This is the peer reviewed version of the following article: Zeng, W., Shu, L., Li, Q., Chen, S., Wang, F. and Tao, X.-M. (2014), Fiber-Based Wearable Electronics: A Review of Materials, Fabrication, Devices, and Applications. Adv. Mater., 26: 5310-5336, which has been published in final form at https://doi.org/10.1002/adma.201400633.

Fiber-based Wearable Electronics: A Review of Materials, Fabrication, Devices and Applications

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Abstract

Fiber-based structures are highly desirable for wearable electronics that are expected to be light-weight, long-lasting, flexible, and conformable. Many fibrous structures have been manufactured by well-established lost-effective textile processing technologies, normally at ambient conditions. The advancement of nanotechnology has made it feasible to build electronic devices directly on the surface or inside of single fibers, which have typical thickness of several to tens microns. However, imparting electronic functions to porous, highly deformable and three-dimensional fiber assemblies and maintaining them during wear represent great challenges from both views of fundamental understanding and practical implementation. This article attempts to critically review the current state-of-arts with respect to materials, fabrication techniques, and structural design of devices as well as applications of the fiber-based wearable electronic products. In addition, this review elaborates the performance requirements of the fiber-based wearable electronic products, especially regarding the correlation among materials, fiber/textile structures and electronic as well as mechanical functionalities of fiber-based electronic devices. Finally, discussions will be presented regarding to limitations of current materials, fabrication techniques, devices concerning manufacturability and performance as well as scientific understanding that must be improved prior to their wide adoption.

1. Introduction

Next generation of wearable electronics demands the systems directly worn on soft and curved human body that is covered with highly extensible skins (with an average elongation from 3% to 55%). ADDIN EN.CITE [Fiber-based wearable electronic systems hold great promises. Fiber-based clothing systems have been made and used by humans for thousands of years as they are soft and deformable, breathable, durable and washable, thus ideal to be explored as the platforms for future wearable electronics.[1] On the other hand, the rapid development of nano-science and nano-technology in the recent decade has accelerated the miniaturization process of electronic devices. Now it is scientifically proven and technically feasible to build electronic functions on the surface or inside a fiber, which typically has an aspect ratio of over 50 with a thickness/diameter in the range from ~1 to 50 microns. Through well established and cost-effective textile production processes, these fibers are further converted into one-, two- and three-dimensional fiber assemblies, e.g. yarns, fabrics, spacer fabrics etc. The convergence of textiles technologies, electrical engineering and electronics, has the potential to combine the positive attributes of each technology, the speed and computational capacity of modern electronics, with the flexible, wearable, and continuous nature of fiber assemblies. The hierarchical nature (fiber - yarn - fabric - product, etc.) of these fibrous structures makes it particularly suitable for the fabrication of wearable electronics.[2]

These fiber assemblies possess many unique characteristics appropriate to wearable systems.

They have softness and flexibility to deform under small external force or their own weights with typical Young's modulus in the range from several MPas to KPas. They normally have large specific surface areas in the order of 10^{2-3} m^2/kg; various levels of porosity up to 99%; structurally defined fiber orientation and packing density. Furthermore, they own an outstanding ability to maintain structural integrity in wear and washing, typically over several millions of loading cycles in dry condition, and some 30 washing cycles according to AATCC standard. Mechanically, they can be stretched, twisted, bent or sheared thus exhibiting unique ability in three-dimensional drape. Thermally, their high porosity and large surface area allow much still air to be trapped as insulator in cold weather, and the porosity is also the route for hot air and water vapor to escape from the human body in hot climate. Breathability, as a major concern for the comfort of the electronic assemblies, is a basic requirement to long-term wrap comfortably around curvilinear human skins with millions of pores.[3] The outstanding fatigue resistance is due to the structures of the fiber assemblies. One of the two important contributing factors is that the induced strain in the fibers is very small even when a large deformation occurs and the fatigue life is exponentially linked to the internal strain. The other factor is the high damage tolerance offered by the fiber assemblies. Fiber assemblies are excellent crack arrestors. The large number of fibers in the assemblies prevents catastrophic failure of the structure. In the fiber assemblies, there is no similar crack propagation to that occurs in solid thin films and no catastrophic rapture upon failure.

In recent years, fibers or fiber assemblies (textile structures) with add-on or built-in electronic or photonic functionality has been an active area of research Fiber-based flexible electronics present exciting possibilities for flexible circuits,[4] interfacing computers/processors,[5] skin-like pressure sensors,[6] conformable radio-frequency identification tags[7] and other devices with the human body.[6a, 8] Examples of potential applications of this technology include military garment devices, biomedical and antimicrobial textiles, and personal electronics.[5a, 9] These research and development activities are primarily driven by the motivation of creating fiber assemblies that have functions of sensing, actuating, communicating and computing etc.[10] The potential for developing light-weight, flexible, and conformable electronic devices on textile products is very significant. Textile substrates offer tremendous opportunities to deploy sensors and other devices, built-in or embedded into the fabric-based network, to create large-area electrical and electronic systems.[11]

For the realization of the fiber-based wearable electronics, the most important consideration is the development of sustainable flexible systems which support high carrier mobility and good overall electrical performance, together with mechanical and environmental stability.[12] The search for fiber-building materials that can be used as active ingredients as well as fibrous substrates still continues in parallel with research in multiple physics of these intrinsically heterogeneous structures. Improved understanding in the material formation, integration, and processing has been advanced and derivation of such knowledge is a result from seamless collaboration of multiple disciplines.

This article reviews the current status of the fiber-based wearable electronics in a light of their future promise in the areas of healthcare, environmental monitoring, displays and human–machine interactivity, energy conversion, management and storage, and communication and wireless networks. It covers conductive materials and fabrication techniques, electronic components, devices and applications of fiber-based wearable electronics. An attempt will be made to review critically the numerous publications in the literature and discussions will also be presented regarding to limitations of current materials and devices with respect to manufacturability and practicality that must be resolved and improved prior to their wide adoption.

2. Conductive materials

One important consideration for fiber-based wearable electronics is the choice of materials used in fabrication and the possibility to confer the high carrier mobility and good overall electrical performance, together with desirable mechanical properties, safety and environmental stability into the flexible devices/systems. The following section will discuss some of the materials and fabrication technology frequently used to accomplish these goals.

2.1 Materials

The development of conductive or semi-conductive materials, which are flexible and soft, is essential for fiber-based wearable electronics because of their unique electronic, chemical and mechanical properties.[13] _ENREF_32 Materials like conductive polymers, metals and metal oxide nanoparticles/nanowires, carbon based micron/nano materials, such as carbon particles (CP), carbon nanotubes (CNTs), carbon fiber and graphene, have been used and investigated. These materials are promising for a variety of applications including flexible optical and electronic devices, and chemical and biological sensors.[14] Devices based made from fibers of such conducting materials typically exhibit enhanced electronic performance, such as higher field-effect, good mobility and steep subthreshold slope, leading to lower operating voltages V, an important consideration in low-power circuit design.

2.1.1 Conducting polymers

Ideally, if all the electronic functionalities could be realized in a fiber itself, such fibers would provide a perfect building material for smart apparel as they could be naturally integrated into textiles during weaving process.[15] Because of the technical complexity of integration of advanced electronic functionalities into a textile fiber, currently there are only few examples of such fibers. Perhaps the most promising materials are organic polymers or compounds of small molecules because they are intrinsically flexible or can be blended in fiber making composite materials. In addition, because they are synthesized from basic building blocks, they can be tuned to have specifically tailored chemical, physical, and electronic properties. Since the discovery that conjugated polymers can be made to conduct electricity through doping,[16] a tremendous amount of research work has been carried out in the field of conductive polymer fibers. These conducting polymers are of great scientific and technological importance because of their unique electronic, electrical, magnetic and optical properties. Nano-scaled π-conjugated organic molecules and polymers have been investigated for sensors, actuators, transistors, flexible electronic devices, and field emission display in the textiles system.[17] There are different routes to prepare fibers of various conducting polymers. Polyaniline nanofibers were prepared by polymerization of aniline.[18] Similarly polypyrrole nanofibers were synthesized (60–100 nm in diameter) in presence of p-hydroxy-azobenzene sulfonic acid as a functional dopant.[19] The fibers have a high conductivity (120–130 S/cm) at room temperature and a photoisomerization function that results from proton doping and isomerization of azobenzene moiety. In particular, poly-(3,4-ethylenedioxythiophene) (PEDOT) has been the most successful conducting polymer due to its high conductivity and solution processability and has being explored as electrodes for flexible and wearable capacitors or photodiodes.[20] However, films made from PEDOT, and other conducting polymers, tend to have a bluish tint, which limits their use in displays.[21] In addition, similarly to semiconducting polymers, stability issues have limited their use in wearable LEDs and solar cells.[22] Several groups have recently demonstrated all-fiber organic transistors which can potentially allow creation of electronic logic circuits by weaving.[23] Despite the great challenge of environmental instability, ongoing research continues to produce better electrically performing and more stable organic semiconductors and conductors towards the fabrication of practical flexible and stretchable electronic devices based on organic materials.

2.1.2 Carbon-based micro/nano materials

0-, 1- and 2-dimensional carbon-based micro/nano materials are promising for flexible and wearable electronics, both as the channel material in field-effect transistors and as transparent electrodes, due to their unique properties such as their high intrinsic carrier mobility (10^6 cm^2 V^{-1} S$^{-1)}$,electrical conductivities (10^4 S/cm) and superior mechanical properties (elastic modulus in the order of 1 TPa), environmental stability and the potential for production at low cost.[24] Porous carbon materials with a large specific surface area and mechanical properties have been frequently employed in wearable electronics, such as CP, CNTs, carbon fibers (including carbon microfibers and carbon nanofibers), graphene, carbon aerogels, et al. Among various carbon materials, CNTs and graphene are the two of the most intensively explored carbon allotropes in materials science, and also been evaluated as the electrode materials with great potential in wearable electronics.[25] Currently, electrodes based on these two well-known carbon materials have become a hot topic for high-performance flexible electronics. It has been demonstrated that commodity cotton threads can be transformed into smart electronic yarns and wearable fabric devices for monitoring of human vital signs using a polyelectrolyte-based coating with CNTs. A stretchable, porous, and conductive textile fabric has recently been invented by a simple "dipping and drying" process using a single-walled carbon nanotube (SWNT) ink.[26] The loading of pseudo capacitor materials into these conductive textiles can lead to a 24-fold increase of the areal capacitance of the device. Compared to CNTs and graphene, CP has been extensively employed because of its low cost, excellent health and safety performance, porous structure and ability to impart high electrical conductivity to an insulating polymer fiber or fiber based textile substrate. Further, these nanoporous conductive architectures can work as both a secondary current collector and an electrode, simultaneously enlarging the surface area and providing both nanoporous channels for low-resistant ion diffusion and nano-sized skeletons for fast electron transfer.[25] A key consideration for CNT-based wearable electronics is the use of individual CNTs versus networks of CNTs.[27] However, large-scale applications of individual CNTs have been limited by the difficulty in their structure control. As a solution, more and more attention has been paid to assemble CNTs into macroscopic fibers in which the CNTs are highly aligned to maintain high mechanical strength and electrical conductivity of individual CNTs.[27-28] The reported value of electrical conductivity of CNT fibers show significant discrepancy, which vary from < 10 to > 5000 S/cm.[29] The electrical conductivity of a pure CNT fiber depended on the electrical properties of the individual CNTs, the intertube contact resistance, and the applied temperature. Recently, Zhao et al. reported an electrical conductivity as high as 6.7×10^{8} S/cm for iodine-doped CNT fibers, which represents a new record for CNT fibers.[30] Considering all their desirable attributes, CNT fibers are anticipated to have a broad range of potential applications, such as fiber-based sensors, transmission lines, microelectrodes and solar cell. The carbon fibers have also been explored as electrode materials for flexible energy-storage because of the notable features including highly-exposed surface areas, high electrical conductivity, and good chemical stability. [31] Particularly, carbon fibers can be woven into various forms cloths. These fabric carbon fibers are outstanding substrates for wearable electronics, and usually combine with pseudocapacitive materials to enhance the energy density of the wearable capacitor.[25, 32]

2.1.3 Metallic nanoparticles /nanowires

Low dimensional nanostructures of metals, e.g. nanowires (NWs) or nanoparticles, are particularly attractive for fiber-based flexible and wearable electronics because they have very high conductivities.[4c, 33] For instance, Ni- and Au-plated Kevlar fibers can display electric conductivity values of 6 S/cm.[34] Silicone fibers filled with Ag flakes reach 470 S/ cm, whereas nylon fiber mats coated with Ag using a commercial electrodeless plating solution exceed ~1800 S/cm when loaded with ~17 wt % Ag.[35] However, the roughness, haze, and stability issues have hindered their emergence in industry. Ongoing efforts are being made on improving the stability of metallic nanowires/nanoparticles and utilizing them in flexibly electronic applications. A recent publication shows the promise of metallic NWs, as demonstrated in a novel all-fiber piezoelectric nanogenerator using a highly stretchable silver coated polyamide fabric as the elastic fabric electrodes.[36] The resultant generator exhibits a high durability (greater than 1,000,000 loading cycles) and good electric power generating performance in a cyclic compression test simulating human walking conditions. Compared to other metal foil or metal coated thin film electrodes, the three dimensional structure of the fabric electrodes provides much reliable electric contact and flexibility, which are critical for soft and wearable generators in which the electrodes are under a large number of deformation cycles.

2.1.4 Fiber-based electrodes

Fiber-based electrodes are light, durable, flexible, foldable and comfortable thus ideal for wearable electronics. They have been extensively studied for various wearable applications, ranging from dry surface bio-potential measurements like ECG, EMG and electric stimulation, electrodes for antenna, photovoltaic cells, electric power nanogenerators, batteries, capacitors, almost all sandwich-structured wearable electronic devices. Textile-structured electrodes like single fibers, yarns and fabrics have been developed and investigated. Some of them are made from CNTs, metals or metal alloys like copper, silver, nickel alloys, stainless steel; others are made from dielectric textiles by surface coating, plating, embroidery, printing, and lamination. Thus there are many hybrid or composite structures, including reduced graphene oxide/nylon yarn, [37] graphene-ferroelectric hybrid electrode,[38] functional coatings on yarn,[39] Poly(styrene- â-isobutylene- â-styrene)-poly(3-hexylthiophene) (SIBS-P3HT) conducting composite fibers,[40] Ag-silicone fibers,[41] fibers containing liquid metal alloy like eutectic gallium indium (EGaIn) injected into the core of stretchable hollow fibers composed of a triblock copolymer, SEBS resin (EGaIn in SEBS resin),[42] a conductive composite mat of silver nanoparticles and rubber fibers, [43] and twisted graphene yarns.[44]

Knitted fabric electrodes have played an important role in a highly durable electric-power generator. By incorporating silver coated polyamide multifilament yarns into elastic knitted fabric electrodes, by which a piezoelectric nonwoven fabric made from $NaNbO_3$ NWs and PVDF composite nanofibers is sandwiched, as shown in Figure 1. Such an all-fiber nanogenerator survives at least 1,000,000 compression cycles without failure.[45]

3. Fabrication technology

3.1 Fabrication Methods Fabrication methods play an important role in determining the characteristics, cost, and stability of the fiber-based flexible and wearable electronics. Generally, various approaches to make fiber-based flexible and wearable electronics can be grouped into two categories. In the first category, electronic devices are fabricated by using conducting fibers made from conductive polymer, metal, carbon, piezoelectric materials, or conventional fibers surface modified with various functional materials.[46] A number of e-textile research groups have focused on conductive threads or yarns to integrate electronics into fabrics.[47] Researchers from Massachusetts Institute of Technology (MIT) and Virginia Tech studied woven metallic organza or piezoelectric materials for the fabric keyboard and music jackets.[47b, 47c] Cottet studied electrical characteristics of polyester yarns that are twisted with a copper (Cu) fiber.[47d] Examples also include the work published by our group, X - Y grids of copper wires were integrated into woven textiles to form interconnect lines.[48] Locher proposed a conducting band interconnection technology between textiles and electronics.[49] . The fiber-based approach has resulted in excellent wearable properties that mimic regular textiles and withstand mechanic deformations like bending, twisting, and stretching.

The second category, which is complementary to the first one, is based on embedding off-the-shelf miniature or thin-film-based electronic components like transducers etc. onto conventional dielectric fabrics as a motherboard or imparting electronic functions on the surface of fabrics by coating or printing or lamination. However, the flexibility or comfort of the fabric may be compromised if the attached components are rigid. Despite substantial improvements over rigid devices, many of current flexible e-textiles cannot fully conform to their surroundings, due to the inability of large elongation in metals and conductive polymers.[50] Further, to maintain essential textile properties such as durability, it is more desirable to integrate electronic functions at the fiber level, however, most of the current work are limited to a single functionality. Except the excellent conductivity, other properties of the flexible conductor are same or similar with the common fibers/yarns and can be easily woven or knitted with common yarn together into a new electrical functional fabric that possesses wearability, process-ability, and flexibility. The stretchable conductors can be knitted or woven with other common yarns into an electric functioned fabric to form designed electric circuit. The electric functioned fabric with embedded (woven or knitted) electric circuit forming the basic grid is the essential materials for e-textiles. A method of combining thin-film flexible electronic devices has been reported at fiber level including sensors and transistors, interconnect lines, and commercial integrated circuits with plastic fibers that can be woven into textiles using a commercial manufacturing process.[51] To weave the flexible and wearable electronics, the electronic fibers are woven the weft direction of a woven fabric by a commercial band weaving machine. This method creates a platform to integrate a large variety of flexible electronic circuits, sensors, and systems on fibers intimately within textile architectures using a commercial manufacturing route.

3.2 Surface mounting technology

Integration of electronic functions within fabrics, with production methods fully compatible with textiles, is therefore of some interest.[52] Surface mounting technology used in electronic industry has its direct sister in textile industry, that is, lamination technology. The thin-film based devices can be attached onto conventional textile fabrics by thermoplastic adhesives. Apart from that, for the fabrication of free standing electronic devices directly on textile substrates, three technologies, i.e. screen printing, digital printing and dip-coating, have been developed to fabricate solution processable wearable devices in textile substrate. One key advantage of these methods is that they facilitate the use of low-cost patterning techniques at room condition. Screen printing screen providing an easily adopted fabrication route for fabrication of wearable electronics, all the layers with different functions are printed on top of the fabric substrate through a layer-by-layer process as shown in Figure 1. This process does not need extra photolithographic and chemical etching processes as each structural pattern is directly defined with every layer application.[53] In addition, screen printing is also compatible with industrial roll-to-roll processes, offering a route to high volume batch fabrication. Our previous work reported a fabric strain sensor screen-printed with activated carbon. Since the conductive pattern is incorporated within the textile, it ensures that sensors are repeatedly positioned in the same location on the body.[6b, 54] This will lead to improved accuracy of the sensor by preventing sensor misplacement. Textile energy storage devices were made by screen printing activated carbon paint onto custom knitted fabrics.[31c] The screen printing technique offers a high areal mass loading while retaining the high intrinsic capacitance of activated carbon. The fabric surfaces normally have a roughness in the order of 10 microns. However, the surface roughness can be greatly improved to the required level for device interfaces by controlled multiple-coating techniques. Further, the screen printing method has excellent applicability on any irregular textile surface that can offers significantly more design freedom and placement capability on fabrics than other methods like weaving and knitting. Screen printed devices have been reported with Figure 2 demonstrating a typical fabrication process for cantilever MEM devices on fabrics.[55]

Compared to the screen printing technology, digital printing technology has the advantage of high spatial precision of ink droplet. Combined with inkjet printing provides an exciting opportunity to apply on-demand material deposition and desktop programmable wiring of designed patterns. The latter has already been demonstrated for metal, CNT and graphene-based inks.[56] In addition, piezoelectric, piezoresistive and capacitive elements also can be developed by digital printing technology for detecting deformation of a fabric.[57] Dip-coating is another possible technique. Conductive yarns were made by dip-coating PVA/CNT on a polyamide yarn.[58] This technique depends greatly on the surface morphology and surface tension of the textile substrate, which can also vary from section to section and may result in non-uniform coatings.[59]

3.3 Conductive nano-coating technologies

Conductive nano-coating technologies are another effective approach to integrate electronic functions within fabrics and improve the performance and functionality of wearable electronics.[60] An appropriate coating technology should impart the desired functionalities and/or provide a suitable interface layer for high durability.[61] Without careful surface engineering, coated textiles by simply adding various properties would not survive during washing and wearing. Surface modification of the fibers is essential to introduce strong surface interactions like covalent or ionic bonds. Due to the large surface area-to-volume ratio and high surface energy of nanomaterials, conductive coating with discrete molecules or conductive nanomaterials can bring individually to designated sites on textile materials in a specific orientation and trajectory through thermodynamic, electrostatic or other methods. A number of approaches have been studied, including thermal and chemical vapour deposition,[62] chemical reduction,[63] electrochemical deposition,[64] pulsed laser deposition.[65] The key consideration is if one can apply durable nano-scaled coatings to textiles in a cost-effective manner while satisfying the requirement of electronic functions. In this regard, low-cost and low-temperature processes without vacuum environment are preferred.

3.4 Self-organizing technologies

Some novel methods by material self-organization[66] have been reported to made fiber-based devices. For example, a fiber-based micro-supercapacitor (SC) have been recently reported using piezoelectric ZnO NWs grown radially around fibers.[67] These fiber SCs comprise two fiber electrodes. Both fibers are covered with arrays of high quality ZnO NWs grown by the hydrothermal method with one-step self-aligned dimensions. Other inorganic semiconducting NWs include Si,[68] GaAs,[69] GaN,[70] Ge[71] due to their flexibility and electronic performance. However, one may ask how well the process of self-organization, assembly, and processing can be controlled at scalable production level to achieve reproducible material properties, especially, when the mechanisms remain elusive and most work are of empirical nature at the present.

4. E-Components, Devices and Applications

Fiber-based wearable electronic devices demand simultaneous achievements of electronic functions and robust mechanical properties.[72] This section presents some representative structures for various fiber-based wearable devices, ranging from a single nano-, or micro-fiber/wire to multiple fiber-level components, [73] _ENREF_110 or from yarn integrated textiles to building blocks on fiber assemblies, with detailed investigation into their corresponding electrical stability under different mechanical deformations, particularly in bending and extension modes. [72, 74] _ENREF_108

4.1 E-Textile Components

4.1.1 Fiber Transistors

The reported fiber transistors can be divided into two categories: fiber organic field-effect transistors (OFET)[75],[76],[77] and wire electrochemical transistors (WECT),[52, 78] as shown in Figure 3. The former used a fiber-based four-layered cylindrical thin film structures,[78b] with insulating materials of either inorganic oxides (i.e., SiO_2) or polymer dielectrics (such as poly-4-vinylphenol (PVP), [76]~10nF/cm^2),[78d] and conducting materials for gates and contacts of metals and conducting polymers (such as aluminum and stainless steel wires, PDOT/PSS). [75,76] Highly ordered single polymer fibers (CDT-BTZ donor-acceptor copolymer single fiber[77a]) were also adopted. WECT was fabricated by suspending two PDOT/PSS coated fibers in a cross geometry and creating an ionic contact by adding an insulating layer/drop of the liquid or gel electrolyte (>10μF/cm^2) at the junction of fibers.[52, 78d] A comparison of the performance between the two kinds of fiber transistors is given in Table 1. Some studies have followed up to fabricate organic electrochemical transistors with a high trans-conductance for bio-sensing applications[79] or to use single cotton fiber for liquid electrolyte saline sensing.[23d] A fiber-based organic electrolyte-gated thin-film transistor based on poly(3-hexylthiophene) (P3HT) and imidazolium ionic liquids was presented, which was able to operate in both field-effect and electrochemical operation modes, and enabled both delivery of large currents or high speeds (<1kHz) at low voltages.[78b]

As a fiber OFET requires precisely positioning and fibers with extremely smooth surfaces due to its sensitivity to the gate insulator thickness, the channel length, and the smoothness of the substrate surface (for prevention of short circuits) ,[80] WECT has more practical significance because of its slight affections by the local geometry and relative ease of manufacture.[80-81] The major drawback of WECT is the long response time and the consequent low switching frequency resulting from the electrodiffusion of ions within the solid electrolyte where the ionic charge carriers have very low mobility.[78a] To break the frequency limitation of WECT would be a very important work in the future as the fiber transistors are basic building blocks of more complicated fiber based electronics that are expected not only confined to quasi-static applications. One possible way is the dimensional scaling, for example, making the on-fiber PDOT:PSS channel thinner (de-doping it requires a smaller number of ions[79]), as the time characteristics of electrodiffusion processes scale with the inverse square of characteristic lengths.[78a] Another direction is the synthesis of new materials, especially the conducting polymers with a higher capacity for storing charge (which is also the focus of present research on batteries and electrochemical capacitors[82]), and further studies of the mechanisms of ion transport in conducting polymers.[79, 83] Besides, exploring ionic liquids and gels that enable higher voltage operations has the potential for the achievement of higher performances. [79, 84]

4.1.2 Fabric Antenna

The vast majority of the research work on fabric antennas in literatures is relevant to patch antennas (rectangular micro-strip antennas) due to their advantages of miniaturization, ease of integration, and good radiation directions. Some typical fabric patch antennas are given in Figure 4, which have upper and lower conductive layers of antenna patch and ground plane and a middle layer of dielectric substrate.[85] Salvado presented a detailed survey of textile materials for wearable antennas,[86] based on which we further examined the studies with reported good antenna performances and traced some recent work, which are summarized in Table 2. Transmission lines for high frequency transmission are necessary for antennas, where woven fabrics with metal fibers, [47d] and embroidered conductive metal-polymer fibers on polymer-ceramic composites [87] are good candidates. Detailed examination was given [88] on the effects of conductive wire types and density, knitted patterns and weave patterns, effective electrical conductivity of the conductive fabrics. The dielectric properties of nonconductive fabrics and the high frequency characterization of the electro-textile materials were also included.

Apart from those reported relative rigid textile patch antennas, another group of stretchable antennas were developed,[4c] made from conductive nano-materials and elastomeric fibers. The effects of washing, long-term ambient storage, temperature and humidity, oxidation, wear in the modes of stretching, bending and folding as well as scratching on textile antennas deserves further studies.

These antennas have been placed in the front, back, or shoulders of the garment. [91] [90a] [92] For application of healthcare, pervasive computing, and wearable personal usage, they offer the possibility of the ubiquitous wireless transmission.[86]

Fabric antenna needs both conductive and dielectric fabrics. The conductive fabrics should meet the requirement of low sheet resistivity ($\leq 1\Omega$/square), homogeneous resistivity distribution over the area, satisfactory flexibility and stretchability.[85] Coated fabrics might perform worse than the fabrics made entirely of conductive fibers, due to discontinuousness that may increase the resistivity, and woven structure is better than knitted one because of its higher geometrical accuracy.[86] Highly conductive fibers and fabrics with outstanding flexibility and stretchability, as well as superior stability of the resistivity and resistivity distribution under extreme mechanical deformation during their assemblage and wearing, are worthy of further studies, not only for conductive layers of the fabric antenna, but also in great need by SCs in wearable energy storage.[93] As for the dielectric fabrics, whose dielectric constant and thickness determine the bandwidth and efficiency performance of a planar microstrip antenna, the major problems are due to the change of dielectric properties due to the moisture absorption of fibers and the thickness change in the elongation, bending, or compressing.[86] Therefore materials with small moisture absorption (regain less than 3%) and suitable for manufacturing of fibers and yarns are preferable for use as substrates and also as conductive components of the antenna,[86] and some materials or structures that can maintain or recover the thickness in mechanical deformation can be further studied to guarantee of a stable fabric antenna.

4.1.3 Electric connector

Connectors provide reliable electric connections between other electronic devices. In wearable electronics, the easy approach is to make largely deformable connectors thus the rigid islands of miniature devices can be linked by stretchable electric connectors as comparing to that make stretchable electronic devices. Three types of approaches will be reviewed in this section. The first approach relies on the development of new stretchable and elastic conductive materials,[94] such as (1) graphene elastomeric composites[95]: graphenes in polydimethylsiloxane (PDMS)[96] or well controlled graphene on PDMS substrates,[97] (2) carbon nanotube elastic materials: SWNT elastic conductor,[98] MWNT/Ag composites in a polystyrene-polyisoprene-polystyrene matrix,[99] and heavily-twisted carbon nanotube ropes,[100] (3) organic elastomer-like conductor based on polyaniline (PANI) conducting polymer,[101] and (4) PEDOT:PSS/PDMS composites,[102] (5) (liquid) metal films or particles (e.g. eutectic gallium indium,[103] gold[104] or silver[105]) in/on elastomeric membranes or fibers. Those organic elastic conductors normally have an electric resistivity in the order of KΩ cm thus do not have sufficient conductivity to work as elastic connecting wires in integrated circuits.[105] However, electric connectors with metal composite can achieve the required conductivity. Noticeably, the conductivity of these composite materials often drops by several orders with applied strains, even within 10%.[101]

The second type of approaches makes stretchable connectors from established brittle and rigid inorganic materials [94, 106] by structural conversion. Examples include (1) planar tortuous wires on elastomeric substrates,[107] such as net-shaped structure,[96, 108]and horseshoe patterns on polyurethane substrate[109]); (2) controlled 3D coil (helical) spring of silicon NWs (diameter: ~30nm) in PDMS substrate (thickness: ~2mm);[106] and (3) a series of out-of-planar controlled wrinkles,[110] such as fully bonded wavy shapes,[111] non coplanar "arc-shaped" mesh[112] and serpentine patterns,[113] of an ultrathin stiff single crystalline silicon on a compliant elastomeric substrate.[114] Such connectors with precisely controlled buckles, created either by the mismatch in thermal expansion coefficients[115] or the pre-stretching and releasing the strain of the substrate,[116] yield various stretchability by changing their wavelength and amplitudes.[117] However, well controlled formation of the wrinkles, similar to those on human skins,[118] require a considerable difference in Young's modulus and thickness between the stiff element (like dermis) and the compliant substrate (like epidermis).[4a, 118-119] For an ultrathin single crystalline semiconductor (thickness: ~20-50nm, Young's modulus: ~130GPa), it needs at least a 1-mm-thick PDMS substrate with ~2MPa Young's modulus.[120] Therefore, the substrate and further encapsulation layer have to be much thicker than the stiff element,[121] limiting the flexibility[113a] of the stretchable connector (since the bending rigidity is proportional to the fourth order of magnitude of the thickness).[122] In addition, local delamination of the stiff element from the compliant substrate,[94, 122] caused by a high concentration of stresses in the crest and the trough,[123] results in cohesive and adhesive fracture, leading to short circuits and limiting the stretchability.[109]

The third type of connectors is based on elastic textile structures, some of which are known highly stretchable and three-dimensionally deformable. Conductive metal wires have been integrated into woven fabrics to create textile circuits;[47d, 124] metal films have been deposited on nonwoven substrates for stretchable interconnects. However, their maximum elongation is limited within 20-30% strain due to the intrinsic geometrical structures of woven[124] and nonwoven textiles. Unlike woven and nonwoven textiles, knitted fabrics interlace yarns in a series of connected loops, and the column and row directions of the loop are referred to as wale and course, respectively. [125] Many knitted fabrics, in comparison to woven and nonwoven fabrics, are much more stretchable (usually more than 100% strain) due to its looped configurations, thus suitable for intimate or next-to-skin wearable electronic systems.

A benchmark analysis is presented for all the three types of electric connectors, their stretchability and corresponding relative change in electrical resistance are summarized in Figure 5(a) and (b). The stretchability has been advanced by means of either structural conversion or new materials from ~3% (SiNW on PDMS substrate[126]) to more than ~400% (wrinkled graphene on PDMS substrate [97]). The relative change in electrical resistance, whereas, varies from ~2.1% (Horseshoe pattern on PDMS substrate [127]) to ~7300% (Ag-MWNT-SIS nano-composite film[99]) with applied strain. This change in resistance may hinder their use as connectors for integrated circuits, in particular, for a high-precision measurement purpose.[105, 128] In contrast, the 3D looped metal fibers in the knitted substrate have exhibited an extraordinarily electrical integrity with almost no change (0.25%) in electrical resistance when uni-directionally stretched 300% in either course or wale direction and three-dimensionally punched by a ball with an average strain of 150%.[129]

For wearable electronics, the fatigue resistance of an electronic system is of vital importance. Here, the fatigue resistance refers to the ability to maintain its electronic functions and mechanical integrity in repeated loading-unloading cycles. For instance, 100,000 or 1 million such cycles are roughly equivalent to continuous wear in active daily life for 10 or 100 days, , respectively. Figure 6 plots the fatigue life at a certain strain and its corresponding relative change in electrical resistance of various previously reported works. The fatigue life varies from 50 cycles at 10% strain with electrical integrity (AgNWs in the PDMS substrate[131]) to 25,000 cycles at 20% strain with 300% relative change in electrical resistance (micro-cracked pattern [135]). The reported low fatigue resistance with significant change in electrical resistance may prevent them from wearable applications. In contrast, when subject to a cyclic uni-directional tensile test at a maximum fabric strain of 60% in the course direction, the fabric connectors with 3D looped metal fibers in the knitted substrate maintain their electrical function and mechanical integrity over 100,000 loading-unloading cycles up to 60% fabric strain, during which the electrical resistance remains almost unchanged (0.09%). This outstanding performance is owing to the structural conversion, that is, the mitigation in the local strain of the metal fibers when they are interlaced with the porous elastic substrate, which has been experimentally confirmed by Raman Spectroscope.[136]

4.1.1 Fiber-based circuitry

Printed electronics using inkjets or classical printing methods has considerable potential to deliver fabric circuitry. An alternative technology is weaving of conductive fibers. Figure 7 demonstrates some reported fiber-based circuitry, such as logic circuits constructed from WECTs,[78a,52] textile inverters made by weaving WECTs or fibers with TFT stack on them,[78d,137] fabric-array memory device.[138] Among them, due to the limitations of WECTs, this type of fabric inverters as well as logic circuits with a very long switch time (15-18 seconds) by using Kevlar multifilament with coatings of PEDOT:PSS and BCB35, as well as electrolyte gel,[78d] which limited them to quasi-static applications. The fabric inverters using TFT fibers (SiN_x coated Kapton fibers with amorphous silicon TFTs fabricated on top) [137] have overcome this problem, as it adopts conventional TFTs on fibers to obtain good performance. The fiber-based memory uses a high tellurium-content chalcogenide glass (GGT and GAST glass fiber), contacted by metallic electrodes internal to the fiber structure to achieve a difference with four orders of magnitudes between its on and off states, while it demonstrated a temperature dependence of the threshold voltage.[138] Fabric circuitry has advantages of better integration within textiles for a wide range of wearable applications. However, its development depends on innovations of fiber electrical components especially fiber transistors, and technologies of integrating E-textile or conventional components onto fibers and fabrics.

The major challenge of the fabric circuitry is the lack of basic fiber electronic element with stable performance and outstanding flexibility due to the following two reasons. 1) The low carrier mobility of organic materials limits the development of the fiber transistors, which is also the bottleneck of organic electronics. [80] New fibrous materials with high mobility are worthwhile for search and study. 2) Highly conductive fibers and fabrics with outstanding flexibility and stretchability are still far below the requirements of wearable large-scale E-textile circuits, as they are the essential conductive parts of the fabric antenna, wearable electronic connector and SC for wearable energy storage. The recent developed graphene fibers,[139] PEDOT:PSS fibers[140] and others may have potentials to address this problem. Another challenge is relevant to the packaging, integration and connection of E-textile components with other fabric and electronic parts. These packages and connections should be flexible as well as robust, which can sustain the friction, deformation and environmental change during the assemblage and daily wearing. However in many practical applications, failure of these package and connections has been reported, like cracking of fiber electronics resulting from poor elongation and bending properties,[80] or connection failure in harsh environments.[141] To go further, the e-textile connectors are expected to provide both robust mechanical and electrical connections, to enhance the overall robustness of the fiber based electronics.

4.2. Sensors and Sensing Networks

Among all fiber-based electronic technologies, the most mature and successful one is the fabric-based sensors, many of which have been not only demonstrated as prototypes reported in papers but also widely used in real applications of wearable sensing and personal protection. Fiber-based sensors include strain sensors, [6b, 54, 142] pressure sensors, [6b, 21, 142h, 143] chemical sensors,[144] as well as optical and humidity sensors [145] etc. Table 3-5 presents a comparison of typical fiber-based sensing techniques, and the typical fiber based sensor and sensing networks present in Figure 8.

Fibers or fibrous materials may acquire their sensing capability via conductive materials printed onto fibers or fabrics. These conductive materials include polypyrrole (PPy), CNT, CP, etc. PPy was first printed onto Lycra/cotton fabrics and resistive fabric strain sensors were made,[142a, 142b] which could realize the detection of human body posture and gesture. Improved PPy fabric strain sensors can have a gauge factor ~80 for a strain of 50%. [142c] Nevertheless, they suffer from poor stability and durability. Carbon nanotubes, due to its piezoresistivity, can either be printed onto cotton fabrics [142d] or spun into yarns [142e] for strain sensing purpose. Cotton fabrics coated with CNT can also work as gas sensors.[142d] However, for CNT including both single wall carbon nanotubes and multiwall carbon nanotubes, the pulmonary toxicity poses potential occupational and environmental health risks when used in soft wearable devices.[146] Non-conductive elastomers doped with conductive fillers also exhibit piezoresistivity. Therefore, composites of carbon particles (CP) and thermoplastic elastomers (TPE) were printed onto woven [142f] and knitted fabrics [142g, 147] for strain measurement. CP/TPE composites fabric strain sensors can measure a strain of 80% after being washed several times in conventional washing machines.[142g] Most of the above sensors suffer from deterioration in performance after a prolonged period of wearing or repeated cycles of tensile deformation. It is worth noting that, to date, the most mature fabric strain sensors in terms of a balanced sensitivity and durability, are stable (repeatability ±5% FSO, full-scale output) in measuring strains up to 50% even after 100,000 loading cycles.[6b] These sensors, which have a coating of composites comprising CP, PDMS and silicone oil on a knitted fabric,[54] have been deployed in the development of fabric pressure sensors [6b, 142h] and further i-Shoe,[142i] a foot pressure mapping system which can give spatial and temporal plantar pressure distributions in most daily activities. The type of strain sensors has a strong strain rate effect thus the gauge factor needs to be experimentally corrected when they are used in medium to high-speed dynamic measurement. Lastly, fabric strain gauges made from carbon fibers or metal fibers can measure large strains under high temperatures.[142j] Also, highly sensitive strain sensor can be made using two interlocked arrays of high-aspect-ratio Pt-coated polymeric nanofibres supported on thin PDMS layers.[142k] This type of sensor can detect strain, pressure, shear and torsion. Its flexibility and durability as a sensor, however, are limited.

Similarly, fiber-based pressure sensors deployed various transduction techniques including capacitive, [21, 143a, 143b] piezoresistive, [6b, 142h, 143c-e, 148] piezoelectric [143f, 143g] and optical types.[143h] Capacitive fabric pressure sensors comprise embroidered electrodes from conductive yarns and spacer fabrics between them. With a pressure measuring range from 0 to 100 kPa, they can be used to detect muscle activity [143a] and sitting posture.[21] There are also fabric sensors by measuring the capacitance at the crossed points of warp and weft conductive yarns.[143b] Apart from the parasitic capacitance and cross-talk between sensor units, these capacitive sensors always require complex reading out circuitry. Piezoresistivity of CNT has also been widely deployed in pressure sensors regardless of the toxicity or potential hazards.[146] CNT has been imbedded into polymer bumps [143c] or membranes [143d, 143e, 148] for pressure measurement. Elastic films with CNT [143e] can be both stretchable and optically transparent, and can behave both as strain and pressure sensors, which may help to realize artificial skins. CNT pressure sensors can achieve an ultrahigh sensitivity: when uniform silk molded PDMS films and SWNT ultrathin films are combined,[148] the sensors have demonstrated sensitivity of 1.80 kPa^{-1}, low detectable pressure limit at 0.6 Pa, fast response time within 10 ms, as well as excellent stability over 67 500 cycles for minute pressure detection. Piezoelectricity of Polyvinylidene fluoride (PVDF) has also been utilized in pressure sensing.[143f, 143g] _ENREF_23 PVDF nanofibers are electro-spun into PVDF fabrics for force measurement.[143f] Another device using poly(vinylidenefluoride-co-trifluoroethylene), or P(VDF-TrFe), has pushed fiber-based pressure sensors to an extreme: a minute pressure of 0.1 Pa can be detected.[143g] Such super-sensitive pressure sensor is based on highly aligned arrays of electrospun nanofibers of PVDF. The preferentially orientated nanofibers of polymer chains of P(VDF-TrFe) were electro-spun with a sub-cm collector disk rotating at 4 000 r.p.m. Such high orientation of nanofibers offers exceptional piezoelectric characteristics. The other extreme of fiber-based pressure sensors is towards high pressure measurement. One typical example is a resistive pressure sensor with a fabric strain sensor mounted on a PDMS cylinder.[142h] This kind of pressure sensor merits a large workable pressure range of 0-8 MPa, a high sensitivity at 1 MPa^{-1} and an excellent repeatability (lowest non-repeatability 2.4% from 0.8 to 8 MPa), which make it possible to measure pressure on soft materials in medium speed impact such as car collision. Currently the strain rate effect of such pressure sensor is being under investigation as discussed in previous fabric strain sensor section. Optical pressure sensors work by detecting light intensity[143h] or use the modulation of wavelength to detect pressure.[143i, 143j, 149] One recent example of this type is a soft fiber optic tactile sensor based on polymer fiber Bragg gratings,[143j] in which two polymer optical fibers (one horizontal and one tilted) are imbedded in a PDMS cube. Sensitivities for normal and shear stress pressures are 0.8 pm/Pa and 1.3 pm/Pa, and the full range is 2.4 kPa and 0.6 kPa respectively. This optical fiber pressure sensors merit high precision within a low pressure range and MRI immunity. But the light souse and detecting device are complicated and costly when compared with the resistive fiber-based pressure sensors.

Apart from strain and pressure sensors, fiber-based materials can also function as chemical sensors using PPy,[144a, 144b] carbon nanotubes [144c-f] _ENREF_27 or photonic methods.[144g, 144h] PPy and CNT have been printed onto fibers or yarns,[144a, 144b, 144d, 144e] electrospun, [144c] or mixed into polyurethane [144f] for chemical sensing including chloroform, THF, ether, NH_3, glucose, albumin. An ideal chemical sensor is sensitive to one particular chemical and immune or at least less sensitive to the others. However, many of the above sensors are sensitive to several chemical stimuli including humidity rather than one specific chemical, which poses great difficulty in real application.

Fabric sensing arrays and networks especially resistive ones, usually use readout and processing approaches with the assistance of transistors and multiplexors, or through electrical impedance tomography.[46a, 142b] _ENREF_39 This inevitably induces a noticeable complexity in circuits and operations, especially for large-scale sensor arrays and networks, because they require considerable numbers of additional electrical components (transistors, diodes, multiplexers, switches, op-amps, current sources, A/D converters, etc.), and a large number of signal processing cycles. On the other hand, measurement errors will be enlarged if there are crosstalk currents, unexpected resistances and leakages of additional electrical components, or mechanical crosstalk interferences. Currently, the bottleneck lies in the high energy consumption in supporting hundreds or thousands of sensors, signal transmissions and the back-end signal processing.

4.3 Wearable Energy Harvesting and Storage

Future generations of wearable electronic systems place a great demand for harvesting energy from the ambient environment or human movement rather than relying on a rechargeable battery power supply.[36] Harvesting energy from environments or human movement is both attractive and technically feasible for wearable electronics. There are vast bodies of reported work on this topic. However, only recently, more sophisticated fiber-based energy conversion and storage units have been reported.

4.3.1 Wearable energy convertors

Solar, mechanical and thermal energy can be scavenged from the environment using devices that were fabricated using flexible fiber or textile materials. For example, metal such as copper and steel or polymer fibers coated with a conductive layer of ITO are usually used as the fiber-shaped photovoltaic device.[152] Zou et al. used a titanium fiber to prepare a fiber-shaped solar cell, the photoelectric conversion efficiency of the fiber-shaped solar cell can increased to 5.41% as compared with that made from a stainless steel fiber.[153] However, the performances of photovoltaic devices are much lower than expected due to the limited flexibility and low stability of electrodes.[154] Thus new fiber electrode materials are highly desired to improve the performance of fiber-based photovoltaic device. Recently, a superior performance of the CNTs fiber-based solar cells have been reported [28c, 152a, 152b, 154-155] by twisted fiber-like electrodes have been used for harvesting solar energy as shown in Figure 9. Significantly, Fe_3O_4 Fe_3O_4/CNT composite fiber based photovoltaic device exhibits a record energy conversion efficiency of 8.03% in fiber-shaped devices.[155c] These fiber-based devices are three dimensionally deformable, while thin-film based ones can drape in one direction. Furthermore they have a much higher level of damage tolerance and fatigue resistance than those made from thin films. Further, these photovoltaic wires can be easily integrated into textiles or other deformable structures through a conventional weaving technique for making flexible, scalable, large-area power supply electronics in the form of woven fabrics or mats.

Apart from batteries and photovoltaic devices, an alternative route is to convert mechanical energy from human movement (such as body movement, muscle stretching, blood pressure) or vibration into electric energy, which may be sufficient for self-powering nano-devices and nano-systems ranging from biomedical sensors, nanorobots, micro-electromechanical systems (MEMS), and even small personal electronics (Figure 10).[156] The synergy between nanotechnology and soft polymeric materials has yielded drastic advancements in nanogenerators, which are mainly related to piezoelectric and triboelectric effects. By the end of 2013, the maximum areal density of harvested energy has reached 0.78 W/cm^2 for piezoelectric nanogenerators and 313 W/m^2 for triboelectric nanogenerators.

Figure 10 shows the available power associated with everyday activities for a 150 lb (68 kg) adult, most of which are lost in the forms of heat and vibrations. They can be recovered for generating electric power. For example, the heel strike from walking is a particularly rich source with 67W of power available from a brisk walker. Harvesting even 1–5% of that power would be sufficient to run many body-worn devices.[157]

Triboelectric effect, also known as contact electrification or triboelectric charging is a contact-induced electrification and the surfaces will be charged electrically when two materials get in contact or rub against each other according to triboelectric series with different relative

polarity.[158] Triboelectric effect depends on not only the bulk materials, but also the upmost layer of the film surface,[159] which can increase the contact area and surface charge density of the device, respectively. In order to enhance the power output performance, materials, such as micro-patterned PDMS film, PTFE film and micro-pattern Al layer, with the largest difference in the ability to attract electrons,[160] modification of surface morphology and device structures with a high separation and contacting rate were explored in nanogenerator based on metal-insulator contact electrification.
Althogh there is just over one year since the first triboelectric nanogenerator reported, the progress has been remarkable with triboelectric nanogenerator's area power density jumped from 3.67mW/m^2 to 313W/ m^2 as shown in Figure 11, almost five order's magnitude. The future certainly looks very bright.

Due to the low frequency of mechanical energy in human motion, an electric generator should possess the capability to harvest energy at low frequencies (<10 Hz).[161] Piezoelectric effect is another feasible method to convert energy from vibration and human motion. Earlier work reported by Shenck, etc. presented a shoe mounted piezoelectric generator using PZT and PVDF film_ENREF_10[162] is inflexible and difficult to be integrated in shoe as a wearable device. At a low frequency motion, the energy stored E_c can be expressed as follow.

$$E_c = d_{ijk}\sigma_{jk} + \mu_{ijkl}\frac{\partial \varepsilon_{jk}}{\partial \chi_l}(i,j,k,l=1,2,3)$$ [163]

The first term on the right-hand side refers to the piezoelectric effect, where σ_{jk} is the stress uniformly distributed across the material and d_{ijk} is the piezoelectric coefficient tensor. The second term on the right-hand side refers to the flexoelectric effect, i.e. the strain gradient ($\frac{\partial \varepsilon_{jk}}{\partial \chi_l}$) induced polarization and μ_{ijkl} is the flexoelectric coefficient tensor. In many cases, the flexoelectric effect is small thus can be ignored. However, in a flexible device, apart from piezoelectric materials, equal attention should be placed upon structural design of the wearable generators in which the significant flexoelectric effect can be utilized or eliminated.
To utilize the direct piezoelectric effect, three major types of nanostructure piezoelectric materials have been investigated:(1) nano-scaled semiconductor piezoelectric materials, including Zinc oxide,[164] cadmium sulfide, zinc sulfide (ZnS), gallium nitride(GaN) [164d, 165] and indium nitride;[166] (2) perovskite structured piezoelectric nano-sized materials, such as lead zirconate titanate(PZT),[166-167] potassium niobate,[168] sodium niobate[169] and barium titanate;[170] and (3) piezoelectric polymers, e.g. Polyvinylidene Fluoride(PVDF).[164i, 171] Traditional piezoelectric semiconductor and ceramic material is rigid and hardly used as mechanical energy harvesting materials. In order to overcome this limitation, flexible devices are fabricated based on PZT nanofibers on flexible substrate(textile,[172] paper,[164t, 173] plastic film) or packaged with flexible polymers, such as Polydimethylsiloxane(PDMS). [169, 174]
However, the fatigue life of energy converters is particularly important for long term application such as wearable electronics. Thus, soft polymeric piezoelectric materials such as PVDF and its copolymer is naturally flexible, biocompatible, lightweight[4] and suitable for energy harvesting. Apart from the brittleness of the materials, electrodes used conventional ones with little compliance to deformation, such as metal or metal oxide coated electrodes, e.g. aurum, silver, aluminum, and ITO. During deformation, the interfacial shear stress causes delamination of the sandwich layers because of mismatch of modulus and Poisson's ratio of the electrode and active layers. The devices lost mechanical integrity and electric connectivity and fail quickly in repeated large deformation thus not suitable for wearable applications. Additionally, the conductivity and contact area of electrodes also influence the power generation according to the

equation metioned above due to the enhancement of the strain gradient. In order to enhance the power output and fatigue life, all-fiber based flexible, soft and wearable piezoelectric energy convertor consisting of a PVDF–$NaNbO_3$ nanofiber and elastic conducting knitted fabrics electrodes made from segmented polyurethane and silver coated polyamide multifilament yarns is proposed shown in Figure12. The fabric electrodes act as dual roles: (1) it works as a normal charge collection network as well as (2) a mechanical element that transfers the uniform compressive pressure on the device into localized deformation in the piezoelectric nonwoven. The front side of the fabric serves as connecting side with PVDF and can maximize the contact area of the fabric electrode which may improve flexoelectric effects due to the induced localized strain gradients. Remarkably, the all-fiber nanogenerator remains working after applying more than 1,000,000 cycles external force.[45]

Since 2006, the accumalating of considerable reasearch efforts has led to a quantum jump in 2012 with respect to the performance of soft and flexible nanogenerators made from piezoelectric materials, and the trend will continue, as demonstrated in Figure 12 evidently. **错误！超链接引用无效。**

Thermoelectric energy harvesting from human body has advantages that heat is steady and large. However, from the viewpoint of the curvature of the human body, typical thermoelectric generator fabricated from rigid semiconductors such as Bi_2Te_3 and SiGe are unsuitable because these thermoelectric generators are composed of thermocouples on a rigid substrate.[175] On the other hand, flexible thermoelectric generator transducer the human body heat efficiently if the flexible thermoelectric generator can be tightly attached on the skin. Several studies have implemented flexible thermoelectric generators, and the techniques require a complicated and precise photolithography fabrication process.[176] Following these previous studies, fiber-based thermoelectric power generators fabricated by evaporating thin Ni-Ag films on flexible fiber substrates have been demonstrated with an open circuit voltage of 19.6 μV/K and a maximum power of 2 nW, and the unique architecture of fiber-based thermoelectric generator is promising for the future development of flexible and wearable electronics. Semiconductor NWs have been investigated as promising thermoelectric materials, among these semiconductor NWs, silicon NWs exhibit interesting and promising thermoelectric properties. By integrating material design with advanced fabrication techniques, the fiber-based thermoelectric generator can serve as one of the sources for powering small electronic systems by directly converting dissipated heat from the human body into electricity.

Several challenges must be met before the realization of wearable fiber-based energy harvesting devices. Enhancement must be made for the overall power conversion efficiency for real applications, which has three components: (1) the internal conversion efficiency of the active materials, (2) the efficiency related to the device, that is, the ability to collect and transfer electric charges, (3) the efficiency determined by the harvesting circuit and storage. One can further enhance the total power by using arrays or networks of nanogenerators, and durability is also a major issue in addition to comfort in wear.

4.3.2 Wearable energy storage

The development in high-performance wearable electronics places a great demand of lightweight and flexible power source and storage devices, without which usage of many electronic devices will be limited in truly wearable systems, such as wearable displays, embedded sensor and sensing networks, electronic newspapers, paper-like mobile phones, and so on.[177] At present, lithium-ion batteries or SCs [4e, 178] are under intensive investigations. Fiber batteries were explored in different forms, such as a cable type composed of several electrode (generally anode) strands coiled into a hollow-spiral (helical) core and surrounded by a tubular outer electrode (cathode);[179] a flexible one with a film electrode by anchoring TiO_2(B) nanosheets on non-woven active carbon fabric (ACF);[180] one with Li_4TiO_{12} nanosheet film electrode;[181] a stretchable battery electrode based on buckled PPy;[182] and a wire-shaped one made by twisted, aligned multiwalled carbon nanotube (MWCNT)/Si composite fiber anodes with a specific capacity of 1670mAh/g.[183] In this article, more attention is paid on the fiber-based SCs or SCs, also named electrochemical capacitors. It is comparatively more attractive against batteries, owing to its distinctive features, including fast charge/discharge rate (in seconds), high power density, and stable cycling life.[4d, 4e, 31b, 67, 178, 184] According to their working principles, they can be divided into three types: double-layer capacitors, pseudocapacitors and hybrid capacitors. They employ electrolytes instead of dielectric materials in capacitors.

Similar to the conventional SC systems, the fiber-based SCs are composed of at least three elements, including two symmetric or asymmetric electrodes, an aqueous/solid electrolyte or/and a separator layer.[178, 184b] The fiber-based SCs can be grouped into three types according to their structures. Figure 13 illustrates members of the first type, that has a one-dimensional fiber shape and comprises two fibers [185] in: (1) parallel pattern,[4d, 4e] for instance, a cable SC made from two parallel three-dimensional PPy-MnO_2-CNT-cotton threads (a);[4d] one packaged by placing two parallel fiber electrodes (composed of a conductive fibrous substrate and electrochemically active materials) into a flexible plastic tube filled with electrolyte and a well designed helical spacer wire (b);[4e] (2) twisted (or intertwined) pattern,[31b, 178, 186] like a two-ply yarn SC based on carbon nanotubes and polyaniline NW arrays (c);[178] a wire-shaped SC by twisting two aligned MWCNT/OMC composite fibers as electrodes (d);[186] a wire-shaped SC fabricated from two intertwined GF@3D-Gs with polyelectrolyte (e);[31b] (3) wrapped pattern, including a SC by entangling a plastic wire covered with NWs around a Kevlar fiber covered with gold-coated NWs (f);[67] and (4) coaxial configuration, such as a SC made by wrapping aligned CNT sheets on an elastic fiber as two electrodes (g);[187] and an Electric Double-Layer Capacitor (EDLC) with a coaxial fiber structure (h).[188]

The second type of fiber-based SCs is in fabric form, as shown in Figure 14, constructed either by coating two-dimensional substrates, including woven, knitting or paper, with functional thin coating layers or by modifying the fibers with chemicals,[189] consisting of (a) a textile EDLC by screen printing an activated carbon paint onto a custom knitted carbon fiber cloth as the current collector; [31c] b) an asymmetric SC made from Co_9S_8 nanorod arrays as positive materials and Co_3O4@RuO_2 nanosheet arrays as negative materials on woven carbon fabrics;[184c] (c) multi-layer graphene/porous carbon woven fabric film using nickel wire meshes as electrode; [190] (d) reduced graphene oxide/manganese dioxide paper electrode;[184d] (e) direct conversion of cotton T-shirt textile into activated carbon textiles as electrode [189] (e). The third type is thin film[184a, 184e, 191] with flexible and soft substrates such as PET and PDMS,[184b] which can be laminated onto textiles or used as stand-alone devices.

_ENREF_122The most distinctive nature of the single fiber-type SCs, as shown in Figure 13, is their comparatively superior mechanical flexibility, with the potential to be woven or knitted into breathable textile structures alone or together with other devices.[4d, 4e, 67, 178, 186] At present, the fiber-type SCs have been integrated in woven fabrics by using existing weaving technology.[31b] Particularly, a single fiber SC made by wrapping aligned CNT sheets on an elastic fiber serve as two electrodes (Figure14 (g)) maintains its specific capacitance of ~18F g^{-1} after being stretched by 75% for 100 cycles;[187] and a coaxial EDLC fiber with a maximum discharge capacitance of 59F g^{-1} and a mechanical strain of 100% has been recently achieved.[188]

However, several critical issues exist in such single fiber-type SCs. The first issue is to raise areal capacitance. Their typical areal capacitance has been advanced from ~1mF/cm^2 to ~40mF/cm^2 through the improvement in the efficient specific area by various approaches, for instance, the involvement of conductive NW arrays on the core fibers or the opened edges of the electrode,[184a] to facilitate the ionic transport.[178, 186] The further enhancement in the capacitance, however, might be more challenging due to the linear configuration of the fiber (or yarn) electrode, which significantly weakens the charge transport ability in the electrode and limits the diffusion of electrolyte ions to the electrode.[4d, 177, 184a, 186] Secondly, it was reported that the capacitance of some fiber-type SC decreases by more than 10% with limited charge/discharge cycles due to the induced mechanical stress between the electrode and electrolyte.[177-178, 186] Thirdly, although the single wire-based SCs can be bent in principle, their electrochemical performance is affected by stress and number of bending cycles since cracks may occur with the presence of inorganic electrode materials (e.g., ZnO) and the weak adhesion between the electrode and electrolyte.[4d, 4e, 178, 184b, 185] The understanding and proper design of fiber hierarchy structures and interfacial properties will play a key role to reduce the interface shear stress and occurrence of crack/delamination as well as crack propagation. Among different structural patterns of the single fiber-type SCs, the coaxial configuration may yield a higher electrochemical performance owing to the rapid ionic transportation with lower contact resistance between two electrodes.[188] It was recently demonstrated that a coaxial EDLC fiber achieved a discharge capacitance of 59 F g^{-1}, much higher than 4.5 F g^{-1} of the EDLC by twisting two CNT fiber together. Additionally, the coaxial SCs are easier to be bent and stretched in the weaving or knitting processes, while the twisted fiber electrodes may easily separate from each other during the bending, and break during the use as they were not stretchable.[192]

Fabric-based SCs, as illustrated in Figure 14, are porous, mechanically flexible, and highly conductive with high accessible surface areas.[189] Thus, their electrochemical performance is comparatively superior than that of the single-fiber SCs due to the enhanced diffusion of the electrolyte ions in 3D porous structure and lower internal resistance.[184d, 189] Superior performance of the fabric-based SCs has been reported including high specific capacitance, good charge/discharge stability, long-term cycling life, high energy density, and high power density. However, their capacitance loss is indispensible and cannot be neglected in the bending or stretching modes, due to the loosening and even delamination in the interface of the electrolyte and electrodes.[31c]

It is highly desirable to integrate the energy conversion and storage functions together in one single device made from fibers or fabrics. In this way, a well balanced and comprehensive plan can guide the overall design of the device architecture, selection of materials and fibrous structures, impedance matching between the converter and storage, and meet the overall requirements of performance of the integrated devices. Currently, examples of a combined device, with one energy conversion segment and one energy storage segment, include a modified polymethyl methacrylate fiber with a dye-sensitized solar cell and a SC whose energy-conversion efficiency was 0.02%;[193] an energy wire with photoelectric conversion and energy storage whose overall photoelectric conversion and storage efficiency reached 1.5%;[194] a single fiber with the functions of photovoltaic conversion and energy storage;[192] a new graphene/CNT composite fiber with a dye-sensitized solar cell and a fiber SC;[195] a novel fiber by coaxially integrating dye-sensitized solar cell and electrochemical capacitor;[196] an integrated power fiber incorporating a dye-sensitized solar cell and a SC with an overall energy conversion efficiency of 2.1%.[197] Although the energy conversion efficiency still needs to be improved, such integrated format may advance the fiber-shaped energy conversion and storage devices.[198]

Conclusion

In this paper, a critical review has been presented on the current state-of-arts of fiber- based wearable electronics. Several aspects have been covered. The performance requirements of fiber-based devices and systems are presented in light of the unique characteristics of fiber assemblies. materials, in particular, nano-scaled inorganic, organic and polymeric materials and their hybrids are examined for developing electronic functions either on single fiber surface, or inside a single fiber or fiber assemblies. Various fabrication techniques are grouped into two major categories, that is, the single-fiber type and the fabric type, with the building elements of devices being single fibers and fabrics, respectively. Summarized descriptions of structures and performance of fiber-based wearable devices are given including electronic components like transistors, antennas, connectors, sensors and sensing networks as well as energy harvesters and storage devices. Their applications are described regarding healthcare, sport, personal protection etc.

Despite of such significant advancements of fiber based wearable electronics, most of the reported prototypes are a long way from fulfilling their final application. It is of great necessity to address the critical issues and future work for the fiber-based wearable electronics, which places a demand for high performance in terms of electronic functions, structural and functional integrity and stability during use, deformability together with comfort of the users.

With respect to materials or fiber electrodes, the fiber-based wearable electronics should be fabricated from highly biocompatible components. However, there are contradictory reports on the biocompatibility of many of the materials or fiber electrodes used in wearable electronics fabrication. For example, CNTs have been reported as highly toxic to cells at high concentrations. Suitable materials and newly designed fabrication technology are urgently needed to achieve high performance that can match that of the current fiber configurations.

It has been demonstrated that fiber-based wearable electronic components, including transistors, antenna, connector, and circuitry, sensors and sensing networks, as well as wearable energy harvesting and storage devices are breathable with fiber assemblies or textile structures, therefore pushing the electronic functions towards next-to-skin applications for a long period usage without any damage to human bodies. The knitted connectors with metal fibers in a soft knitted substrate are most promising for integrated circuits since its electrical resistance remains unchanged over a large deformation, fatigue life as well as more than 30 washing cycles. Although the developed discrete fiber based electronics show good performance, they are still far below the requirements of modern, super large-scale integrated circuits, and the roughness of fiber electronics is still too high that that it is not suitable for the traditional integrated circuit technology. Compared with conventional silicon-based or thin-film-based electronic devices, however, fiber-based devices are involved with (1) multiple materials with vast difference in properties, (2) multiple scales of three dimensional structures from nano-, micro-, meso- then macro-scales. Thus, more critical issues, including electrical, electrochemical, as well as electromechanical performance, are induced from research platform to the commercialization of the fiber-level components and devices. The currently most challengeable issue is the further development of small-sized electronics on microfibers, especially the microfiber-based transistors, and the performance of various components and devices with the marriage of electronics and textiles should be considered. To enable electronics directly contact soft, elastic, and curved human bodies, it requires the electronics to be porous, flexible, stretchable, reliable, durable as well as washable.

Other issues include the improving performance of wearable electronic, creation truly multifunctional fabrics; the encapsulation of electronic devices on fabric; and the long-term stability of these devices for potential applications. To realize connection of the knitted connectors with conventional electronic components, fabric circuitry, sensors and sensing networks, wearable harvesting devices, wearable energy storage devices including lithium-ion batteries and SCs is still big a challenge. To date, the areal capacitance is limited due to poor charge transport ability in the electrode; the electrochemical property degrades under charge/discharge cycles due to induced mechanical stress; the bendability, stretchability, as well as durability needs to be further enhanced. Thus, the understanding and proper design of fiber hierarchy structures and interfacial properties will play a role to reduce the interface shear stress and occurrence of crack/delamination as well as crack propagation.

In addition, the issues have a common feature of multiple disciplines concerning electronics, materials, solid mechanics, surface chemistry and thermodynamics etc. Most reported works have focused on the materials and fabrication of individual novel devices and their potential applications, however, up to date, there has been few systematical fundamental studies in the literature on the highly complex fiber-based electronic devices and systems. Most of the involved mechanisms remain elusive. Design tools for such devices and systems should be developed based on much improved fundamental understandings.

Acknowledgements

The authors acknowledge the funding support from Research Grants Council of Hong Kong SAR Government (Project No. PolyU5272/11E and PolyU5251/13E).

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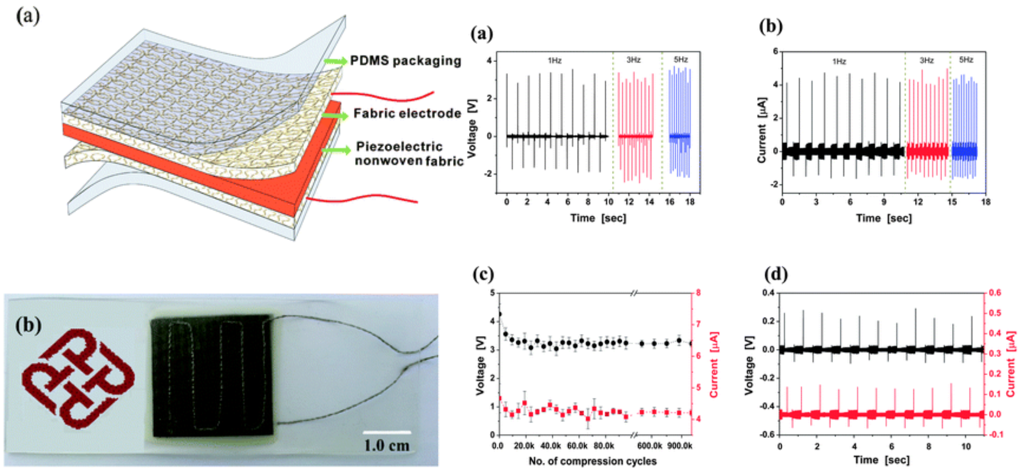
Figures and tables



(i) (ii)

Figure 12 Highly durable piezoelectric nanogenerator based on PVDF/$NaNbO_3$ nanocomposite and conductive fabric electrodes.[45]

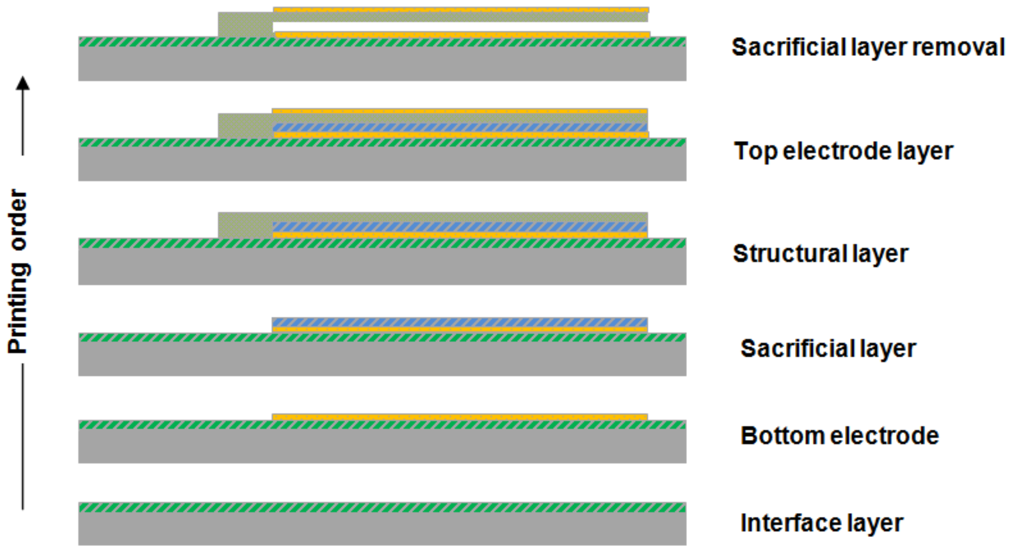


Figure 2. Printing sequence of a capacitive cantilever though layer-by-layer screen printing process.[55]

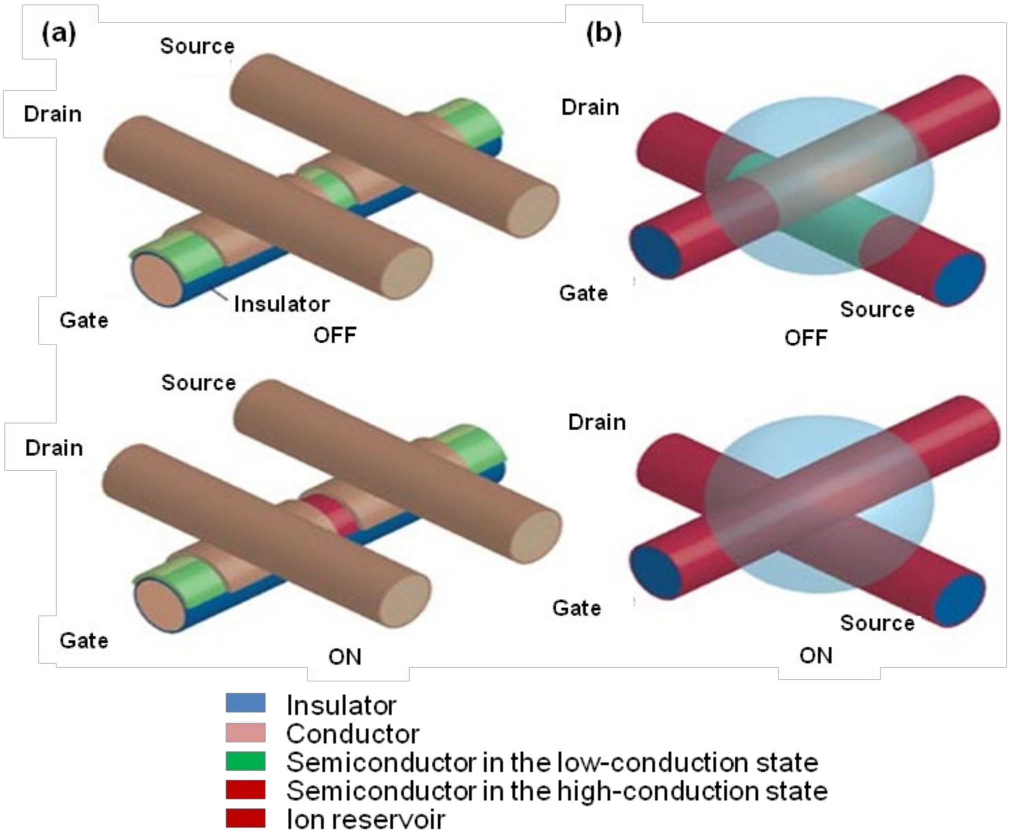


Figure 3. Fiber transistors: (a) fiber organic field-effect transistors (OFETs), (b) wire electrochemical transistors (WECT). [78a]

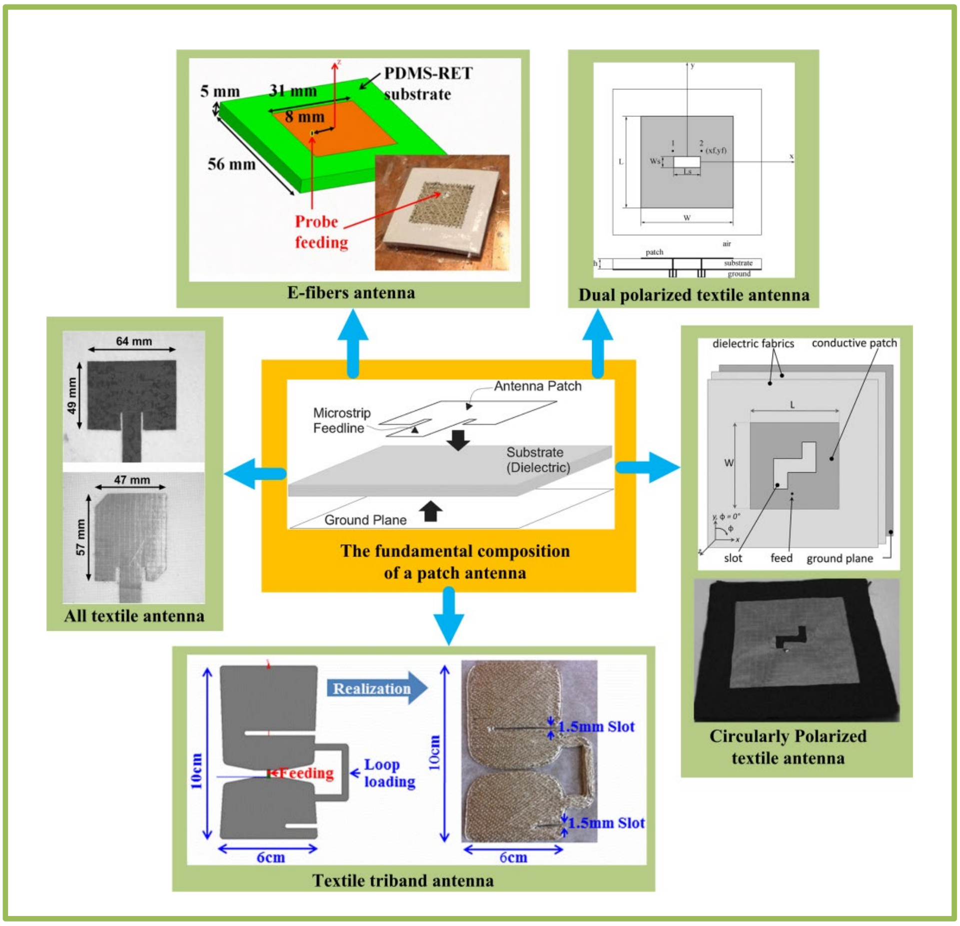


Figure 4. Fabric antennas based on the fundamental composition of a patch antenna: E-fiber antenna, [87] textile triband antenna,[89] dual polarized textile antennas,[90] all textile antenna,[85] and circularly polarized antenna.[91]

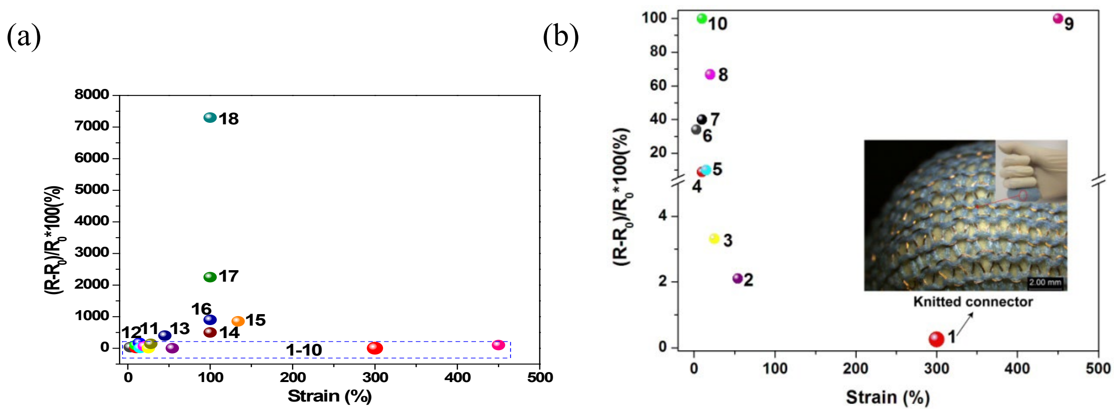


Figure 5. Figure 5 Relative change in electric resistance of benchmark connectors plotted against strain: (a) The samples with normalized resistance from 0% to 8000%; (b) Enlarged one with normalized resistance within 100%. (1: Knitted connector;[129] 2: Horseshoe;[127] 3: CNT loop;

[100] 4: PEDOT:PSS-PDMS;[102] 5: Ag-PDMS;[130] 6: SiNW-PDMS;[126] 7: AgNW-PDMS;[131] 8: Net-shaped;[108] 9: AgNW/PEDOT:PSS;[132] 10: Graphene-PDMS;[97] 11: Au-PDMS;[111c] 12: Ag-Silicone fiber; [105] 13: Cu-woven;[5b] 14: Metal/elastomer fiber;[103] 15: SWNT-rubber;[133] 16: PANI:SEBS-g-MA/SEBS;[101] 17: AgNW-PUA;[134] 18: Ag-MWNT-SIS[99]). The knitted connector exhibits the lowest change of 0.25% at the highest strain of 300%.

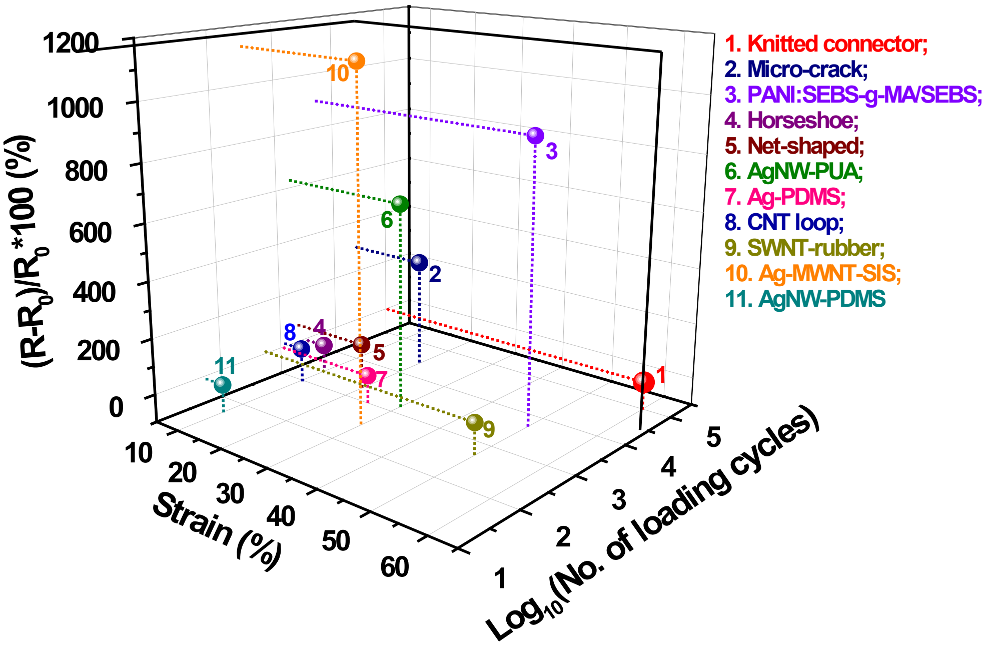


Figure 6 Relative change in electric resistance of benchmark connectors plotted as a function of strain and loading cycles in logarithmic scale (1: Knitted connector;[129] 2: Micro-crack;[135] 3: PANI:SEBS-g-MA/SEBS;[101] 4:Horseshoe;[127] 5: Net-shaped;[108] 6: AgNW-PUA;[134] 7: Ag-PDMS;[130] 8: CNT loop;[100] 9: SWNT-rubber; [133] 10: Ag-MWNT-SIS;[99] 11: AgNW-PDMS[131]). The knitted connector has the highest number of cycles (100,000) at the highest strain of 60%.

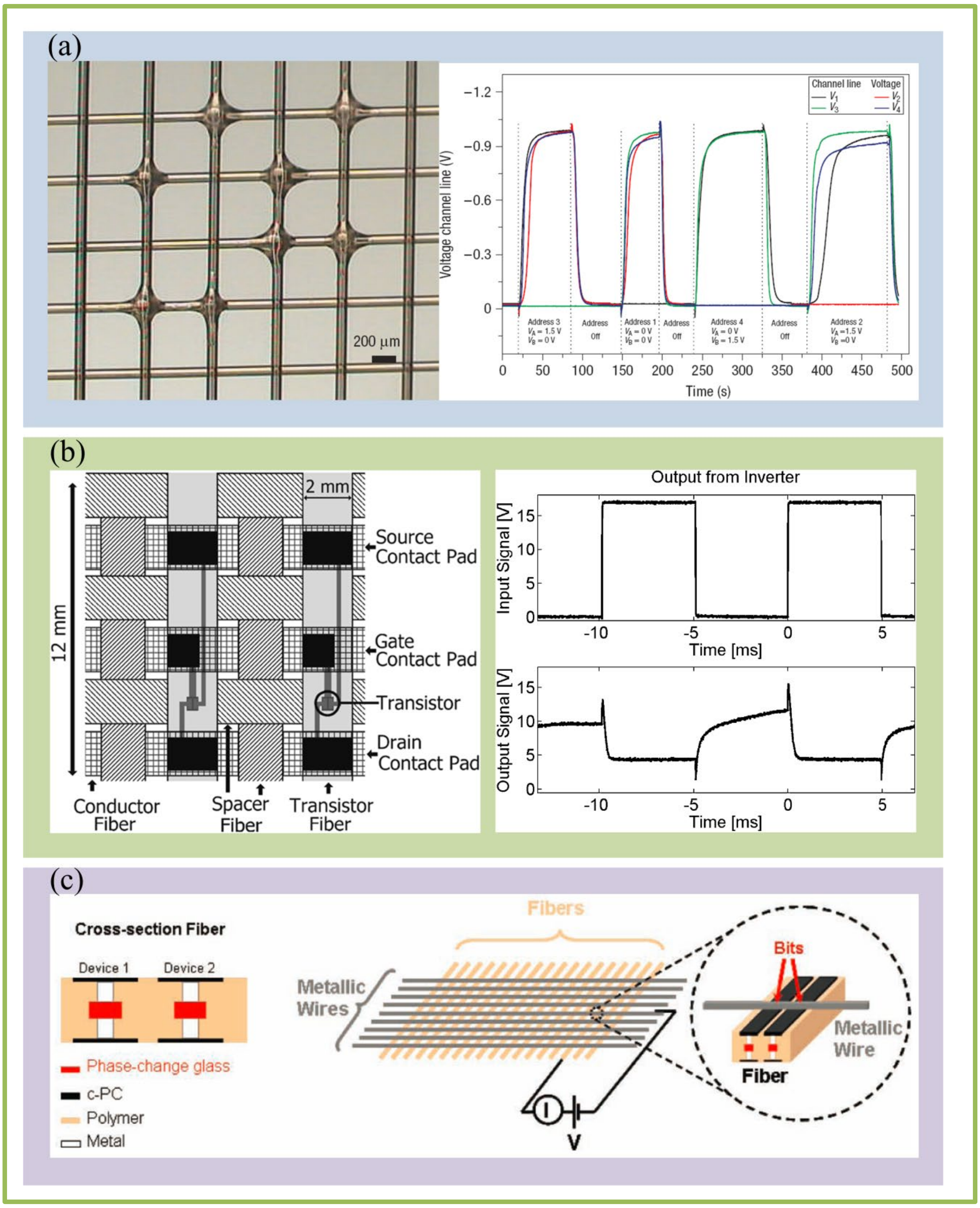


Figure 7. Fiber circuitry: (a) A binary tree multiplexer constructed from WECTs and their dynamic electrical characteristics,[52, 78a] (b) A woven inverter circuit and its dynamic electrical characteristics,[137] (c) Fiber-based fabric-array memory device.[138]

Figure 8. Fiber-based sensors: (a) Fabric bio-potential electrode and its SEM photo,[150] (b) Pulse-driven fiber nanogenerator by ZnO thin films grown around a carbon fiber as a strain sensor,[6a] (c)Vibration sensor arrays of piezoelectric fibers in gloves for detection and suppression of Parkinson's tremor in the hand,[151] (d) Carbon loaded elastomer sensorized garment for kinesthetic monitoring, (e) Strain-gauge sensor based on the reversible interlocking of Pt-coated polymer nanofibres,[142k] (f) Carbon nanotube strain sensor for human motion detection,[20c] (g)Woven electronic fibers with sensing and display functions,[5b] (h) In-shoe plantar pressure monitoring in daily activities by fabric pressure sensors.[142i]

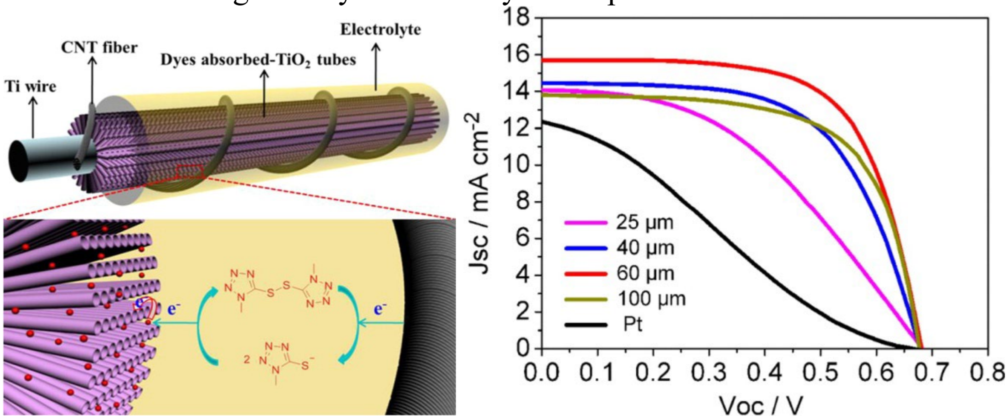


Figure 9. Dye-sensitized photovoltaic wires based on CNT fiber.[155f]

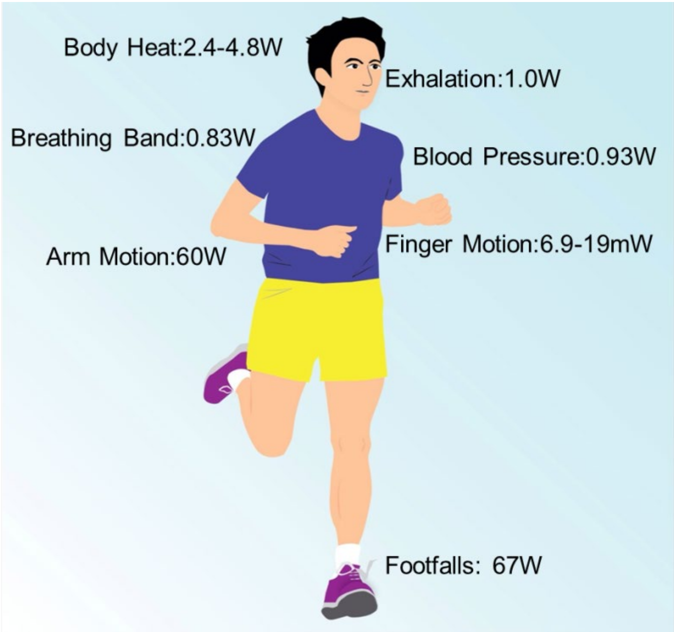


Figure 10. Available power for everyday bodily activities of human being.[156] _ENREF_4

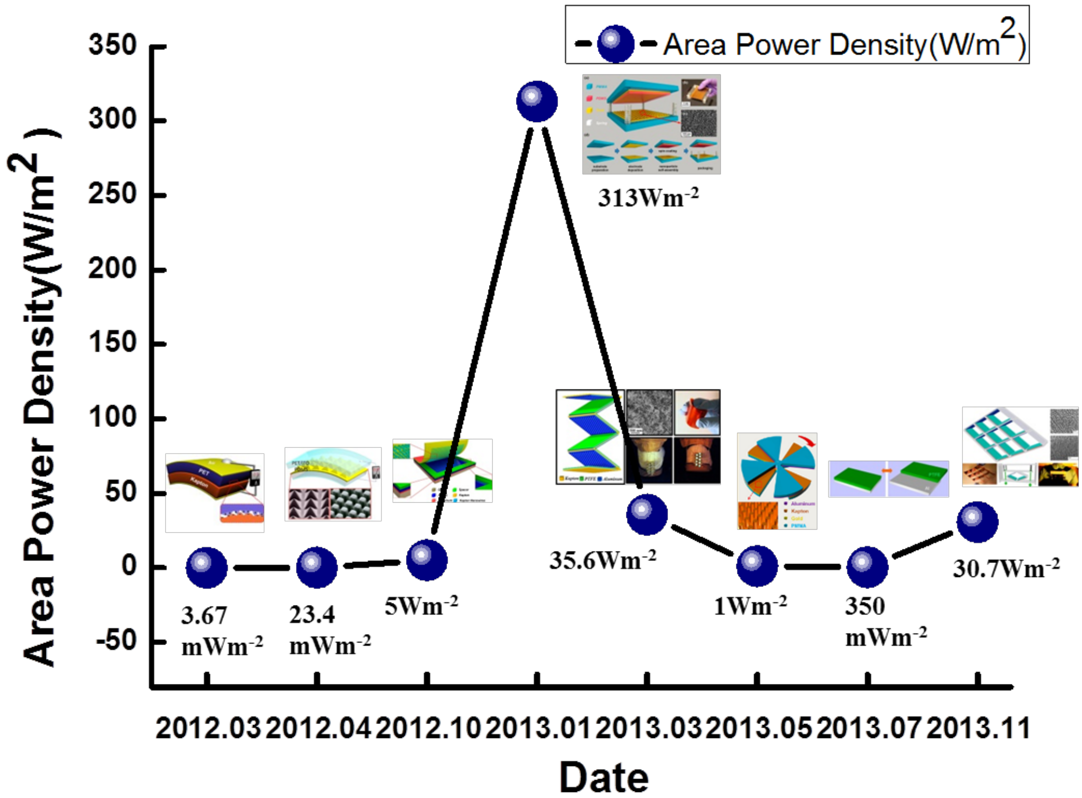


Figure 11.A summary on the power density of various triboelectric nanogenerators

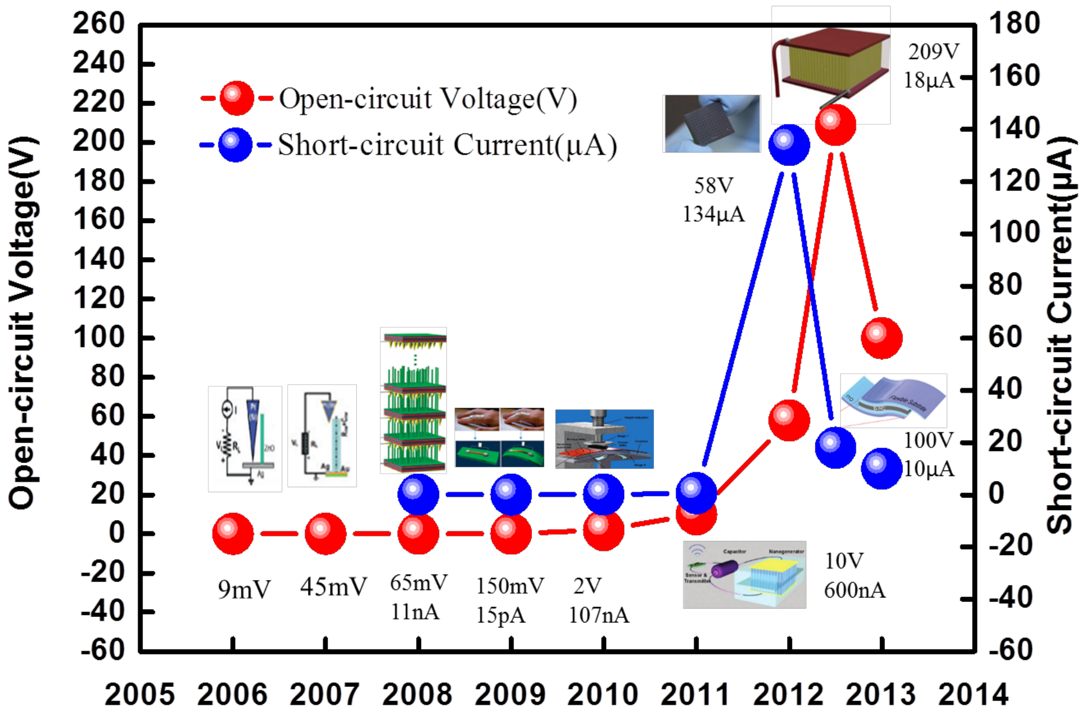


Figure 12 A summary on the development of piezoelectric nanogenerators since 2006

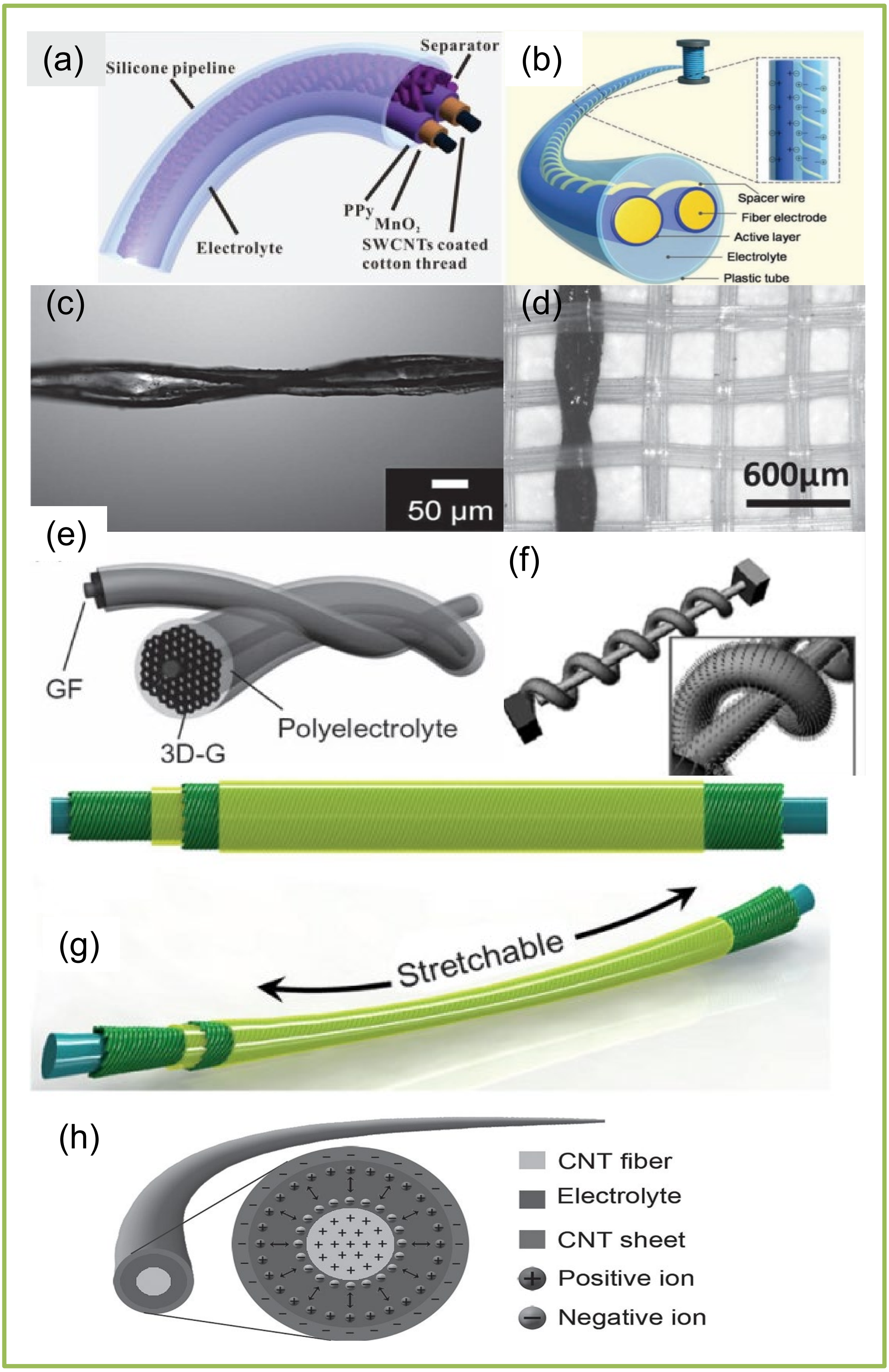


Figure 13. Single fiber-type SCs. Parallel pattern: (a) a cable SC based on two parallel three-dimensional PPy-MnO2-CNT-cotton threads[4d] and (b) one packaged by placing two parallel fiber electrodes into a flexible plastic tube filled with electrolyte and a well designed helical

spacer wire;[4e] Twisted pattern: (c) a two-ply yarn SC based on carbon nanotubes and polyaniline NW arrays,[178] (d) a wire-shaped SC by twisting two aligned MWCNT/OMC composite fibers,[186] and (e) a wire-shaped SC fabricated from two twined GF@3D-Gs with polyelectrolyte;[31b] Wrapped pattern: (f) a fiber-based electrochemical capacitor by entangling a plastic wire covered with NWs around a Kevlar fiber covered with gold-coated NWs;[67] Coaxial configuration: (g) a fiber-shaped SC by wrapping aligned CNT sheets on an elastic fiber[187] and (h) a coaxial EDLC fiber.[188]

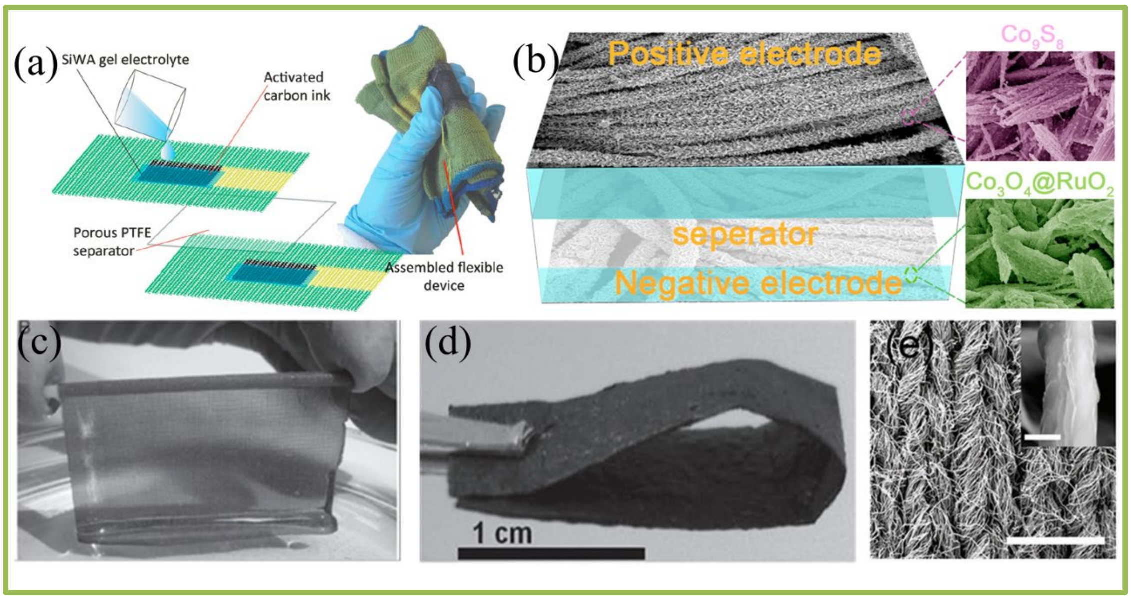


Figure 14. Fabric-type SCs: (a) a textile double-layered SC by screen printing an activated carbon paint onto a custom knitted fabric of carbon fibers as the current collector;[31c] (b) an asymmetric SC based on Co9S8 nanorod arrays as positive materials and Co3O4@RuO2 nanosheet arrays as negative materials on woven carbon fabrics; [184c] (c) multi-layer graphene/porous carbon woven fabric film using nickel wire meshes as electrode;[190] (d) reduced graphene oxide/manganese dioxide paper electrode;[184d] (e) direct conversion of cotton T-shirt textile into activated carbon textiles as electrode.[189]

Table 1 A comparison of the performance between fiber OFET and WECT

Category	Fiber OFET	WECT
Mobility	>0.5 $cm^2 V^{-1} s^{-1}$ [76] Up to 1.4 $cm^2 V^{-1} s^{-1}$	Very low
Operating	About 9-20 V	0-1.5V

voltages		
On/off ratio	10^3-10^5	10^2-10^3
Advantages	Good electrical characteristics for many e-textile applications.[76]	Very low operating voltages, relatively simple fabrication process, helpful for realization of analogue and digital micro-electronics directly into textile, and integration of electronic function on new carriers.[52]
Disadvantages	High operation voltages, complex manufacturing process, poor stability when fibers under mechanical stress,[78b] significant dielectric leakage, and poor reliability. [76]	Long switch time (>4-5seconds),[78d] long response time. It might limit WECT technology to quasi-static applications with very low frequencies.[78a]

Table 2 Textile patch antennas

Antenna	**Conductive layers**	**Dielectric layer**	**Antenna gain**	**Frequency Band**
E-fiber antenna[87]	Embroidered surface of flexible silver-coated Amberstrand fibers	PDMS substrate	5.6dB(planar) 3.0dB(curvi-linear)	2.2 GHz
Textile triband antenna[89]			2 dB	2.45 GHz (GSM), 1.9 GHz (PCS), 900 MHz (WLAN)
Dual polarized textile antennas[90]	FlecTron for ground plane and ShieldIt for patch,	A protective, water-repellent, fire-retardant foam	6-7 dB	2.45 GHz
All textile antenna[85]	Nickel-plated woven fabric, silver plated knitted fabric, silver-copper-nickel plated woven fabric	A woolen felt and a polyamide spacer fabric	4.4 dB, 5.5 dB	2.4 GHz
Circularly polarized antenna[91]	Silver and copper plated low-loss nylon woven fabrics	Cordura woven fabrics	-	1575 MHz (GPS) 1625 MHz (Iridium Satellite)

Table 3. Summary of fiber-based strain sensor

Key material	Transduction technique/ Modulation parameter	Advantage	Disadvantage
PPy [142a-c]	Resistive/ Resistance	Excellent sensitivity Softness Large strain measuring range	Stability Durability Hysteresis
Pt nano fibers [142k]		Excellent sensitivity Shear force detection Pressure detection Torsion detection	Limited flexibility Durability Coupling of pressure, shear and torsion
Carbon fibers [142j]		High temperature working range	Temperature sensitive Strain rate effect
CNT [142d, 142e]	Piezoresistive/ Resistance	Good sensitivity Softness and compliance Robust and chemically resistance	Toxicity Potential hazards Hystersis
CP composite [6b, 54, 142f-i, 143a]		Good sensitivity Softness and compliance Robust and chemically resistance Excellent stability Repeatability Low cost	Strain rate effect Hysteresis

Table 4 Summary of fiber-based pressure sensor

Key material	Transduction technique/ Modulation parameter	Advantage	Disadvantage
CP composites[6b, 54, 142h]	Piezoresistive/ Resistance	Good sensitivity Softness and compliance Robust and chemically resistance Durability Repeatability Tunable measuring ranges Low cost	Hysteresis of composite material Restricted to pressure sensing Strain rate dependent
CNT[143c-e]		Good sensitivity Softness and compliance Robust and chemically resistance Tunable measuring ranges	Toxicity Potential hazards Hysteresis
PVDF, P(VDF-TrFe)[143f, 143g]	Piezoelectric/ Voltage	Ultrahigh sensitivity Well suited for dynamic applications Mechanically flexible Thin films and low weights possible Robust and chemical resistance	Detect dynamic pressure only Not suitable for static applications Charge amplifier required Not stretchable
Optical fibers[143h]	Optical /Light intensity	Facile fabrication Large area application possible Flexibility and durability Immune to electromagnetic interference	Bulky in size Signal attenuation due to bending
Fiber Bragg gratings [143i, 143j, 149]	Optical / Wavelength	Excellent sensitivity Normal and shear force detection Large area application possible Flexibility and durability Low cost Immunity to electromagnetic interference	Bulky in size Signal attenuation due to bending

Table 5 Summary of fiber-based chemical and optical sensor

Sensor type	**Key material**	**Transduction technique/ Modulation parameter**	**Advantage**	**Disadvantage**
Chemical sensor	PPy[144c-f]	Resistive/Resistance	Good sensitivity Flexibility and durability Large area application possible	Toxicity Potential hazards
	CNT[144g]	Piezoresistive/ Resistance	Flexibility and durability	Bulky in size
	Optical fibers[144h]	Optical/ Vertebrae olfactory	Immunity to electromagnetic interference	Signal attenuation due to bending
Optical sensor	Fiber Bragg gratings[145]	Optical/ Wavelength	Flexibility and durability Immunity to electromagnetic interference	Bulky in size Signal attenuation due to bending