Fiber-Shaped Electronic Devices

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electronic fiber wearable electronics electronic textiles fiber electronics

1. Introduction

Electronic fiber is a building block of electronic textiles (e-textiles) for developing wearable electronics. In practical applications, fiber-shaped devices have attracted great attention as a potential alternative to conventional planar-type electronic devices. Because of their structural features, which enable them to be sewn into various fabrics, electronic fibers are an ideal device platform for realizing the three-dimensional (3D) deformability, light weight, breathability, washability, and comfort required for e-textiles [1][2][3]. Their one-dimensional (1D) shape allows fiber devices to maintain their electronic functions under various kinds of mechanical deformation and stimuli. Moreover, electronic devices with different functionalities can be fabricated onto a 1D substrate, and monofunctional fibers can be woven together into an integrated device or e-textile [4]. The use of such fiber technologies will allow various electronic systems for computing, information technology, and communications to be easily incorporated in e-textiles, which can accommodate diverse functional fibers into an unlimited number of structures. For example, smart integrated textiles can be used to process and digitize mechanical, chemical, electrical, and thermal data gathered by fiber units that sense and react to the human body and the environment [5].

Recently, fiber electronics have advanced rapidly with the development of flexible electronics, stimuli-responsive sensors, and soft electronic materials. Unlike conventional electronic devices, electronic fibers require diverse fabrication methods, such as fused printing, spinning, electrodeposition, chemical vapor deposition, casting, rolling, molding, and thermal drawing [1][6][7][8][9][10][11][12][13]. These scalable fabrication processes have themselves been developed to achieve more precise patterning and uniform deposition of the active materials. Improvements in fiber technology have allowed basic device units to be produced in fiber form. The shape, composition, and architecture of electronic fibers can be adjusted by using suitable soft materials and fabrication processes to optimize function and performance [4][14]. With the rise of smart clothing and artificial intelligence (AI) technology, functional fibers with sensing, computing, memory, energy storage, energy-harvesting, and display capabilities have attracted much interest in the fiber industry [5]. In response to the demand for deformable devices, various types of fiber-shaped electronic components have been successfully developed, including transistors, memory devices, memristors, artificial synapses, sensors, light-emitting diodes (LEDs), and energy devices. To investigate the practical applications of these fiber-shaped devices, researchers have woven them into fabrics and integrated them into textiles [5].

2. Device Applications

In this section, we focus on recent research about directly integrating fibriform electronic devices into textiles, apart from attaching electronic components. Monolithic integration could potentially simplify the manufacturing process and improve user comfort. Integrating analog and digital microelectronics into textiles has attracted significant attention, but the integrating of electronic functions into a textile structure while retaining the mechanical properties of the textile still requires a great deal of effort.

2.1. Electronic Devices

2.1.1. Transistors

Transistors are one of the key electrical components of integrated electronic circuits that amplify and convert electrical signals simultaneously. They can also be applied to a variety of optoelectronic devices, such as displays, integrated circuits (ICs), memory devices, synaptic devices, and sensors. To date, most transistors have been fabricated on planar and rigid substrates. The development of flexible fiber-shaped transistors to give fabrics computational ability is still at an early stage because of the ongoing challenges involved in forming uniform films and high-resolution patterning on fiber substrates, and interconnecting fiber electrodes [2]. Thus, fabrication methods for electronic fibers and textile-compatible technology have been chosen as the primary focus of this research area.

Fiber-shaped transistors have mainly been fabricated using mechanically flexible materials with a coaxial structure. The dielectric, semiconductor, and electrode materials are sequentially coated onto an electrode core using solution (dip-coating, spray, etc.) and vapor processes (sputtering, atomic layer deposition, chemical vapor deposition, etc.) [15][16]. Various semiconducting materials have been applied to create a fibriform channel layer, such as polymers [17][18], organic small molecules [3][15][19], single-walled carbon nanotubes (SWCNTs) [17][20], and metal oxides [21][22]. For instance, Kim et al. fabricated organic field-effect transistor (OFET) fibers on Au microwires (**Figure 1**a) [23]. The OFET fiber was made from a coaxial bi-layer composed of 2,8-difluoro-5,11-bis (triethylsilylethynyl)anthradithiophene (diF-TESADT) as an organic semiconductor and poly(methyl methacrylate) (PMMA) as the insulating polymer [23]. The diF-TESADT: PMMA blend solution was coaxially die-coated and solidified with vertical phase-separation. The dimension of the spirally wrapped CNT microelectrodes was controlled using a rolling-transfer method, and the OFET fiber showed a maximum field-effect mobility of 0.68 $cm^2V^{-1}s^{-1}$ and good output current characteristics [23]. 2D crystals of organic small molecules (2DCOS) were used to fabricate fibriform OFETs through a jigsaw-puzzle physical-chemical method [19]. 2DCOS film was prepared using a solution epitaxy method, and then transferred onto a planar substrate to fabricate the OFETs [19]. The

2DCOS-based FETs were then peeled off and attached to the target fibers. The 2DCOS fiber transistors showed competitive electronic characteristics: a high field-effect mobility of 1 $cm^2V^{-1}s^{-1}$, well-balanced ambipolarity via the p−n junction, high inverter gain up to 12.4, and a near-infrared photoresponsivity of 1.06×10^4 A W^{-1}, with photodetectivity of 10^{13} Jones [19]. Heo et al. reported reel-processed 1D complementary metal-oxide-semiconductor (CMOS) logic circuits based on SWCNT transistors (**Figure 1**b) [16]. P- and n-type SWCNT fiber transistors were demonstrated using selectively chemical doping and a photochemical patterning technique [16]. The device exhibited high hole mobility of 4.03 $cm^2V^{-1}s^{-1}$ (electron mobility of 2.15 $cm^2V^{-1}s^{-1}$) and a gain of 6.76 with good dynamic operation at an applied voltage of 5.0 V [16]. Park et al. also fabricated fiber-shaped FETs with an Al_2O_3−MgO nanolaminate insulator and an In−Ga−Zn−O (IGZO) semiconductor [21]. The Al_2O_3−MgO and IGZO layers were deposited using a thermal atomic layer deposition system and radio-frequency sputtering, respectively [21]. The resulting fiber-shaped IGZO FETs exhibited an on- and off-current ratio above 10^8 and good electron mobility of more than 3 $cm^2V^{-1}s^{-1}$ with a leakage off-current of less than 10^{-9} A [21].

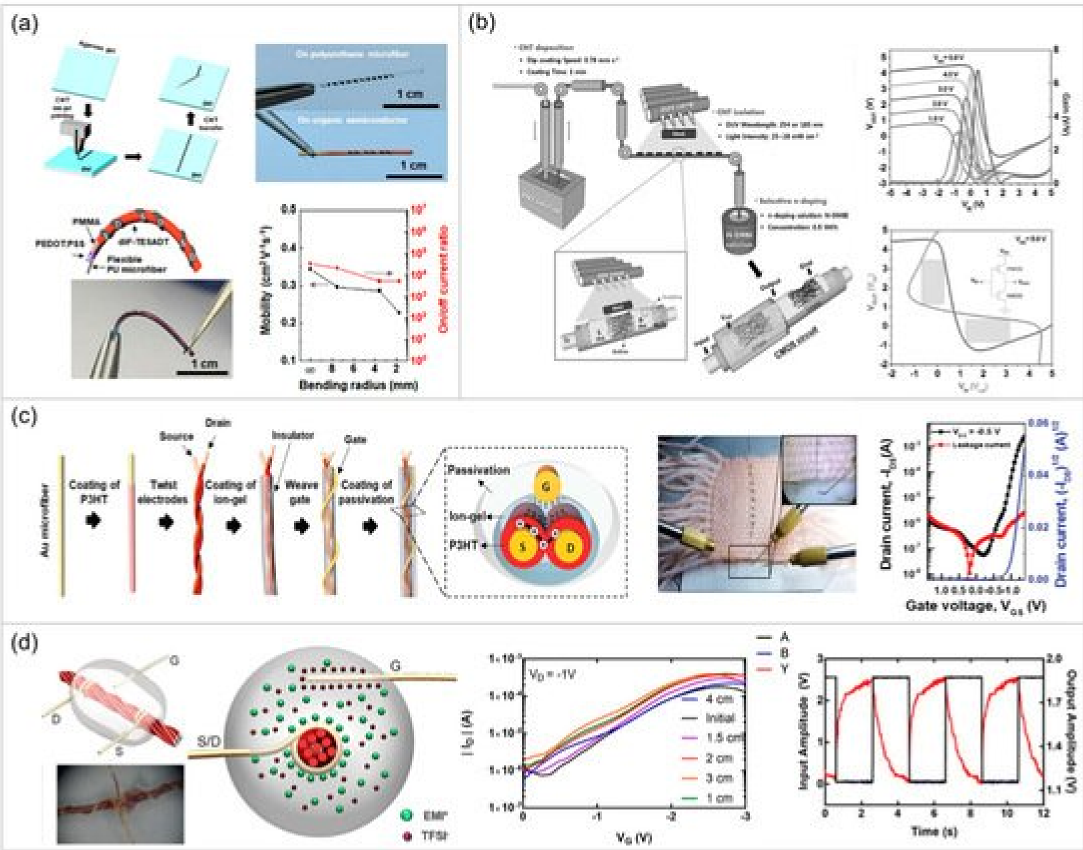

Figure 1. (**a**) Top: schematic of the rolling-transfer process of printed CNT microelectrodes (left) and photographs of the spirally wrapped CNT microelectrodes on fiber substrates (right). Bottom: schematic and photograph of a flexible fiber OFET (left), field-effect mobilities and on/off current ratio with various bending radii (right). Reproduced with permission Ref. [23]. Copyright 2020, American Chemical Society. (**b**) Left: schematic illustration of a fabrication process for fiber-shaped CMOS circuitry. Right: electrical properties of the 1D complementary inverters. Reproduced with permission Ref. [16]. Copyright 2017, Wiley-VCH. (**c**) Left: schematic illustration of a fabrication process of a fiber-shaped OFET with the twisted structure and a solid ion-gel electrolyte. Right: photograph and transfer characteristics of the fiber-shaped OFET embedded in a fabric. Reproduced with permission Ref. [24].

Copyright 2019, Wiley-VCH. (**d**) Left: schematic illustration and photograph of the ionogel-gated fiber transistor. Middle: transfer characteristics of the ionogel-gated transistor with different bending radii. Right: electrical characteristics of logic gate NAND (A and B curves: two logic gate inputs, Y curve: output from the circuit). Reproduced with permission Ref. [20]. Copyright 2019, American Chemical Society.

Many obstacles continue to limit the practicality of using 1D FETs for electronic circuits. One of the main issues is that 1D FETs still require sophisticated fabrication techniques that demand a vacuum process such as thermal evaporation, sputtering, or atomic layer deposition, which is unsuitable for commercialization [24]. Moreover, the high operating voltages required by OFETs, along with their low conductance values and unstable electrode interconnections, need to be resolved. In this regard, a new device design strategy has been developed for high-performance 1D FETs. Kim et al. fabricated fibrous OFETs with a twisted structure and a solid ion-gel electrolyte (**Figure 1**c) [24]. The source and drain (S/D) fiber electrodes were coated with an organic semiconductor and twisted together. The twisted assembly of electrode fibers was then surrounded by an ion gel, and the gate wire was then wound around that [24]. The resulting fibrous OFETs achieved milliampere-level output current and a good on/off ratio of 10^5 at low gate voltages (below −1.3 V) [24]. Their work reveals a promising structural strategy that could help overcome the current limitations of coaxial fiber FETs.

As another class of fiber transistors for wearable electronic devices, fiber-shaped organic electrochemical transistors (OECTs) have been explored because they can simplify the complex manufacturing processes required for coaxial fiber OFETs [18][25]. The OECTs use an electrolyte instead of an insulating layer of FETs, and therefore they do not need a smooth fiber substrate [25]. By applying a gate voltage, ions are injected from the electrolyte into the top surface or inner part of the semiconducting film, thereby doping the channel [26]. However, OECTs operated by doping/de-doping conducting polymers can work only in the depletion mode, and the response time is longer than that of OFETs due to slow ion transport in the ionic liquid [26]. Hamedi et al. demonstrated electric double-layer capacitor-gated (EDLC) transistors on sputter-coated metal fibers using poly(3-hexylthiophene) (P3HT) and imidazolium ionic liquid [11]. In the EDLC-OFETs, the channel conductivity was modulated by electrolyte polarization upon exposure to an electric field [11]. Therefore, the demonstrated EDLC transistors operated below 1 V and exhibited large current densities and improved switching speeds [11]. Owyeung et al. also demonstrated CNT transistors on linen threads, using a colloidal silica-based ionic liquid gel that induced all-around electrostatic gating (**Figure 1**d) [20]. The thread substrate was knotted with S/D Au wire, and then the P3HT (or CNT) semiconductors and ionogel were sequentially deposited by drop casting onto the thread [20]. These ionogel-gated transistors were applied as a switch and a multiplexed diagnostic device with simple logic gates (NAND, NOR, and NOT) [20].

Electrochemical and electrolyte-gated transistors can easily be integrated into woven circuitry in textiles and operated at low voltages. However, the low reliability in switching behavior under chemical and bias stress must be improved before their application will be practical. For this reason, highly reliable electrolyte-based materials should be developed.

2.2. Sensing Devices

Wearable 1D sensors have been developed to accurately monitor the environment and health, which can be characterized using various optical, mechanical, and chemical signals [1]. The flexible and compact sensor devices can conform to dynamic and irregularly shaped surfaces to collect high-quality data. This section briefly describes the most widely realized fiber-shaped sensor systems.

Detecting human motion is necessary for medical care, sports science, and rehabilitation [27]. Wearable motion sensors can contribute to the quick diagnosis of characteristic movement disorders, including sudden paralysis and tremors in the body, and to quality care of physical diseases, such as Alzheimer's disease, Parkinson's disease, and diabetes [27]. To track human motion in real time, wearable mechanical sensors that can detect continuous deformation have been developed.

Meng et al. reported a sensing textile system for biomonitoring and interacting over the Internet (**Figure 2**a,b) [28]. A 3-ply-twisted polyester–silver fiber was made by entwining polyester fibers around a silver wire to form a triboelectric layer and an electrode on a silver-coated polyester fabric (**Figure 2**c) [28]. The hybrid fibers were stitched onto the silver-coated fabric, where they detected a continuous pulse wave induced by a combination of triboelectrification and electrostatic induction that originated from the fiber when it was mechanically deformed by human skin (**Figure 2**c) [28]. The textile-based sensor exhibited a high sensitivity of 3.88 V kPa^{-1} in sensing tiny ambient pressure signals, and continuous operation across 80,000 cycles [28]. Based on the sensors, a wireless biomonitoring system (WBS) was developed to collect patients' health data, wirelessly transmit those data, and display the data through an APP interface on a mobile phone (**Figure 2**d) [28]. The WBS was able to diagnose obstructive sleep apnea and hypopnea syndromes, even with body movements [28]. The textile-based WBS highlights the great potential of smart textiles for personalized health care [28]. The triboelectric fiber device could have applications in a fiber rescue sensor [28]. A 3D honeycomb-structured triboelectric nanogenerator (TENG) based on a flame-retardant wrapping yarn was developed by Li and coworkers [29]. The sustainable and durable single-electrode triboelectric yarn was fabricated through a continuous, hollow-spinning, fancy twister process [29]. The conductive core yarn was wrapped with polyimide yarn for a core–sheath structure [29]. The TENG fibers offer flame retardancy and reduce vibration and noise [29]. Because the fibers can perform both energy harvesting and emergency signal transmission, the woven TENG fabric could be applied to locate a survivor's position in a fire and thereby enable the timely search and rescue of victims [29].

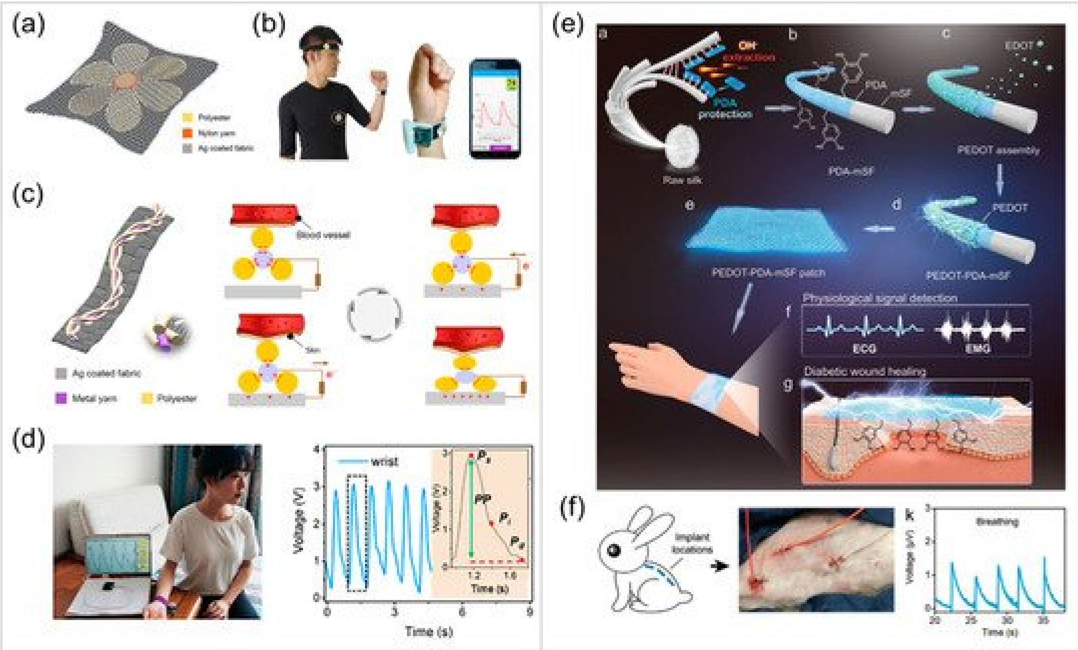

Figure 2. (**a**) Schematic illustration of the as-fabricated textile-based sensor. (**b**) Photographs of a wireless biomonitoring system based on a wearable textile sensor. (**c**) Schematic illustration of a 3D honeycomb-structured triboelectric nanogenerating fiber and working mechanism. (**d**) The textile-based wireless biomonitoring system and the acquired pulse wave signals when worn by a woman. (**a**–**d**) Reproduced with permission Ref. [28]. Copyright 2020, Elsevier. (**e**) Schematics of the fabrication process and a silk-based patch for diabetic wound healing. (**f**) A photograph of patches implanted as electrodes in a rabbit's back (left image) and signals detected after breathing. (**e**,**f**) Reproduced with permission Ref. [30]. Copyright 2021, Wiley-VCH.

2.3. Light-Emitting Fibers

Fiber-shaped light-emitting devices have attracted great attention. Incorporating fiber LEDs into clothes is expected to maximize human–machine communication [31]. Therefore, fiber LED devices have been developed using inorganic LEDs, organic LEDs (OLEDs), light-emitting electrochemical cells (LECs), and phosphorescent electroluminescent devices (PELDs) [32].

Mi et al. reported ultra-stretchable electroluminescent fibers (up to 400% stretch) that can display a pixel-based controllable light-emitting pattern (**Figure 3**a) [33]. A dip-coated zinc sulfide (ZnS) electroluminescent layer and a dielectric layer were sandwiched between two liquid metal-coated electrodes (eutectic gallium-indium, EGaIn) [33]. The cross-point of the ZnS-based fiber and the EGaIn-based fiber acted as an electroluminescent pixel that formed an electroluminescent fabric matrix when woven (**Figure 3**b) [33]. The pixel pattern on the fabric could be displayed using a direct-current (DC)–alternating-current converter connected to a Bluetooth switch in the electric circuit (**Figure 3**c) [33]. Zhang et al. developed continuous electroluminescent fibers using a one-step extrusion method (**Figure 3**d) [34]. The outer electroluminescent layer, containing ZnS particles with a silicone elastomer as a protecting layer, was simultaneously extruded with two inner parallel hydrogel electrodes [34]. Because of its unique single-fiber structure, the electroluminescent fibers emitted light in all directions [34]. The luminance of the light-emitting fiber was recoverable at 300% stretch, and retained after 100 stretching cycles [34]. These electroluminescent fibers were woven into a stretchable fabric to produce display patterns (**Figure 3**e) and applied to implement a brain-interfaced camouflage system (**Figure 3**f) [34]. The electroluminescent textile reacted to neuronal responses to decoder lights [34]. The resulting textile display represents a promising wearable communication platform.

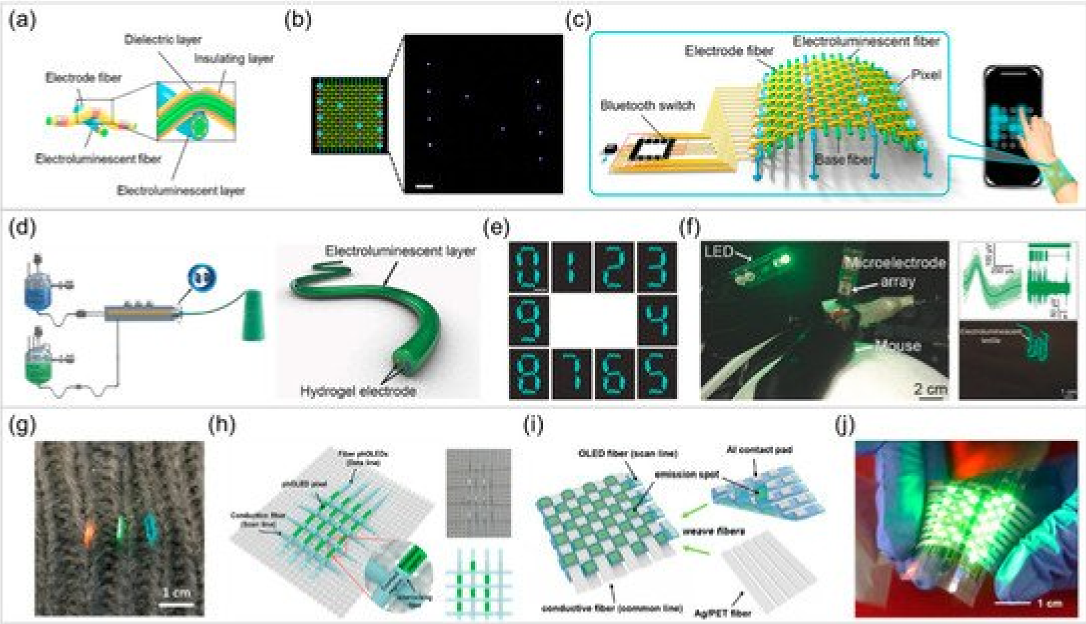

Figure 3. (**a**) Schematic illustration of a pixel structure in the electroluminescent fabric. (**b**) Schematic illustration and photograph of the electroluminescent fabric showing the pattern "N". (**c**) Schematic illustration of the smart electroluminescent fabric being functionalized by connecting Bluetooth. (**a**–**c**) Reproduced with permission Ref. [33]. Copyright 2021, American Chemical Society. (**d**) Schematics of the simultaneous extrusion process and the light-emitting fiber (**e**) Photograph of an electroluminescent textile displaying numbers from 0 to 9. (**f**) Photograph of the real-time brain-interfaced camouflage of the fiber under green illumination. (**d**–**f**) Reproduced with permission Ref. [34]. Copyright 2018, Wiley-VCH. (**g**) Photograph of the RGB fiber PELDs, which are woven into clothes. (**h**) Left: schematic illustration of the textile display and a magnified schematic showing the contact region, the emission region, and the interlocking fiber. Right: photograph of the resulting textile display, which is integrated into the textile, visualizing the letter information "A". (**g**,**h**) Reproduced with permission Ref. [31]. Copyright 2021, Wiley-VCH. (**i**) Schematic illustration of the woven OLED textile display consisting of orthogonally arranged arrays of interconnectable OLED fibers and conductive fibers. (**j**) Photograph of the working woven textile device comprising 10 × 10 fiber arrays by the passive matrix scheme. (**i**,**j**) Reproduced with permission Ref. [35]. Copyright 2021, American Chemical Society.

2.4. Energy-Harvesting/Storage Devices

Stiff and rigid batteries and energy harvesting devices hinder the development of wearable devices, which require flexibility [36]. Batteries with high capacity, a long-term cycling life, and energy-generating capabilities are also needed to build higher-level wearable electronic systems that include logic circuits [36]. Large-scale quantitative data transfer and computing consume a great deal of power. Therefore, it is important to develop deformable and durable energy harvesting/storage devices with high energy density. To meet the requirements of wearables, fibriform energy harvesting and storage devices have been demonstrated during the past decade. In this section, we describe recent efforts to develop fiber-shaped energy harvesting and storage devices.

Given that portable batteries have gradually become important in the wearable device industry, fiber-shaped batteries should have high capacities, long lifetimes, and excellent mechanical robustness. Recently, various shapes and materials have been used to realize fiber batteries. Both fiber-shaped lithium- and sodium-ion batteries with 3D interconnected hexagonal structures have been developed, using exclusive ion transport and efficient pseudocapacitive charge storage [37]. Li et al. developed a washable zinc-ion battery (ZIB) using double-helix yarn electrodes and a polyacrylamide electrolyte [38]. The yarn ZIB exhibits a high specific capacity (302 mAh g^{-1}) and volumetric energy density (54 mWh cm^{-1}), as well as excellent knittability and stretchability (up to 300% strain) [38]. Owing to its tailorable properties, long-yarn ZIB was woven into a textile that was used to power a flexible LED belt [38]. High-capacity aqueous zinc-ion battery fibers were also reported by Liao et al. (**Figure 4**a) [37]. The fibrous Zn-ion batteries, composed of V_6O_{13}/CNTs, can harvest energy from ambient air to recharge without an additional power supply (**Figure 4**b) [37]. The resulting battery fibers presented a high specific capacity (371 mAh g^{-1} at 200 mA g^{-1}), stable switching (>5000 cycles at 5 A g^{-1}) and recharging of ~60% upon exposure to air (**Figure 4**c) [37]. The self-charging battery fiber also acted as a strain sensor in an integrated wearable fingertip device (**Figure 4**d) [37].

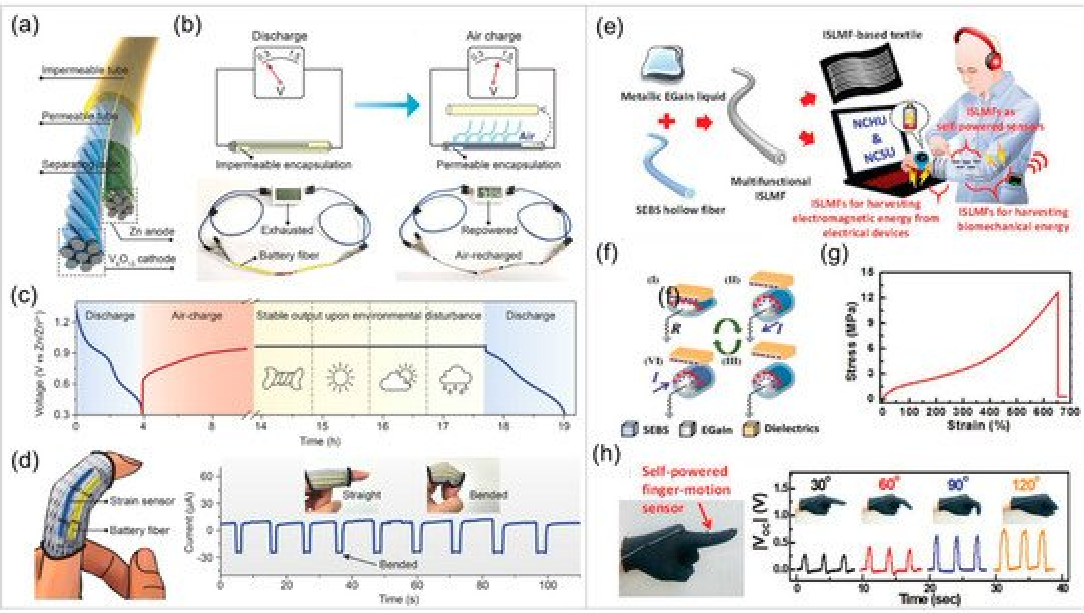

Figure 4. (**a**) Schematic of the double-layer-encapsulated Zn-ion battery fiber. (**b**) A thermometer powered by two air-rechargeable VCF/Zn battery fibers connected in series, shown in exhausted (left) and air-recharged (right) states, respectively. (**c**) The air-rechargeable VCF/Zn battery fiber presents stable voltage output under various environmental disturbances. (**d**) Left: schematic illustration of a strain sensor fiber powered by VCF/Zn battery fibers integrated in a flexible fingertip. Right: current-time curve of the strain sensor fiber upon the increasing bending cycle. (**a**–**d**) Reproduced with permission Ref. [37]. Copyright 2021, Royal Society of Chemistry. (**e**)

Schematics of the fabrication process of the fiber TENG and its uses in collecting ambient energy and self-powered sensing. (**f**) Schematic illustration of the working mechanism for collecting energy from human motion. (**g**) Stress–strain curve of the fiber TENG. (**h**) Left: photograph of the fiber TENG as a self-powered finger-motion sensor. Right: real-time outputs when a finger is bent at different angles. (**e**–**h**) Reproduced with permission Ref. [39]. Copyright 2021, Wiley-VCH.

For sustainable and self-sufficient use, energy harvesting technologies that can generate electric energy from the human body and its surroundings are required [40][41]. TENGs convert mechanical energy into electricity by triboelectrification and electrostatic induction. Wearable TENGs can collect low-frequency and irregular mechanical energy from body motion [39]. In previous research, fiber TENGs used thread-like metal wires, but those TENGs exhibited mechanical limitations such as low stretchability and elasticity. Although designing 2D or 3D textile architectures by knitting, weaving, or braiding different fiber TENGs can improve their deformability, the individual fibers remain mostly undeformed [39]. Lai et al. fabricated intrinsically stretchable fiber TENGs (>650% strain) that can harvest mechanical and electromagnetic energy (**Figure 5**e–g) [39]. Poly(styrene-b-(ethylene-co-butylene)-b-styrene) hollow elastomeric fibers filled with liquid metal EGaIn produced energy through triboelectricity (160 V m^{-1} and ~360 μW m^{-1}) and induced the electrification of the liquid metal (± 8 V m^{-1} at 60 Hz and ~8 μW m^{-1}) [39]. The fibers acted as textile power supplies and sensors self-powered by touch and motion (**Figure 5**h) [39].

To integrate various functions in a single fiber and realize versatile energy fibers, Han et al. fabricated a multifunctional coaxial energy fiber for energy generation, storage, and use [42]. The energy fiber comprises a fiber-shaped TENG, supercapacitor, and pressure sensor in a coaxial geometry [42]. Each energy unit showed a length-specific capacitance density of 13.42 mF cm^{-1}, stable charging/discharging cycling (~96.6% loss), maximum power generation of 2.5 μW, and good tactile sensitivity of 1.003 V kPa^{-1} (below 23 kPa) [42]. The demonstration of a soft and multifunctional energy fiber makes it an attractive option for human–machine interactive systems, intelligent robots, and smart tactile-sensing clothes [42].

3. Integrated Smart Electronic Textiles

Integrated wearable systems offer promising opportunities to continuously monitor a user's surrounding environment and health. Furthermore, they facilitate communication, external-environment sensing, and power generation and supply. Recent research has focused on combinations of processors, sensors, displays, and energy systems to provide more reliable and accurate information [27].

The fiber-shaped device structure provides attractive possibilities in electronics. For example, electronic fibers could be integrated into a single device that could convert human/environmental information into electrical signals and then process those data. When the electrical fiber components are woven together into e-textiles, they are connected in parallel or series to improve the output current and scale-down. Although 1D electronic devices output a limited current, an integrated system could maximize the electrical performance. The multi-functionalization and integration of 1D devices are required if e-textiles are to have broad applications. For instance, an integrated fiber-shaped supercapacitor and sensor could monitor the wearer's health and external environment without requiring an external power source. Accordingly, self-powered electronic devices have also attracted considerable attention due to their potential for application in wearable monitoring technology and personalized intelligent systems [43][44]. Two fiber-shaped devices could be twisted to produce a 1D electronic system and then integrated by connecting a common electrode to form a 2D configuration that can function as both an energy harvester and an electronic device. Such a design strategy represents one promising avenue for future electronics. Although other considerations, such as comfort and washability, are important for wearable electronics, the performance and function of integrated e-textiles is already advancing.

As a bridge to interaction in human-portable devices, display textiles offer a real-time communication function that could help reduce a user's difficulties in speech or speaking [34]. Recently, Shi et al. wove a large-area display textile based on electroluminescent units formed at the weft–warp contact points within the fabric (**Figure 6**a) [45]. The solution-processed luminescent warp and conductive weft fibers contained ZnS phosphor dispersed in an insulating polymer, and ionic-liquid-doped polyurethane gel, respectively [45]. A multifunctional integrated textile system was then demonstrated by weaving that display textile with a fiber-based keyboard and power supply (**Figure 6**b) [45]. This integrated e-textile showed useful communication and interactive navigation display functions (**Figure 6**c) [45]. Such smart textiles could be used as wearable communication tools in the future.

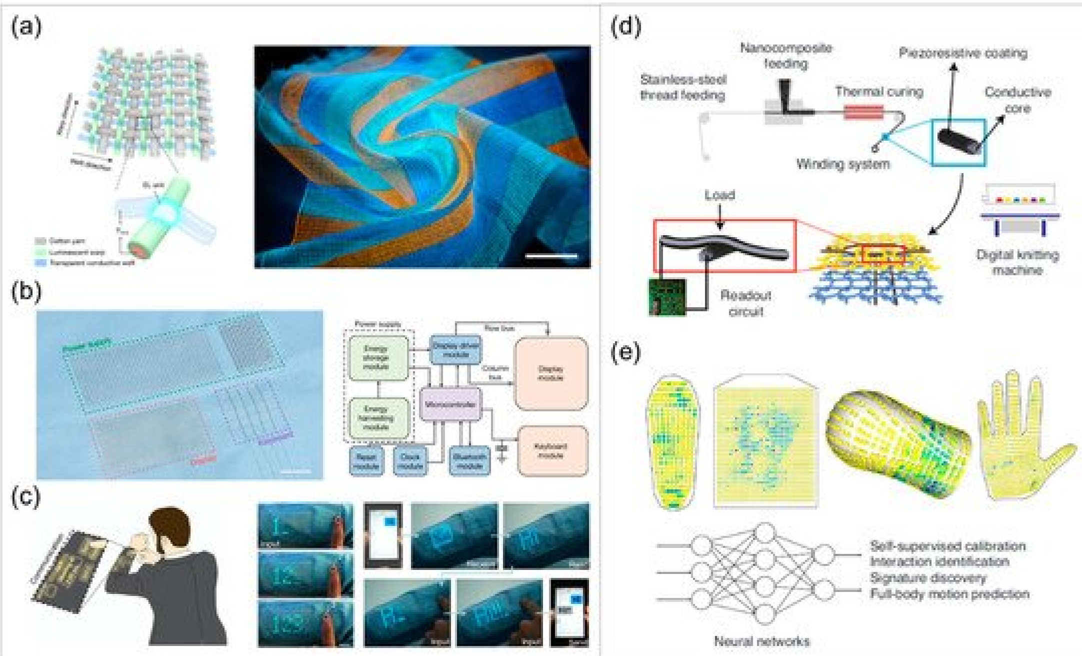

Figure 6. (**a**) Left: Schematic of the woven display textile. Each contacting luminescent warp and transparent conductive weft forms an EL unit (inset). Right: photograph of a multicolor display textile under complex deformations. (**b**) Left: photograph of an integrated textile system composed of display, information input, and power supply modules. Right: system-level block diagram of the integrated textile system (**c**) Left: conceptual illustration presents the idea that textiles integrated with a display and keyboard can be used as a communication platform. Middle: information is input onto the clothing by pressing the keys that are woven into the textile. Right: receiving and sending messages between the integrated textile system and a smartphone. (**a**–**c**) Reproduced with permission Ref. [45]. Copyright 2021, Springer Nature. (**d**) Schematic illustration of the scalable manufacturing of

tactile sensing textiles using a customized coaxial piezoresistive fiber fabrication system and digital machine knitting. A commercial conductive stainless-steel thread is coated with a piezoresistive nanocomposite. (**e**) Examples of tactile frames collected during human–environment interactions, and their applications explored using machine learning techniques. (**d**,**e**) Reproduced with permission Ref. [46]. Copyright 2021, Springer Nature.

Wearable sensory interfaces that can record, model, and understand human–environment interactions are important in the development of wearable healthcare and robotics. Luo et al. combined fiber-shaped sensors with machine learning to process and interpret a mass of tactile data [46]. The piezoresistive fibers comprised 3-ply stainless-steel threads coated with graphite nanoparticles, copper nanoparticles, and polydimethylsiloxane elastomer [46]. The functional fibers in a core-sheath structure could be woven into large-scale textiles using digital machine knitting (**Figure 6**d) [46]. To learn diverse human–environment interactions through tactile textiles, computational workflows based on AI have also been developed [46]. The AI-powered smart textiles can classify the sitting poses and motions of their human users (**Figure 6**e) [46]. The demonstration of tactile learning using a textile platform is expected to be applicable to cognitive science and the imitation learning of intelligent robots [46].

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