor is still retained at more than 90%, indicating the excellent stretchability and electrochemical stability of the resulting supercapacitor.

3.1.2 Fiber batteries

Typically, flexible batteries contain a positive electrode (anode, a lithium-containing compound), a negative electrode (cathode, carbon material), and an electrolyte. Flexible fiber batteries especially flexible LIBs have been extensively studied to power wearable electronics. Sharing similar configuration with fiber supercapacitors, fiber batteries actually operate in a different charge storage mechanism, which relies on the Li⁺ insertion/extraction in bulk electrodes instead of charge accumulation at the electrode-electrolyte interface in supercapacitors. During charging, Li⁺ deintercalated from the cathode moves through the electrolyte to the anode. During discharging, Li⁺ embedded in the anode moves back to cathode. The electrons in the outer circuit flow in an opposite direction of ion motions. The reversible movement of Li⁺ between the cathode and anode or called Li⁺ insertion/extraction process allows flexible LIBs for the realization of energy storage and conversion.

In 2012, Kim et al. designed the first fiber LIB, a mechanically flexible coaxial LIB cable by respectively utilizing a hollow-spiral anode (Cu wire coated with Ni-Sn) and a conventional LiCoO₂ (LCO) cathode (Figure 6A and B). The hollow-spiral anode was obtained by winding the twisted bundles of Ni-Sn coated Cu wires around a circular rod with a diameter of 1.5 mm and stretching axially to reach an outer diameter of approximately 1.2 mm after removal of rod. Then, Al wire as cathode current collector was wound on the hollow-spiral anode, followed by coating LCO cathode slurry. Finally, the liquid LiPF₆-containing organic electrolyte was injected into the empty space to produce a cable-type battery. As shown in cross-sectional optical image (Figure 6C), the cable battery
was constructed with a hollow-spiral anode, modified PET layer as separator, Al wire, tubular cathode, and packaging tube, with an outer diameter of several millimetres. Compared with nonhollow anode system, the cable-type battery with the hollow structure anode exhibited superior battery performance, including a higher capacity, more stable cycling, and lower internal resistance (Figure 6D and E), attributed to the hollow structure with enlarged surface area and the better electrolyte permeability to active materials. In addition, the cable battery still exhibited stable electrochemical performance under large strain, such as bending and twisting deformations (Figure 6F), showing its excellent mechanical flexibility.

CNTs have been extensively explored as current collector and active materials in flexible energy-related devices contributed to the unique features of outstanding electrical and mechanical properties. CNTs in a fiber format can be easily dry spun from spinnable CNT arrays having tunable diameters and lengths. Ren et al. 93 designed a fiber microbattery by twisting the uniform growth of MnO2 nanoparticles on the aligned CNT fiber (CNT/MnO2 composite fiber) as positive electrode and Li wire as negative electrode, achieving a volumetric capacity of 109.6 mAh/cm³ at $5 \times 10^{-4}$ mA (Figure 7A-C). To achieve a higher capacity, Lin et al. fabricated a fiber battery by pairing Si/CNTs composite fiber and Li wire in parallel. 94 The Si/CNTs fiber was obtained by deposition of Si onto aligned CNT sheets, followed by twisting composite sheets to form a flexible composite fiber (Figure 7D-F). The as-designed Si/CNTs fiber showed combined merits of high energy capability of Si and super mechanical/electrical properties of CNTs, as well as the inhibited volume expansion of Si during the processes of charging and discharging. The assembled fiber battery showed good flexibility with no obvious capacitance decay over continuous 100 cycles of bending deformation. To replace rigid lithium metal wire, a full fiber-shaped battery by coupling LiMn2O4/CNT (LMO/CNT fiber, cathode) and Li4Ti5O12/CNT (LTO/CNT fiber, anode) paralleling, without the need of current-collecting metal substrate and polymer binder95 (Figure 7G-I). The resulting fiber-shaped battery (length: 1 cm) delivered a specific capacity of 70 mAh/g at 0.05 mA with a capacity retention of about 85% after 100 charge-discharge cycles. Again, this fiber battery was highly flexible enough to be deformed into diverse shapes or woven into electronic textile and even performed stably after 1000 cycles of bending.

Furthermore, an elastic battery with stretchability was assembled in a spring structure by simply winding two composite fibers, LMO/CNT and LTO/CNT as the cath-
ode and anode, around an elastic substrate and subsequently coated with gel electrolyte, displaying a capacity retention of over 80% after 200 cycles of stretching by up to 100%. When applied PDMS fiber as elastic substrate, a full battery exhibited a discharge specific capacity of 91.3 mAh/g under 0.1 mA/cm with a capacity retention of 88% after stretching at a strain of 600% (Figure 8A-C). The maximal stretching strain can be engineered by tuning the radius of the fiber substrate, that is, an increased radius of the fiber substrate gives a large strain. To avoid the use of elastic substrates, spring CNT fibers with coil-structure loops were further applied to construct elastic electrodes bearing LMO and LTO as cathode and anode to efficiently reduce both the volume and weight of devices. In addition to the mechanical flexibility, fiber batteries are also desired to heal itself to recover the electrical/ electrochemical properties operated under various deformations (eg, folding, bending, and twisting) during practical uses. Recently, inspired by the self-healing phenomenon in nature, polymers with self-healing functionality have been explored to heal mechanical fracture by reconnecting the damaged interface with reversible chemical or physical interactions. Gao et al. designed a flexible, all-fiber LIBs with self-healing ability in diameters of hundred micrometers, thick enough to observe the reconnection of the broken parts (Figure 8D). The assembled battery was composed of porous RGO fibers containing SnO2 quantum dots as anode, spring-like RGO fibers containing LCO nanoparticles as cathode, LiClO4-containing gel electrolyte, and a self-healing carboxylated PU packaging layer. The length of the spring-like cathode can be readily tuned to match the capacity of the anode. Similarly, the self-healing mechanism can be explained by abundant hydrogen bonds existing in the supramolecular network.
which can reconstruct at the broken surface after cutting. The as-fabricated LIB showed stable and good recovery of electrochemical performance, delivering a specific capacity of 82.6 mAh/g with an 82.2% capacity retention over 50 cycles under bending and twisting, and retaining a specific capacity of 50.1 mAh/g with a 50.3% capacity retention over five healing cycles at a current density of 0.1 A/g (Figure 8E and F). These above results reveal remarkable flexibility and self-healing property, providing great possibility to design flexible and self-healing power sources well performing under complex deformations toward next-generation wearable electronics.

Impressively, rational incorporation of other active materials into aligned CNT fibers can also realize other novel types of batteries, such as the hybrid fiber of aligned CNT, mesoporous carbon, and GO layer as fibrous sulfur cathode to fabricate a cable-shaped Li-S battery. Notably, many reported flexible batteries use flammable or toxic organic electrolytes. When it comes to practical applications in wearable electronics, the unwanted leakage of electrolytes can create great safety hazards. To explore safe batteries, Peng and coworkers designed flexible, fiber-shape aqueous Na-ion batteries by dropping the suspensions of Na0.44MnO2 (NMO) and carbon-coated NaTi2(PO4)3 (NaTi2(PO4)3@C, NTPO@C) onto stacked CNT sheets to produce composite fibers (CNT/NMO cathode and CNT/NTPO@C anode) and employing Na2SO4 solution as the electrolyte (Figure 8G). The designed fiber-shaped Na-ion batteries display remarkable electrochemical performance, as well as high flexibility and safety. In addition, the batteries with Na+ -containing biocompatible solution, such as normal saline solution, cell-culture medium, can still operate well. These above results indicate the potential in wearable and implantable electronic devices. Also, the as-fabricated fiber electrode can consume dissolved oxygen in aqueous Na+ solutions, through an electrochemical deoxygenation process and change the local pH, implying promising applications in biological or medical field.

Aligned and cross-stacked CNT sheets offer rich void space for efficient gas diffusion and oriented microchannels for electrolyte infiltration, continuous pathways of
electron transport due to its outstanding electrical properties \((10^2-10^3 \text{ S/cm})\) and high mechanical strength for self-standing. Therefore, CNT sheets-based air cathode endows the metal-air batteries with stable cycling performance at high current and structural stability against mechanical deformations. Typical examples of flexible fiber metal–air batteries include aligned CNT sheet air electrode for fiber Li-air battery,\(^{101,102}\) aligned cross-stacked CNT sheet air cathode for fiber Zn–air battery,\(^{103}\)Ag-coated cross-stacked CNT sheet air cathode for fiber Al-air battery (Figure 8H).\(^{100}\)

### 3.2 Fiber actuators

Many natural plants can sense external environmental stimuli to autonomously fulfill different functional missions such as seed dispersal and nutrient intake. Typical examples include the leaves of the mimosa will close when touched, and the pine cone scales and wheat awn will close/open under different environmental humidities. The natural phenomena have inspired the development of actuators (artificial muscles) capable of transforming electrical, thermal, or chemical energy to the useful mechanical energy.

CNT-based fiber actuators can be designed to respond to different stimuli, for example, electric,\(^{25,104}\)solvents/vapors,\(^1\)moisture.\(^{26,105}\)Popular mechanisms to explain the actuation are molecular order (eg, LC elastomers, shape memory polymers, and dielectric elastomers) and volume change due to the mass transport, thermal volume expansion, or phase transitions. Foroughi and coworkers have pioneered the exploration of CNT fibers as electromechanical actuators that realize the electrical-to-mechanical energy conversion.\(^2\)The CNT fiber functioned as a torsional actuator, exhibiting a rotation of 15 000° and a rotation speed of 590 rpm in a three-electrode system filled with an organic electrolyte (Figure 9A and B). The simultaneous contraction and rotation were driven hydraulically by internal pressure associated with ion insertion when immersed in the electrolyte, similar to electrochemical double-layer charge injection occurred in CNT-based supercapacitors (Figure 9C and D). In addition to electrolytes, CNT fibers can further produce electromechanical torsion (lengthwise contraction and rotary torsion) in air or liquid media, such as water and organic solvents, resulted from electromagnetic attraction between individual CNTs upon applying the current.\(^{106}\) Compared to 2D membrane actuators with simple bending and unbending behaviors, the above-mentioned fiber actuators can deliver distinctive torsional rotation, which is more desirable for the implementation of complex tasks. However, they suffered from the limitation of the use of the electrolytes, thus, leading to the restriction of operation voltage or temperature. Therefore, electrolyte-free actuating system is demanded for practical applications.

CNT yarns obtained from spinnable nanotube arrays have attracted wide investigation for fiber-shape devices, benefitting from their super mechanical strength, flexibility along with nanotube arrangement. Inserting twist to a CNT yarn can enlarge their mechanical strength, which is contributive to the development of high-performance artificial muscles. Chen et al.\(^1\)designed hierarchically arranged helical fibers (HHFs) constructed from the twisted multiply fibers of helical assembly of MWCNTs (Figure 9E). The massive multiscale gaps, nanoscale gaps among the adjacent twisted fibers, are favorable for the rapid diffusion of solvents/vapors, thus, enabling a facilitated actuating performance. Upon the absorption of ethanol droplet, a twisted 20 primary fibers reversibly rotated a 570 times heavier copper paddle (mass: 75 mg) generating the largest rotary speed and contraction of 6361 rpm and approximately 10% during the process of rotation. These mechanically flexible and strong HHFs can be further woven into a smart textile capable of lifting a 100 times heavier copper ball (mass: 240 mg) 4.5 mm rapidly (within milliseconds) upon the spraying of ethanol (Figure 9F), generating the output power of 49 W/kg during the initial 50 ms, which is comparable to mammalian skeletal muscles (50 W/kg). In another work, Di et al.\(^{24}\)showed an incandescent tension annealing process (ITAP) can stabilize the coil-structure CNT yarns via strengthening the mechanical property of the yarn structure to prevent unwanted irreversible untwist, thus, eliminating the need to tether torsional artificial muscles (Figure 9G). This ITAP involves incandescently heating twisted CNT yarns under electric current to a temperature of approximately 2000°C while a weight is attached at the yarn end to offer tensile load. Upon exposure to acetone vapor, a coiled ITAP yarn with the dimension of 24 mm in length and 100 mm in thickness reversibly rotated a 6100 times heavier rotor by 630° (corresponding to a rotation of 26° per mm of muscle length) (Figure 9H). The maximum rotational speed of the rotor was 44 rpm, and the muscle lifted a weight corresponding to a 2.9 MPa load by about 0.7% of the yarn length. Such CNT twisted yarns show promising application of torsional actuator with high torsional speed and large torque, and reversible torsional actuation.

In addition to the response to organic solvents/vapors, CNTs-based fiber actuators can also be made into water/moisture driven actuation. He et al. fabricated hierarchically helical CNT fiber with hydrophilic ability when treated pristine fibers with oxygen plasma (Figure 9I).\(^{105}\)The hydrophilic secondary fiber (HSF) from 10-ply
hydrophilic primary fibers (HPFs) with an oxygen level of 10.9% generated a contractive stress of approximately 13.6 MPa and the corresponding peak stress rate of 21.7 MPa/s upon absorption of a water droplet. The contractive stress outputs could be further optimized by tuning the oxygen contents in the HPF. Besides, the HSF was also sensitive to moisture, producing a contractive stress of approximately 22.8 MPa when exposed to a relative humidity of ≥80% (Figure 9J). Besides the contractive actuation, the HSF also generated a rotation upon exposure to water, with a maximal torsional torque of 0.4 N m/kg and high reversibility of rotary actuation, demonstrating the possibility in smart window (Figure 9K). Such fast mechanical response can be attributed to the hierarchy of channels at nano- and micronscales, which provide adequate capacity for water infiltration driven by capillary force, and the resulting volume expansion of the helices finally triggers the contraction and rotation. Particularly, hybrid CNT yarns with volume-change guest infiltration into a twisted yarn has been demonstrated to develop electrolyte-free muscles which do not need the device packaging and reduces the actuator weight. Changing guest dimension causes torsional rotation and contraction of the twisted yarn host. For example, actuator based on a wax-filled CNT yarn due to the thermal volume expansion of paraffin wax by electrical, chemical, or photonical excitation, or a hydrophilic poly(diallyldimethylammonium chloride)
FIGURE 10  (A) Schematic to the conductive paths of the PU/AgNW fiber strain sensor under unstretching and stretching. (B) Responsive curve of a PU/AgNW strain sensor on the wrist under cyclic bending. Reproduced with permission from Ref. [72]. Copyright 2019, American Chemical Society. (C) Left: Schematic of changes in AgNWs and AgNPs in the composite fiber (0.5 wt% AgNW–AgNP embedded SBS fiber) under 50% strain. (Scale bar of SEM image: 4 μm); Right: the smart glove containing the composite fibers on each finger. Reproduced with permission from Ref. [109]. Copyright 2015, Wiley. (D) Top: preparation of CNTs/PU helical yarn; bottom: the CNTs/PU helical yarn strain sensor to detect the resistance change during walking. Reproduced with permission from Ref. [115]. Copyright 2020, American Chemical Society. (E) Schematic to a bisheath buckled structure designed for strain sensor; (F) the bisheath buckled fiber strain sensor can monitor different walking patterns. Reproduced with permission from Ref. [116]. Copyright 2017, Wiley

(PDDA) guest-CNT yarn upon water absorption/relative humidity change or even magnetic particle-filled CNT yarns by external magnetic field can be driven. Intriguingly, hybrid CNT yarn can be developed into bioactuators to sense glucose concentration driven by the volume expansion of glucose-sensitive guest hydrogel, suggesting the promising application in implantable, self-actuating drug delivery systems.

3.3 Fiber sensors

Strain sensor is an indispensable part for wearable electronics, which has been developed for human motion detection and healthcare monitoring. So far, various types of strain sensors have been constructed based on the transduction methods of piezoelectricity, capacitance, resistivity, etc. Among them, resistive sensors are of great research interest attributed to their simplified fabrication, low energy consumption, and easy measurement, etc.

Conventional strain sensors constructed from metals and semiconductors have the limitations of poor stretchability (<5%) and low sensing ability (low gauge factor), which are far from the requirements of wearable sensors. Recently, high-performance fiber strain sensors have been studied by embedding conductive fillers, such as AgNWs, CNTs, and graphene, into elastic polymer matrix for their integrated merits of flexibility, stretchability, and wearability. Zhu et al. integrated AgNWs into PU fibers in a structure of conductive AgNW filled into the surface layer of the PU matrix to form densely conductive networks. The manufactured PU/AgNW fibers manifest good electrical conductivity (3.1 S/cm), high breaking elongation (265%), wide response range (43%), and fast response (49 ms) and durability, contributed to the combined effects of highly stretchable PU matrix and the conductive AgNW network plus the enhanced interfacial stability (Figure 10A and B). In another design to further improve the electrical conductivity and breaking elongation, Lee et al. proposed highly stretchable conductive fibers consisting of AgNWs and AgNPs embedded in elastomeric polymer
poly(styrene-block-butadiene-block-styrene, SBS) by wet spinning of an AgNW-dispersed SBS solution, followed by Ag precursor absorption and hydrazine reduction for strain sensors. The composite fibers with 0.56 wt% AgNW-AgNP deliver a maximum breaking elongation of 900% and the highest conductivity of 2450 S/cm, attributed to the addition of rigid and conductive fillers of AgNWs and AgNPs to the SBS polymer matrix. To prove the practicality of the composite fiber in stretchable electronic devices, the composite fiber was attached to an artificial glove as a strain sensor to monitor the various motions of fingers with good response speed and recoverability (Figure 10C).

In addition to metal nanowires, CNT has been recognized as ideal conducting filler for fabricating conductive fiber with its excellent electrical or mechanical properties. CNT-based strain sensors are usually made from random CNT mixed with polymers, for example, cellulose nanofibers (CNFs) and SWCNTs by the combined three-roll-mill and wet-spinning strategy.110 Meng et al.111 developed a coaxial fiber containing cellulose wrapping oriented CNTs by coaxial wet-spinning technology using a rotating coagulating bath. The resultant coaxial fiber exhibited excellent mechanical strength ascribed to the existence of hydrogen bonding and van der Waals interactions. The coaxial fiber functioned as strain sensor which can be explained by the changes of contact conductive paths under stretching. However, these strain sensors still exhibit limited stretchability and low strain range. To further achieve high stretchability and wide detection range, strain sensors have been fabricated from elastic polymers, for example, CNT/thermoplastic PU fiber with a multilayer-hollow-monolith structure,112 PU/CNT@Fe2+ fibers.113 By a coating approach, Zhi et al.114 developed a CNT/cotton/PU core-spun yarn strain sensor that is capable of identifying the motions of finger and elbow, and even the eye winking. By virtue of physical interaction between CNT and the cotton/PU yarn, the as-obtained composite yarn can undergo the stretching up to 300% and can be stably operated for a long-term test (ca. 300 000 cycles) under 40% strain. Zhao et al.115 reported a stretchable helical CNTs/PU composite yarn comprising of the electrospun aligned PU nanofibers film, spray coating of CNT dispersion onto PU nanofibers film, and continuous twisting process to form a helical yarn (Figure 10D). Benefiting from the winding-locked CNT network and helical structure design, the helical CNTs/PU yarn has a maximum elongation of 1700%, stable conductivity and resistance recoverability within 900% stretching. Moreover, the helical yarn can work as a strain sensor to capture human motions (eg, walking) with stable signal response, presenting the possibility in applications of wearable electronics and large-strain sensors.

Various microstructures have been proposed for fiber strain sensors such as the bisheath buckled structure,116 a twistable sandwich fiber composed of buckled CNT electrodes,117 the layer-by-layer assembly of graphene on spiral elastic fiber,118 and buckled graphene ribbon119 to enhance the strain detecting performance. Buckling structures have been demonstrated as a straight structural design to achieve fiber strain sensor with high stretchability and linearity. Through a stretch-release process, the buckling structures can be formed to keep the conductivity stable along the prestretching direction. Baughman et al.120 reported a fiber strain sensor in hierarchically buckled sheath-core structure, by wrapping CNT sheets on a prestretched rubber fiber core with CNT orientation parallel to the fiber direction, achieving a quite high stretchability up to 1320%. Furthermore, Liu et al. designed a bisheath buckled structure of buckled CNT sheets and buckled rubber on the elastic fiber (Figure 10E). The as-fabricated resistive strain sensor can be reversibly stretched high to approximately 600%, displaying a linear and large resistance increase of 102 and 160% for strains of 0-200% and 200-600%, respectively. Such large resistance change arises from the decreasing contact area between neighboring CNT buckles during stretch. Moreover, the bisheath buckled fiber strain sensor can identify different walking patterns of extending, flexing, squatting, marching, and jumping (Figure 10F). The sensitivity of the fiber strain sensor can be altered by modifying the formed buckling structure via simply changing the fabrication strain.

4  |  INTEGRATED FIBER ELECTRONICS

Apart from single function has been successfully demonstrated, integrated systems are required to follow. Flexible fiber energy storage devices particularly supercapacitors and batteries are essential part in wearable electronics. It is well known that supercapacitors have high power density whereas batteries have high energy density. To realize high energy and power densities in one device, a twisted fiber hybrid energy device (Figure 11A)121 fabricated by twisting three hybrid fibers of CNT/ordered mesoporous carbon (OMC), CNT/LTO, and CNT/LMO, demonstrating the combined advantages of a LIB and a supercapacitor with both high energy (50 mWh/cm3 or 90 Wh/kg) and power densities (1 W/cm3 or 5970 W/kg). To meet the requirement of self-powered system, it is desirable for integrated function of energy conversion and storage. Therefore, a coaxial “energy fiber”38 contains two parts of photovoltaic conversion and energy storage, comprising of TiO2 nanotube-modified Ti wire and aligned CNT sheet as two electrodes, delivering an entire photoelectric conversion and storage efficiency of 0.82% with CNT layer thickness of 20 μm (Figure 11B
FIGURE 11  (A) Schematic structure of the devices comprising of LIB and supercapacitor segments. Reproduced with permission from Ref. [121]. Copyright 2015, Wiley. (B) Schematic diagram of the circuit connection in charging and discharging process. (C) Charging-discharging curve at 0.1 μA during the discharging process. Reproduced with permission from Ref. [38]. Copyright 2013, Wiley. (D) Schematic structure of the solar-powered coaxial-fiber stretchable sensing system. Reproduced with permission from Ref. [40]. Copyright 2019, Elsevier. (E) Schematic structure of coaxial fiber CF@TiO₂@MoS₂ electrode for energy harvesting and storage. Reproduced with permission from Ref. [6]. Copyright 2016, Wiley.

and C). Besides, the “energy fiber” can be further woven into flexible textiles. In addition to the solar energy, another renewable energy of wind can also be stored to charge the battery (Zn–Ag₂O battery). A coaxial-fiber integrated system (Figure 11D) was assembled by integrating solar cells (the outer layer), an aqueous Zn–MnO₂ battery (PEDOT@MnO₂/CNT fiber as cathode and Zn/CNT fiber as anode, the middle layer), and a stretchable MWCNT/TPE strain sensor (the inner layer) to realize multifunctionality of energy harvest, storage, and utilization. Specifically, the solar cell harvested solar energy that further stored as chemical energy in the Zn–MnO₂ battery, affording a continuous power source for the fiber strain sensor. This self-powered strain sensing system can operate under a strain up to approximately 180% and stably respond to both static and dynamic strain, presenting the effectiveness in real-time monitoring of human behaviors. These aforementioned integration systems were built up by connecting several monofunctional device together, which still suffered from the entire device of light weight and small size challenges. Therefore, a MoS₂-based fiber electrode (CF@TiO₂@MoS₂) was developed to achieve versatile applications to fulfill all purpose in a single electrode, including dye-sensitized solar cell (DSSC), supercapacitor, LIB, and electrocatalytic HER (Figure 11E), suggesting a great potential for designing one-device-multiple-functions for smart wearable electronics.

5  |  CONCLUSION AND OUTLOOK

To date, carbon-based fiber materials especially CNT fibers and graphene fiber have been the focus of research in fiber devices considering their superior electrical and mechanical properties, allowing them as flexible building blocks in constructing wearable devices. Compared to conventional metallic fibers, CNT fibers/yarns have become attractive for their fascinating structural flexibility, light weight and chemical stability. Ascribed to the van der Waals interaction between CNT bundles, continuous CNT fibers can be readily drawn from their spinnable arrays under twisting or aqueous suspensions, called dry-spinning and wet-spinning approaches. However, the high cost of aligned CNT arrays and limited fiber length have restricted the
scalable manufacturing of CNT fibers to a certain extent. Besides, the fiber alignment and impurities removal are of importance to the fiber density, enabling the production of a high-performance CNT-based fiber. The doping of intrinsic CNT has also been proved to be an efficient strategy for improving the electrical conductivity. To realize more functions, CNT fiber has been incorporated with guest materials, but the maintaining alignment of CNTs in composite fiber during the fabrication process should also be taken into account.

Functional fibers are in great demand due to their advantageous properties of small size, flexibility, knittability, and integrability, which pervade a diverse range of wearable electronic devices including batteries, supercapacitors, actuators, sensors, displays, solar cells, etc. Although encouraging progress has been made, it is still challenging for industrial applications. Flexible fiber supercapacitors/batteries have served as essential power supply for wearable devices, whereas several critical issues need to be addressed. Although organic electrolyte can expand electrochemical window which is correlated with device performance, it suffers from the safety problem. Therefore, employment of solid-state electrolyte is demanded to avoid the electrolyte leakage problem. However, the unwanted heavy encapsulating materials add extra weight/volume, and greatly reduce the energy density of the electrochemical device. Besides, the existing energy harvesting/storage devices are still too bulky for wearable and flexible application. Research on the material manufacturing and innovative structure design should be directed to being miniaturized in the future. Crucial parameters to evaluate actuator include response speed, displacement, and durability. More attention should be focused to design electrolyte-free fiber actuator to eliminate the need of the liquid electrolyte and complicated three-electrode electrochemical setup. Extra efforts need to be further exerted to develop torsional actuators as artificial muscles with high performance in terms of controllable actuating direction (which can translate mechanical motions to accomplish specific tasks), novel actuator structure (eg, high degree of inserted twist) and actuating mechanism (eg, piezoelectric and electrostrictive effects), high-speed response (rotational speed), and large torsional strokes as well as prolonged cycling stability without fatigue. Massive production techniques are also required for the commercialization of actuating systems. Incorporation of the CNT hybrid yarn with guest materials showing thermally, electrically, or chemically induced volumetric change (eg, moisture-sensitive PDDA, thermosensitive paraffin wax) can produce yarn rotation and contraction. Moreover, biocompatible materials should be carefully selected for their great potential in surgical robotics and medical devices. The operational stability of the strain sensor is strongly dependent on the interfa-
2. Foroughi J, Spinks GM, Wallace GG, et al. Torsional carbon nanotube artificial muscles. Science. 2011;334:494-497.
3. Huang Y, Huang Y, Zhu M, et al. Magnetic-assisted, self-healable, yarn-based supercapacitor. ACS Nano. 2015;9:6242-6251.
4. Wang L, Wang L, Zhang Y, et al. Weaving sensing fibers into electrochemical fabric for real-time health monitoring. Adv Funct Mater. 2018;28:1804456.
5. Wen Z, Yeh M-H, Guo H, et al. Self-powered textile for wearable electronics by hybridizing fiber-shaped nanogenerators, solar cells, and supercapacitors. Sci Adv. 2016;2:e1600097.
6. Liang J, Zhu G, Wang C, et al. MoS$_2$-based all-purpose fibrous electrode and self-powering energy fiber for efficient energy harvesting and storage. Adv Energy Mater. 2017;7:1601208.
7. Wang S, Liu N, Su J, et al. Highly stretchable and self-healable supercapacitor with reduced graphene oxide based fiber springs. ACS Nano. 2017;11:2066-2074.
8. Cheng Y, Zhang H, Wang R, et al. Highly stretchable and conductive copper nanowire based fibers with hierarchical structure for wearable heaters. ACS Appl Mater Interfaces. 2016;8:32925-32933.
9. Lee J, Shin S, Lee S, et al. Highly sensitive multifilament fiber strain sensors with ultrabroad sensing range for textile electronics. ACS Nano. 2018;12:4259-4268.
10. Zhong W, Liu C, Xiang C, et al. Continuously producible ultrasensitive wearable strain sensor assembled with three-dimensional interpenetrating Ag nanowires/polyolefin elastomer nanofibrous composite yarn. ACS Appl Mater Interfaces. 2017;9:42058-42066.
11. Li Y-L, Kinloch IA, Windle AH. Direct spinning of carbon nanotube fibers from chemical vapor deposition synthesis. Science. 2004;304:276-278.
12. Dalton AB, Collins S, Muñoz E, et al. Super-tough carbon-nanotube fibres. Nature. 2003;423:703-707.
13. Ericson LM, Fan H, Peng H, et al. Macroscopic, neat, single-walled carbon nanotube fibers. Science. 2004;305:1447-1450.
14. Lu W, Zu M, Byun J-H, Kim B-S, Chou T-W. State of the art of carbon nanotube fibers: opportunities and challenges. Adv Mater. 2012;24:1805-1833.
15. Zhang M, Atkinson KR, Baughman RH. Multifunctional carbon nanotube yarns by downsizing an ancient technology. Science. 2004;306:1358-1361.
16. Zhang X, Jiang K, Feng C, et al. Spinning and processing continuous yarns from 4-inch wafer scale super-aligned carbon nanotube arrays. Adv Mater. 2006;18:1505-1510.
17. Cong H-P, Ren X-C, Wang P, Yu S-H. Wet-spinning assembly of continuous, neat and macroscopic graphene fibers. Sci Rep. 2012;2:613.
18. Dai H. Carbon nanotubes: synthesis, integration, and properties. Acc Chem Res. 2002;35:1035-1044.
19. Li M, Zu M, Yu J, Cheng H, Li Q. Stretchable fiber supercapacitors with high volumetric performance based on buckled MnO$_2$/oxidized carbon nanotube fiber electrodes. Small. 2017;13:1602994.
20. Cheng X, Zhang J, Ren J, et al. Design of a hierarchical ternary hybrid for a fiber-shaped asymmetric supercapacitor with high volumetric energy density. J Phys Chem C. 2016;120:9685-9691.
21. Chen X, Lin H, Deng J, et al. Electrochromic fiber-shaped supercapacitors. Adv Mater. 2014;26:8126-8132.
22. Zhang Y, Bai W, Cheng X, et al. Flexible and stretchable lithium-ion batteries and supercapacitors based on electrically conducting carbon nanotube fiber springs. Angew Chem Int Ed. 2014;53:14564-14568.
23. Lima MD, Li N, Jung de Andrade M, et al. Electrically, chemically, and photonically powered torsional and tensile actuation of hybrid carbon nanotube yarn muscles. Science. 2012;338:928-932.
24. Di J, Fang S, Moura FA, et al. Strong, twist-stable carbon nanotube yarns and muscles by tension annealing at extreme temperatures. Adv Mater. 2016;28:6598-6605.
25. Xu L, Peng Q, Zhu Y, et al. Artificial muscle with reversible and controllable deformation based on stiffness-variable carbon nanotube spring-like nanocomposite yarn. Nanoscale. 2019;11:8124-8132.
26. Kim SH, Kwon CH, Park K, et al. Bio-inspired, moisture-powered hybrid carbon nanotube yarn muscles. Sci Rep. 2016;6:23016.
27. Hyeon JS, Park JW, Baughman RH, Kim SJ. Electrochemical graphene/carbon nanotube yarn artificial muscles. Sens Actuat B Chem. 2019;286:237-242.
28. Lin H, Gong J, Miao H, et al. Flexible and actuating nanoporous poly(ionic liquid)–paper-based hybrid membranes. ACS Appl Mater Interfaces. 2017;9:15148-15155.
29. Son W, Chun S, Lee JM, et al. Highly twisted supercoils for superelastic multi-functional fibres. Nat Commun. 2019;10:426.
30. Zang C, Li H, Huang A, et al. Rational design of a flexible CNTs@PDMS film patterned by bio-inspired templates as a strain sensor and supercapacitor. Small. 2019;15:1805493.
31. Yang Z, Deng J, Chen X, Ren J, Peng H. A highly stretchable, fiber-shaped supercapacitor. Angew Chem Int Ed. 2013;52:13453-13457.
32. Shang Y, He X, Li Y, et al. Super-stretchable spring-like carbon nanotube ropes. Adv Mater. 2012;24:2896-2900.
33. Cai Z, Li L, Ren J, Qiu L, Lin H, Peng H. Flexible, wearable and efficient microsupercapacitor wires based on polyaniline composite fibers incorporated with aligned carbon nanotubes. J Mater Chem A. 2013;1:258-261.
34. Chen X, Qiu L, Ren J, et al. Novel electric double-layer capacitor with a coaxial fiber structure. Adv Mater. 2013;25:6436-6441.
35. Zhang H, Han W, Xu K, et al. Metallic sandwiched-aerogel hybrids enabling flexible and stretchable intelligent sensor. Nano Lett. 2020;20:3449-3458.
36. Fang B, Xiao Y, Xu Z, et al. Handedness-controlled and solvent-driven actuators with twisted fibers. Mater Horiz. 2019;6:1207-1214.
37. Shang Y, Wang J, Ikeda T, Jiang L. Bio-inspired liquid crystal actuator materials. J Mater Chem C. 2019;7:3413-3428.
38. Zhang Z, Chen X, Chen P, et al. Integrated polymer solar cell and electrochemical supercapacitor in a flexible and stable fiber format. Adv Mater. 2014;26:466-470.
39. Sun H, Jiang Y, Xie S, et al. Integrating photovoltaic conversion and lithium ion storage into a flexible fiber. J Mater Chem A. 2016;4:7601-7605.
40. Zhang Q, Li L, Li H, et al. Ultra-endurance coaxial-fiber stretchable sensing systems fully powered by sunlight. Nano Energy. 2019;60:267-274.
41. Zhu Y-H, Yang X-Y, Liu T, Zhang X-B. Flexible 1D batteries: recent progress and prospects. Adv Mater. 2020;32:1901961.
42. Zhou Y, Wang C-H, Lu W, Dai L. Recent advances in fiber-shaped supercapacitors and lithium-ion batteries. *Adv Mater*. 2020;32:1902779.
43. Stoppa M, Chioriero A. Wearable electronics and smart textiles: a critical review. *Sensors*. 2014;14:11957-11992.
44. Heo JS, Eom J, Kim Y-H, Park SK. Recent progress of textile-based wearable electronics: a comprehensive review of materials, devices, and applications. *Small*. 2018;14:1703034.
45. Ding S, Jiu J, Gao Y, et al. One-step fabrication of stretchable copper nanowire conductors by a fast photonic sintering technique and its application in wearable devices. *ACS Appl Mater Interfaces*. 2016;8:6190-6199.
46. Wei Y, Chen S, Lin Y, Yuan X, Liu L. Silver nanowires coated on cotton for flexible pressure sensors. *J Mater Chem C*. 2016;4:935-943.
47. Tang Z, Jia S, Wang F, et al. Highly stretchable core–sheath fibers via wet-spinning for wearable strain sensors. *ACS Appl Mater Interfaces*. 2018;10:6624-6635.
48. Zeng W, Shu L, Li Q, Chen S, Wang F, Tao X-M. Fiber-based wearable electronics: a review of materials, fabrication, devices, and applications. *Adv Mater*. 2014;26:5310-5336.
49. Zheng X, Wang R, Yangyang W, Yali L. Carbon nanotube and graphene multiple-thread yarns. *Nanoscale*. 2013;5:11831-1187.
50. Matsumoto H, Imaizumi S, Konosu Y, et al. Electrospun composite nanofiber yarns containing oriented graphene nanoribbons. *ACS Appl Mater Interfaces*. 2013;5:6225-6231.
51. Zhen G, Shin Y, Byun J, Chou TW. Graphene-based fibers: a review. *Adv Mater*. 2015;27:5113-5131.
52. Chen Y, Wang R, Sun J, Gao L. Highly conductive and ultrastretchable electric circuits from covered yarns and silver nanowires. *ACS Nano*. 2015;9:3887-3895.
53. Ma R, Kang B, Cho S, Choi M, Baik S. Extraordinarily high conductivity of stretchable fibers of polyurethane and silver nanofibers. *ACS Nano*. 2015;9:10876-10886.
54. Ma R, Lee J, Choi D, Moon H, Baik S. Knitted fabrics made from highly conductive stretchable fibers. *Nanot Lett*. 2014;14:1944-1951.
55. Shi B, Wang T, Shi L, Li J, Wang R, Sun J. Highly stretchable and strain sensitive fibers based on braid-like structure and silver nanowires. *Appl Mater Today*. 2020;19:100610.
56. Baughman RH, Zakhidov AA, de Heer WA. Carbon nanotubes—the route toward applications. *Science*. 2002;297:787-792.
57. Vigolo B, Pénicaud A, Coulon C, et al. Macroscopic fibers and ribbons of oriented carbon nanotubes. *Science*. 2000;290:1331-1334.
58. Jiang K, Li Q, Fan S. Spinning continuous carbon nanotube yarns. *Nature*. 2002;419:801.
59. Vigolo B, Poulin P, Lucas M, Launois P, Bernier P. Improved structure and properties of single-wall carbon nanotube spun fibers. *Appl Phys Lett*. 2002;81:1210-1212.
60. Muñoz E, Suh D-S, Collins S, et al. Highly conducting carbon nanotube/polyethyleneimine composite fibers. *Adv Mater*. 2005;17:1064-1067.
61. Feng J-M, Wang R, Li Y-L, et al. One-step fabrication of high quality double-walled carbon nanotube thin films by a chemical vapor deposition process. *Carbon*. 2010;48:3817-3824.
62. Motta M, Moisala A, Kinloch IA, Windle AH. High performance fibres from 'dog bone' carbon nanotubes. *Adv Mater*. 2007;19:3721-3726.
63. Al-Graiti W, Yue Z, Foroughi J, et al. Probe sensor using nano-structured multi-walled carbon nanotube yarn for selective and sensitive detection of dopamine. *Sensors*. 2017;17:884.
64. Peng H, Sun X, Cai F, et al. Electrochromatic carbon nanotube/polydiacetylene nanocomposite fibres. *Nat Nanotechnol*. 2009;4:738-741.
65. Xu Z, Sun H, Zhao X, Gao C. Ultrastretch fibers assembled from giant graphene oxide sheets. *Adv Mater*. 2013;25:188-193.
66. Li D, Müller MB, Gilje S, Kaner RB, Wallace GG. Processable aqueous dispersions of graphene nanosheets. *Nat Nanotechnol*. 2008;3:101-105.
67. Xiang C, Young CC, Wang X, et al. Large flake graphene oxide fibers with unconventional 100% knot efficiency and highly aligned small flake graphene oxide fibers. *Adv Mater*. 2013;25:4592-4597.
68. Yu D, Goh K, Wang H, et al. Scalable synthesis of hierarchically structured carbon nanotube–graphene fibres for capacitive energy storage. *Nat Nanotechnol*. 2014;9:555-562.
69. Cheng H, Dong Z, Hu C, et al. Textile electrodes woven by carbon nanotube–graphene hybrid fibers for flexible electrochemical capacitors. *Nanoscale*. 2013;5:3428-3434.
70. Zhu G-J, Ren P-G, Guo H, Jin Y-L, Yan D-X, Li Z-M. Highly sensitive and stretchable polyeurethane fiber strain sensors with embedded silver nanowires. *ACS Appl Mater Interfaces*. 2019;11:23649-23658.
71. Zhao Y, Dong D, Wang Y, et al. Highly stretchable fiber-shaped supercapacitors based on ultrathin gold nanowires with double-helix winding design. *ACS Appl Mater Interfaces*. 2018;10:42612-42620.
72. Zu M, Li Q, Wang G, Byun J-H, Chou T-W. Carbon nanotube fiber based stretchable conductor. *Adv Funct Mater*. 2013;23:789-793.
73. Zhou G, Byun J-H, Oh Y, et al. Highly sensitive wearable textile-based humidity sensor made of high-strength, single-walled carbon nanotube/poly(vinyl alcohol) filaments. *ACS Appl Mater Interfaces*. 2017;9:4788-4797.
74. Lee J, Lee D-M, Jung Y, et al. Direct spinning and densification method for high-performance carbon nanotube fibers. *Nat Commun*. 2019;10:2962.
75. Wang X, Qiu Y, Cao W, Hu P. Highly stretchable and conductive core–sheath chemical vapor deposition graphene fibers and their applications in safe strain sensors. *Chem Mater*. 2015;27:6969-6975.
76. Cruz-Silva R, Morelos-Gomez A, Kim H-i, et al. Super-stretchable graphene oxide macroscopic fibers with outstanding knotability fabricated by dry film scrolling. *ACS Nano*. 2014;8:5959-5967.
77. Cheng Y, Wang R, Sun J, Gao L. A stretchable and highly sensitive graphene-based fiber for sensing tensile strain, bending, and torsion. *Adv Mater*. 2015;27:7365-7371.
78. Mo F, Liang G, Huang Z, Li H, Wang D, Zhi C. An overview of fiber-shaped batteries with a focus on multifunctionality, scalability, and technical difficulties. *Adv Mater*. 2020;32:1902151.
81. Liu B, Tan D, Wang X, Chen D, Shen G. Flexible, planar-integrated, all-solid-state fiber supercapacitors with an enhanced distributed-capacitance effect. Small. 2013;9:1998-2004.
82. Xiao X, Li T, Yang P, et al. Fiber-based all-solid-state flexible supercapacitors for self-powered systems. ACS Nano. 2012;6:9200-9206.
83. Zhang D, Miao M, Niu H, Wei Z. Core-spun carbon nanotube yarn supercapacitors for wearable electronic textiles. ACS Nano. 2014;8:4571-4579.
84. Yu D, Qian Q, Wei L, et al. Emergence of fiber supercapacitors. Chem Soc Rev. 2015;44:647-662.
85. Wang H, Forse AC, Griffin JM, et al. In situ NMR spectroscopy of supercapacitors: insight into the charge storage mechanism. J Am Chem Soc. 2013;135:18968-18980.
86. Miller JR, Simon P. Electrochemical capacitors for energy management. Science. 2008;321:651.
87. Zhang LL, Zhao X. Carbon-based materials as supercapacitor electrodes. Chem Soc Rev. 2009;38:2520-2531.
88. Zhai Y, Dou Y, Zhao D, Fulvio PF, Mayes RT, Dai S. Carbon materials for chemical capacitive energy storage. Adv Mater. 2011;23:4828-4850.
89. Frackowiak E, Béguin F. Carbon materials for the electrochemical storage of energy in capacitors. Carbon. 2001;39:937-950.
90. Wang F, Wu X, Yuan X, et al. Latest advances in supercapacitors: from new electrode materials to novel device designs. Chem Soc Rev. 2017;46:6816-6854.
91. Bae J, Song MK, Park YJ, Kim JM, Liu M, Wang ZL. Fiber supercapacitors made of nanowire-fiber hybrid structures for wearable/flexible energy storage. Angew Chem Int Ed. 2011;50:1683-1687.
92. Kwon YH, Woo S-W, Jung H-R, et al. Cable-type flexible lithium ion battery based on hollow multi-helix electrodes. Adv Mater. 2012;24:5192-5197.
93. Ren J, Li L, Chen C, et al. Twisting carbon nanotube fibers for both wire-shaped micro-supercapacitor and micro-battery. Adv Mater. 2013;25:1155-1159.
94. Lin H, Weng W, Ren J, et al. Twisted aligned carbon nanotube/silicon composite fiber anode for flexible wire-shaped lithium-ion battery. Adv Mater. 2014;26:1217-1222.
95. Ren J, Zhang Y, Bai W, et al. Elastic and wearable wire-shaped lithium-ion battery with high electrochemical performance. Angew Chem Int Ed. 2014;53:7864-7869.
96. Zhang Y, Bai W, Ren J, et al. Super-stretchable lithium-ion battery based on carbon nanotube fiber. J Mater Chem A. 2014;2:11054-11059.
97. Rao J, Liu N, Zhang Z, et al. All-fiber-based quasi-solid-state lithium-ion battery towards wearable electronic devices with outstanding flexibility and self-healing ability. Nano Energy. 2018;51:425-433.
98. Fang X, Weng W, Ren J, Peng H. A cable-shaped lithium sulfur battery. Adv Mater. 2016;28:491-496.
99. Guo Z, Zhao Y, Ding Y, et al. Multi-functional flexible aqueous sodium-ion batteries with high safety. Chem. 2017;3:348-362.
100. Xu Y, Zhao Y, Ren J, Zhang Y, Peng H. An all-solid-state fiber-shaped aluminum–air battery with flexibility, stretchability, and high electrochemical performance. Angew Chem Int Ed. 2016;55:7979-7982.
101. Wang L, Pan J, Zhang Y, Cheng X, Liu L, Peng H. A Li-air battery with ultralong cycle life in ambient air. Adv Mater. 2018;30:1704378.
102. Zhang Y, Wang L, Guo Z, Xu Y, Wang Y, Peng H. High-performance lithium–air battery with a coaxial-fiber architecture. Angew Chem Int Ed. 2016;55:4487-4491.
103. Xu Y, Zhang Y, Guo Z, Ren J, Wang Y, Peng H. Flexible, stretchable, and rechargeable fiber-shaped zinc–air battery based on cross-stacked carbon nanotube sheets. Angew Chem Int Ed. 2015;54:15390-15394.
104. Chen P, He S, Xu Y, Sun X, Peng H. Electromechanical actuator ribbons driven by electrically conducting spring-like fibers. Adv Mater. 2015;27:4982-4988.
105. Lee S, Chen P, Qiu L, et al. A mechanically actuating carbon-nanotube fiber in response to water and moisture. Angew Chem Int Ed. 2015;54:14880-14884.
106. Guo W, Liu C, Zhao F, et al. A novel electromechanical actuation mechanism of a carbon nanotube fiber. Adv Mater. 2012;24:5379-5384.
107. Lee DW, Kim SH, Kozlov ME, Lepró X, Baughman RH, Kim SJ. Magnetic torsional actuation of carbon nanotube yarn artificial muscle. RSC Adv. 2018;8:17421-17425.
108. Lee J, Ko S, Kwon CH, Lima MD, Baughman RH, Kim SJ. Carbon nanotube yarn-based glucose sensing artificial muscle. Small. 2016;12:2085-2091.
109. Lee S, Shin S, Lee S, et al. Ag nanowire reinforced highly stretchable conductive fibers for wearable electronics. Adv Funct Mater. 2015;25:3114-3121.
110. Wan Z, Chen C, Meng T, et al. Multifunctional wet-spin filaments through robust nanocellulose networks wrapping to single-walled carbon nanotubes. ACS Appl Mater Interfaces. 2019;11:42808-42817.
111. Jing C, Liu W, Hao H, Wang H, Meng F, Lau D. Regenerated and rotation-induced cellulose-wrapped oriented CNT fibers for wearable multifunctional sensors. Nanoscale. 2020;12:16305-16314.
112. Gao J, Wang X, Zhai W, et al. Ultrastretchable multilayered fiber with a hollow-monolith structure for high-performance strain sensor. ACS Appl Mater Interfaces. 2018;10:34592-34603.
113. Zhuang Z, Cheng N, Zhang L, Liu L, Zhao J, Yu H. Wearable strain sensor based on highly conductive carbon nanotube/polyurethane composite fibers. Nanotechnology. 2020;31:205701.
114. Wang Z, Huang Y, Sun J, et al. Polyurethane/cotton/carbon nanotubes core-spun yarn as high reliability stretchable strain sensor for human motion detection. ACS Appl Mater Interfaces. 2016;8:24837-24843.
115. Gao Y, Guo F, Cao P, et al. Winding-locked carbon nanotubes/polymer nanofibers helical yarn for ultrastretchable conductor and strain sensor. ACS Nano. 2020;14:3442-3450.
116. Wang R, Jiang N, Su J, et al. A bi-sheath fiber sensor for giant tensile and torsional displacements. Adv Funct Mater. 2017;27:1702134.
117. Choi C, Lee JM, Kim SH, Kim SJ, Di J, Baughman RH. Twistable and stretchable sandwich structured fiber for wearable sensors and supercapacitors. Nano Lett. 2016;16:7677-7684.
118. Park JJ, Hyun WJ, Mun SC, Park YT, Park OO. Highly stretchable and wearable graphene strain sensors with controllable sensitivity for human motion monitoring. *ACS Appl Mater Interfaces*. 2015;7:6317-6324.

119. Wang Y, Yang R, Shi Z, et al. Super-elastic graphene ripples for flexible strain sensors. *ACS Nano*. 2011;5:3645-3650.

120. Liu ZF, Fang S, Moura FA, et al. Hierarchically buckled sheath-core fibers for superelastic electronics, sensors, and muscles. *Science*. 2015;349:400-404.

121. Zhang Y, Zhao Y, Cheng X, et al. Realizing both high energy and high power densities by twisting three carbon-nanotube-based hybrid fibers. *Angew Chem Int Ed*. 2015;54:11177-11182.

122. Li C, Zhang Q, E S, et al. An ultra-high endurance and high-performance quasi-solid-state fiber-shaped Zn–Ag$_2$O battery to harvest wind energy. *J Mater Chem A*. 2019;7:2034-2040.

**Author Biographies**

Xiaopei Zhang is pursuing her Master degree supervised by Prof. Jixin Zhu and Dr. Huijuan Lin in the Institute of Advanced Materials at Nanjing Tech University. Her research topic is related to constructing functional nanomaterials for wearable electronic devices including textile-based sensors and supercapacitors.

Huijuan Lin completed her PhD project “porous poly(ionic liquids) based actuators” in the Max Planck Institute of Colloids and Interfaces, and gained her Ph.D. degree from Potsdam University in 2017. Since 2017, she has the position of Associate Professor at Nanjing Tech University in China. Currently, she is interested in developing nanostructured materials for flexible electronic devices.

Jixin Zhu received his Ph.D. degree from Nanyang Technological University in 2012. From 2012 to 2014, he joined the TUM CREATE as a postdoctoral fellow. After a postdoc financed by the Max Planck Institute of Colloids and Interfaces, he started his own research group in the Institute of Advanced Materials at Nanjing Tech University and became a full Professor in 2015. He was selected as “2018 Highly Cited Researcher.” His research interest focuses on advanced functional materials and energy-related applications.

Wei Huang received his Ph.D. degree from Peking University in 1992. In 1993, he began his postdoctoral research in National University of Singapore. In 2001, he was appointed as a chair professor with Fudan University, where he founded and chaired the Institute of Advanced Material (IAM). In 2006, he was appointed as the deputy president of Nanjing University of Posts and Telecommunications. He assumed his duty as the president of Nanjing Tech University (2012) and was appointed as deputy president and provost of Northwestern Polytechnical University (2017). He is the academician of Chinese Academy of Sciences. His research interests include organic/flexible electronics, nanomaterials, and nanotechnology, etc.

**How to cite this article:** Zhang X, Lin H, Shang H, Xu J, Zhu J, Huang W. Recent advances in functional fiber electronics. *SusMat*. 2021;1:105–126. https://doi.org/10.1002/sus2.1