textiles

Review

Electrically Conductive Textile Materials—Application in Flexible Sensors and Antennas

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Abstract: This paper reviews some prominent applications and approaches to developing smart fabrics for wearable technology. The importance of flexible and electrically conductive textiles in the emerging body-centric sensing and wireless communication systems is highlighted. Examples of applications are discussed with a focus on a range of textile-based sensors and antennas. Developments in alternative materials and structures for producing flexible and conductive textiles are reviewed, including inherently conductive polymers, carbon-based materials, and nano-enhanced composite fibers and fibrous structures.

Keywords: conductive textiles; smart fabrics; textile sensors; textile antennas; inherently conductive polymers; nanoparticles

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1. Introduction

Smart fabrics and wearable electronics are set to succeed portable electronics as the next milestone in the modern information technology era. To be considered "smart", a textile structure must integrate the capability to sense and respond to stimuli from the environment [1–5]. In the broad sense, the stimuli and response of smart textiles can be of varied origins, including chemical, thermal, magnetic, and electrical [1]. The latter is associated with the category of smart textiles that combines electronics with textile structures, referred to as electronic textiles or e-textiles [6], although other terminology such as "textronics" has been used [7–9]. One major challenge to the success of wearable e-textile technology resides in the development of lightweight and flexible components, and fibrous structures with high electrical conductivity able to withstand the stresses associated with wearing and caring for the textile [2,6]. Indeed, the lack of flexibility and the weight associated with metallic conductors are key obstacles to overcome in the bourgeoning field of electronic textiles or e-textiles [2,10]. Use of conventional metallic conductors often results in rigid and inflexible fabrics that cannot maintain their functionality when exposed to harsh environmental conditions or after undergoing fabric care processes such as washing [2,10]. Therefore, flexible, deformable, stretchable, and durable conductive threads are critically needed for durable smart fabrics that capture and convey information and enable computing while accommodating the drape and movement of the human body. In recent decades, multiple approaches have been pursued in research to address this challenge using the flexibility and versatility of textile structures, along with innovations in the field of particulate and fibrous materials. This paper presents a review of notable application examples, and some of the approaches reported in the research literature aimed at developing conductive textile structures that are flexible, deformable, and stretchable. In the following sections, we first discuss textile-based sensors and antennas, then review alternative materials adopted for processing conductive textiles, including inherently conductive polymers, carbon-based fibers and additives, and nano-enhanced composite structures.

2. Background—Examples of Applications

In recent years, the function of clothing has expanded beyond basic physical protection from the environment and conquered the role of an interface with the potential to sense, transduce, and communicate information about the body and its surroundings. Clothing is, today, envisioned as a primary node in the concept of Internet of Things (IoT), connecting humans to the broad range of smart objects with digital functionalities [11,12]. For this vision to be realized, there is a pressing need for flexible, deformable, stretchable, and durable conductive textiles that enable smart fabrics to capture and convey information while accommodating the drape and movement of the human body. As a result, new technology has been introduced to textile structures in order to integrate electronic devices, such as sensors [13–16], antennas [10,17], and energy storage devices [18–20].

2.1. Textile-Based Sensors

Examples of textile sensors range from simple responses to chemical or biological stimuli, to more sophisticated signal acquisition, computation, and communication. For instance, nanocomposite nanofiber membranes containing functional fillers that can sense and react to specific chemical stimuli have been envisaged in protective clothing for soldiers exposed to chemical and biological warfare agents, or agricultural workers against pesticides [21,22]. Such applications rely on the chemical reactions between the functional nano-fillers and the target substance to sense and possibly neutralize the potentially toxic chemical compound [21,22].

Another category of textile-based sensors relies on the electrochemical properties and responses of conductive textiles. The sensing capability of those textiles may be a function of the change in electric conductivity with exposure to the target stimulus. For example, Devaux et al. [15] melt-spun conductive multi-filament yarns with conductivity that varies depending on relative humidity, enabling their use as relative humidity textile sensors based on conductivity measurement. Textile sensors based on the change in electrical conductivity are referred to as conductometric sensors and have been suggested for use in detecting a variety of Volatile Organic Compound (VOC) vapors [23,24], and metabolic biological compounds such as urea and uric acid [25]. Other electrochemical sensors, referred to as amperometric or potentiometric, measure the electric current or potential, respectively, resulting from oxidation or reduction reactions in the presence of the targeted substance [14]. Both amperometric and potentiometric textile-based sensors are common in biomedical research [14,26–28]. Liu et al. [26] developed an amperometric glucose biosensor using polypyrrole (PPy) nanofibers. Ekanayake et al. [27] adopted a similar principle for an amperometric glucose biosensing, but used PPy nanotubes rather than nanofibers. An example of a textile-based potentiometric sensor was reported by Manjakkal et al. [29] and shown to be responsive to pH variation. Parrilla et al. [30] developed a textile-based stretchable potentiometric sensor array with the capability of simultaneously responding to multiple ions, thus allowing the measurement of electrolyte concentrations in human sweat.

In addition to chemical stimuli, textile-based sensors have also been developed with a response to physical stimuli including pressure, motion, and mechanical strain [31–40]. Those sensors are typically based on piezoresistive fibrous materials with electrical resistance that varies under mechanical loading [34,36–41], or on capacitive textile actuators with capacitance that varies with mechanical strain [31,42–44]. Piezoresistive properties are desirable in strain sensor applications because they allow measurement of the response to strain through the corresponding variation of resistivity. However, such variation becomes a challenge when consistent conductivity is needed in stretchable structures [45,46].

Capacitive strain sensors are typically based on the parallel-plate structure (Figure 1) in which one dielectric layer is sandwiched between two conductive electrodes and the capacitance is dependent on the area between the two electrodes [31,42–44]. In the structure developed by Nur et al. [43], the dielectric layer is pre-stretched, leading to a wrinkled capacitive sensor at a relaxed state (Figure 1). According to the authors, this design expands the gauge factor (GF or sensitivity) of the sensor beyond the theoretical limit of the material [43]. The strain sensor reported in this research exhibited a GF of 3.05 [43], whereas the maximum sensitivity achieved using the typical parallel plate model is GF = 1 (Figure 1).

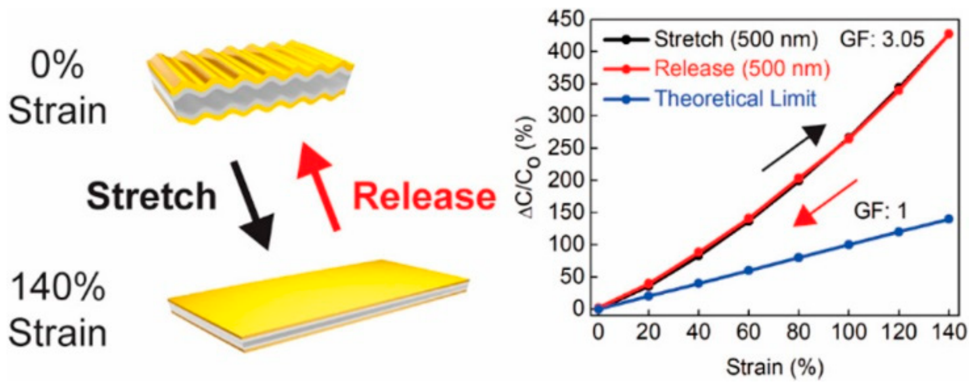

Figure 1. Illustration of a capacitive strain sensor (**left**), and capacitive response curves during loading and unloading (**right**). Reprinted with permission from [43]. Copyright 2018 American Chemical Society.

A third type of textile-based sensors with response to mechanical stimuli relies on piezoelectric materials and structures, which generate an electric charge when subjected to mechanical loading [47–50]. Figure 2 shows an illustration of a textile-based piezoelectric pressure sensor developed by Tan et al. [50] using a layered structure consisting of a top and bottom conductive polyester fabric/reduced graphene oxide (rGO) substrates, a polyvinylidene fluoride (PVDF) membrane, and zinc oxide (ZnO) nanorods. The piezoelectric actuator transforms the energy generated by the mechanical stimulus, in this case pressure, into voltage (Figure 2e,f). The same principle based on piezoelectric textile structures has been suggested for use in energy harvesting [47,49,51].

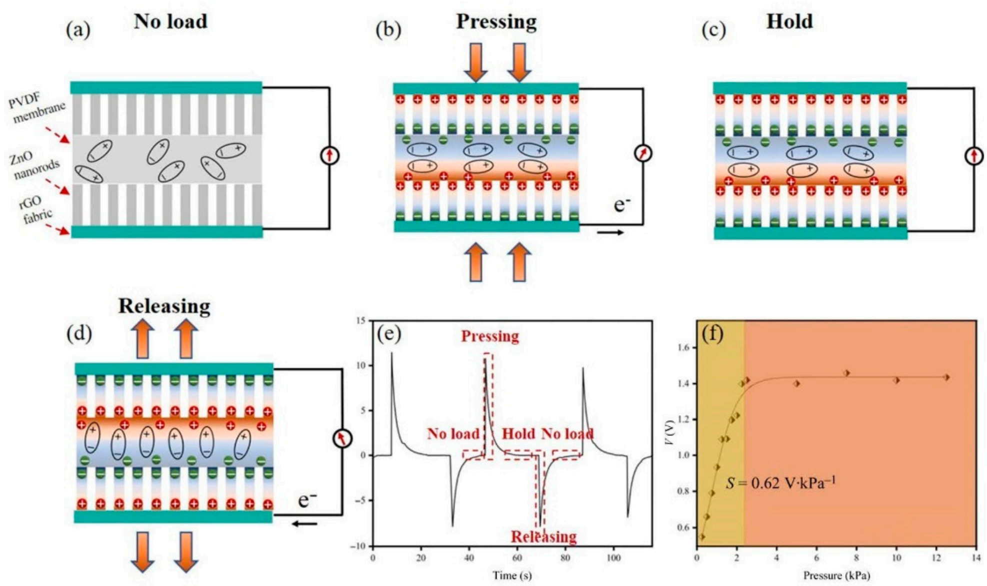

Figure 2. Illustration of a piezoelectric pressure sensor at different load states (**a**–**d**) and output voltage response for each state (**e**) and under varied pressure (**f**). Reprinted with permission from Springer Nature [50]. Copyright 2021 Springer Nature.

Wearable applications utilizing textile sensors often combine arrays of sensors to simultaneously measure multiple parameters [52–56]. Liu et al. [52] presented a system that monitors health indicators including electrocardiogram (ECG), respiratory activity, and temperature using a combination of a dedicated ECG module, six motion sensors, and a temperature sensor. Fan et al. [55] developed a machine knitted sensor array made of a set of "all-textile" pressure sensors that simultaneously monitors arterial pulse and respiratory activity. Similarly, Keum et al. [56] combined capacitive pressure sensors on a large textile substrate, thus enabling multi-point monitoring.

In most monitoring applications, signal acquisition using sensors of different types is followed by wireless transmission of the signal for data processing. For instance, Mattmann et al. [32] developed a garment prototype with an array of strain sensors to collect data relevant to upper body postures during physical exercise, then wirelessly transmit the data to a computer using Bluetooth. The need for such data transmission has led to efforts seeking the development of textile-based antennas. Flexible planar—also referred to as microstrip—antennas represent the category with the greatest applicability to wearables and smart clothing with wireless communication capability [57]. The following section briefly reviews some of the advances made in developing such lightweight, flexible, and conformal textile-based antennas for wireless data transmission.

2.2. Textile-Based Antennas

With the development of wearable applications integrating both data acquisition and transmission capabilities, the scope of antenna devices has expanded into body-centric systems requiring lightweight and highly conformal alternatives to conventional solutions [58,59]. The use of wearable textile antenna systems was suggested for many fields, including space applications [58,59], medical diagnosis [60], and in support of first responders such as firefighters and paramedics [61,62]. Applications in competitive athletic garments that enable collection and transmission of biomechanical and physiological information were also explored [63].

As mentioned, microstrip patch antenna geometry was identified as the most adaptable to wearables and smart clothing because of its low profile and potential flexibility [57,64–66]. A typical microstrip patch antenna consists of a conductive radiating patch, a dielectric substrate, and a ground plane, as shown in Figure 3. The conducting patch is bonded to the dielectric substrate which is superposed on a conductive layer on the opposite side, acting as a ground plane. Figure 4 shows an example implementation of the microstrip patch antenna using a denim fabric as a substrate [67].

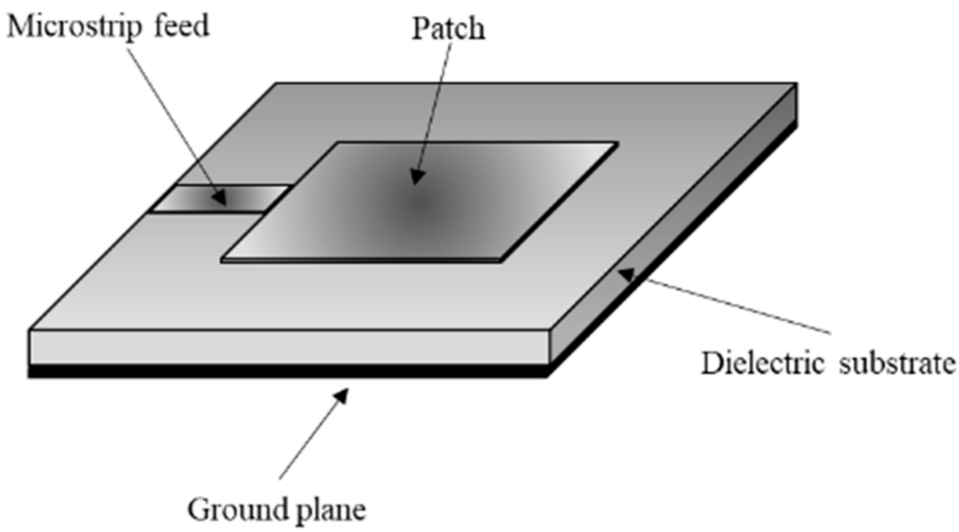

Figure 3. Schematic illustration of a planar microstrip patch antenna.

Figure 4. Example of a textile-based implementation of the microstrip patch antenna design using copper tape as radiating patch and denim fabric as the substrate. Reprinted with permission from [67] under the Creative Commons Attribution License.

When it comes to building antennas, metals have long been the material of choice because of their outstanding electrical conductivities. Thus, to build conformal antennas, researchers [67–71] have developed textile microstrip patch structures by integrating copper tapes (e.g., Figure 4) or metallic woven fabrics (e.g., Figure 5) as patch and ground plates with dielectric fabric substrates. However, thin metallic wires cannot withstand the mechanical stresses in the weaving process; therefore, woven metallic cloths tend to be coarse and stiff [10]. Such metallic cloth is often rigid and inflexible and lacks the conformal properties required for wearable applications.

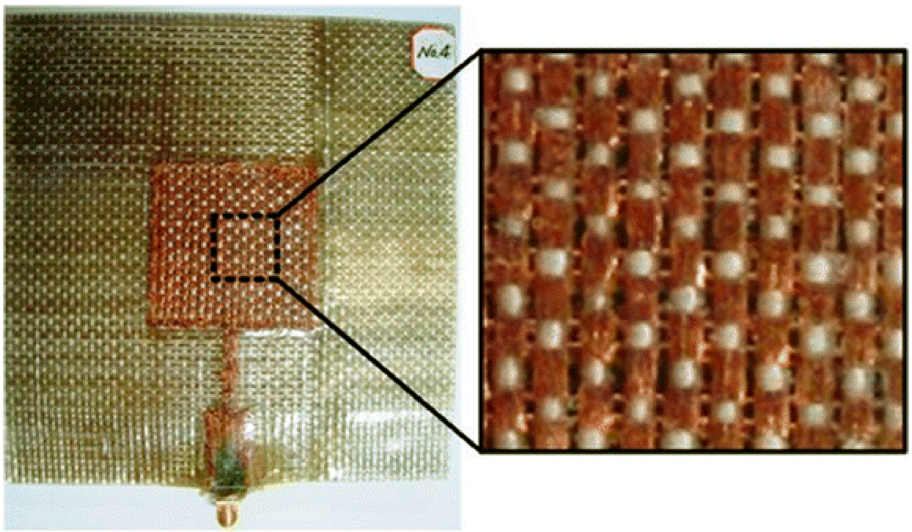

Figure 5. Example of a textile-based implementation of the microstrip patch antenna design using woven copper yarn as a radiating patch and woven glass fabric as the substrate. Reprinted with permission from [71] under the Creative Commons Attribution License.

Flexible alternatives to pure metal conductors have been proposed to address the challenges above. Kohls et al. [72] used nickel/silver plated nylon fabric strips as conductive elements to develop a lightweight and conformal antenna for use in a "Body-Worn Antenna Vest" (BWAV) for military applications. More recently, Bayram et al. [17] developed a conductive fabric patch made of cotton dip-coated with single-walled carbon nanotubes (SWNTs), and further sputter-coated with gold or silver particles for enhanced conductivity. The researchers then embedded the patch in a polydimethylsiloxane (PDMS)-ceramic composite serving as a flexible dielectric substrate [17]. A similar flexible PDMS-ceramic composite substrate was reported by Wang et al. [73]. In Wang et al.'s research, the conductive material used for the radiating patch consisted of a silver-coated filament embroidered on a polyester fabric then affixed to the dielectric composite substrate [73]. In an all-textile implementation of the microstrip patch antenna, bicomponent threads based on traditional Zari silver yarn wrapped around a silk core were embroidered on a cotton substrate (Figure 6) and shown by Anbalagan et al. [74] to be an effective solution for a wearable antenna with robust properties and with industrial, scientific, and medical applicability.

Figure 6. Example of a textile-based implementation of the microstrip patch antenna design using embroidered Zari (silver metallic yarn wrapped on a silk core) as radiating patch. Reprinted with permission from [74]. Copyright 2019, Wiley Periodicals, Inc.

Beyond the approaches discussed above, technology for alternative conductive materials has been sought to overcome the limits of metals in flexible sensors and antennas. The following sections present a review of research focusing on inherently conductive polymers, carbon-based materials, and nanocomposite structures with conductive performance.

3. Alternative Materials for Conductive Textiles

In the field of alternative non-metal-based conductive textiles, electrostatic discharge (ESD) structures are readily achievable and relatively common [75–77]. However, components for smart textiles require conductivity that significantly exceeds the ESD range, if they are to be used as substitutes for metallic conductors in fabrics that effectively convey information and enable computing. The ESD Association standard [78] defines dissipative materials as having a conductivity ranging from 1×10^{-11} S/cm to 1×10^{-4} S/cm. On the other hand, conductive materials are defined as materials with conductivity higher than 1×10^{-4} S/cm. Figure 7 illustrates the conductivity ranges of different materials based on the ESD Association standards.

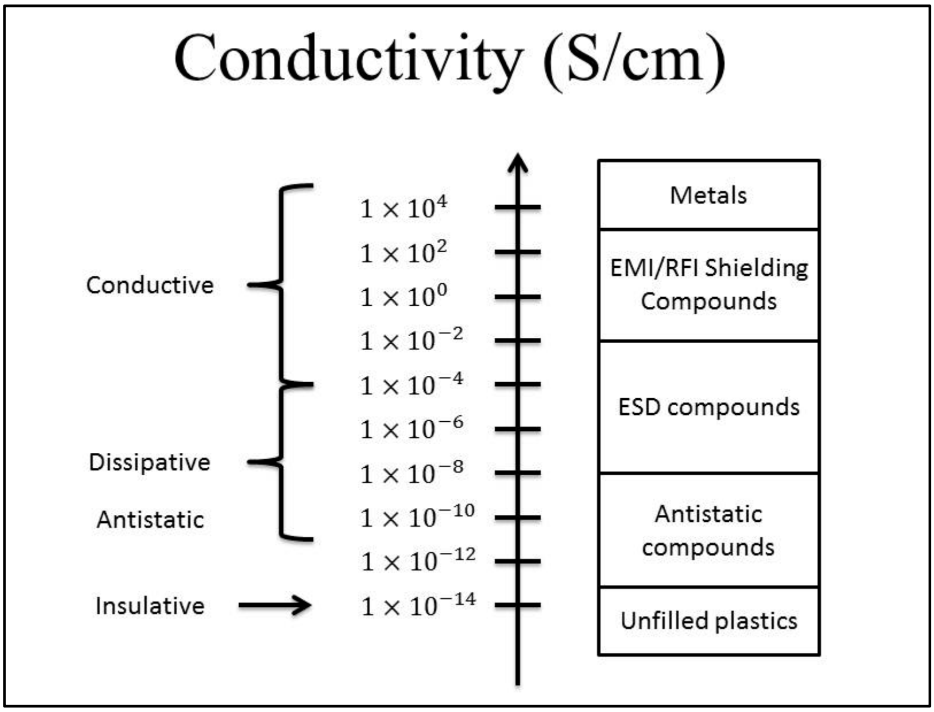

Figure 7. Conductivity ranges for different applications [78,79].

Numerous references in the literature dealing with conductive textiles report conductivities in the dissipative range. Higher conductivity with good mechanical properties must be achieved in order to develop light-weight materials that could replace metallic fabrics. The reported attempts to achieve this goal can be classified in three major categories: (1) inherently conducting polymers, (2) carbon fibers and fibrous structures, and (3) nano-enhanced composite systems combining insulating polymer matrices with conductive additives. In the following section, we comment on those approaches.

3.1. Inherently Conductive Polymers

After Shirakawa, Heeger, and MacDiarmid were awarded the Nobel Prize in Chemistry in 2000 for the discovery of polyacetylene in the mid-1970s, and the subsequent development of conductive polymers into a new research field [80], conductive polymers gained renewed attention because of their potential utilization in antistatic and electromagnetic interference (EMI) shielding applications and in flexible conductive materials [81]. Unlike traditional polymers, conducting polymers have valence electrons in delocalized orbitals which will have high mobility when the materials are "doped" by oxidation [82].

Since the late 1970s, a number of inherently conductive polymers have been studied [83], including polyaniline (PANi) [84,85], PPy [84,86], and PEDOT:PSS [poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate)] [87–89]. One of the early challenges with many inherently conductive polymers was their lack of processability and the difficulty of transforming them into usable structures [84]. A notable approach attempted to overcome this challenge was the use of textile substrates as structural reinforcement for the conductive polymers. For instance, Gregory et al. [84] polymerized PPy and PANi onto nylon, polyester, and quartz fabrics and formed flexible conductive textile structures without deteriorating the mechanical and tactile properties of the fabrics.

One of the polymers cited above, PANi, has attracted considerable attention, among the many different types of conductive polymers, because its monomer, aniline, is inexpensive. Oh et al. [90] prepared PANi-nylon conductive fabrics by immersing the nylon fabric in an aniline solution and initiating oxidative polymerization to synthetize the PANi component. The authors report achieving a fabric with a conductivity of 0.6×10^{-1} S/cm. Diaz-de Leon [91] electrospun doped PANi and obtained a fiber with an average diameter of

10 μm and a conductivity of 0.76 S/cm, similar to that of the bulk material. Zhou et al. [92] also fabricated ultra-thin electrospun nanofibers (<30 nm) using doped PANi and reported a bulk fiber conductivity of 10^{-2} S/cm. In situ polymerization of aniline on non-woven fabrics made of polypropylene was reported by Qi et al. [24] as a successful approach to producing a fabric with conductivity that varies in the presence of various VOCs (including ethanol, chloroform, toluene, acetone and ethyl acetate), enabling its application as conductometric gas sensor. More recently, Sharifi et al. [93] synthetized conductive PANi/cellulosic fiber nanocomposites using the in situ chemical oxidation polymerization of aniline. By optimizing the experimental conditions, the researchers achieved a conductivity of 1.486×10^{-2} S/cm.

Using another conductive polymer, Kaynak et al. [94] prepared conductive yarns of nylon, wool, and cotton. The method they used consisted of applying a layer of PPy on the substrate by continuous vapor polymerization. Vapor-phase polymerization is a process achieved by pre-treating a substrate with an oxidant, then exposing it to the monomer in vapor phase. After exposure of the substrate, a conducting polymer layer forms on the substrate surface. The researchers found that conductivity of the coated yarns could be controlled by modifying reactant concentrations and synthesis parameters. However, the authors state a maximum conductivity "approximately four orders of magnitude smaller than that of metals".

Using similar methods, Xu et al. [95] reported higher conductivity levels in PPy/poly(*p*-phenylene terephthalamide) (PPTA) composite fibers with an electrical conductivity of 0.68 S/cm. Recently, Barani et al. [96] imparted conducive properties to cotton fabric through in-situ polymerization of PANi and PPy coatings onto the fabric. The authors compared the sheet resistance of the produced structures and found the PPy coating to produce the best conductivity [96].

According to the literature reviewed, it appears that a wide range of moderate conductivity levels could be achieved depending on the approach adopted (Figure 8). However, one major drawback of the conducting polymers discussed above is poor mechanical properties compared to metals and to other alternatives (see next section). In addition, conductive polymers do not match the electrical properties of metallic and semi-conductive materials and most of the literature shows conductivities in the ESD range or low EMI range at best (refer to Figures 7 and 8).

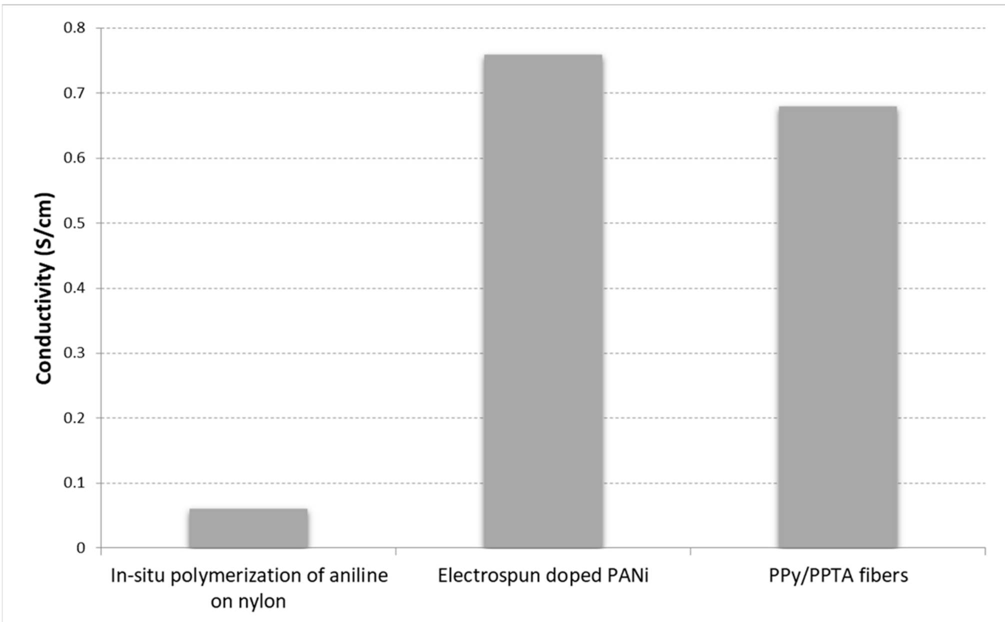

Figure 8. Example conductivity levels of PANi and PPy based materials according to the literature.

Although the conductivity levels reported above are limited to the ESD and EMI ranges, the materials and structures based on inherently conductive polymers offer the potential for higher conductivity with optimized processing conditions. There have been reports of relatively high conductivity levels achieved with doped ultra-thin film structures of PEDOT:PSS. Secondary dopants or additives, such as alcohols or high boiling point solvents, are sometimes added to the dispersion to improve the electrical conductivity of PEDOT:PSS films [97,98]. Xia et al. [89] achieved a conductivity of 103 S/cm in a 130-nm thick PEDOT:PSS film through spin-coating and cosolvent doping [89]. Similarly, Yan et al. [88] used centrifugation, spin-coating, and solvent treatment to form a PEDOT:PSS thin film (93 nm in thickness) on a silicon wafer. The authors report a film conductivity in excess of 443 S/cm [88]. It has also been reported that under optimal processing conditions (doping solvent and pressure) PANi could reach a conductivity in the range of 5.35–7.56 S/cm in pellet form [99]. These results indicate the potential for higher conductivity levels in fibrous and laminate structures based on those materials. For instance, notable progress with PDOT:PSS-based fibers was recently made by Seyedin et al. [100–102]. The authors produced polyurethane (PU)/PDOT:PSS fibers with a range of conductivity levels depending on PDOT:PSS loading in the composite fiber [100–102]. Thus, a high conductivity of up to 25 S/cm was achieved with a 25 wt% loading of PDOT:PSS in PU [100].

3.2. Carbon-Based Fibrous Materials

Carbon fibers are lightweight, flexible, and high-strength materials produced from precursors such as polyacrylonitrile (PAN), pitch, or rayon by a series of carbonization processes. They are used in the construction of aircrafts, space shuttles, sporting goods, and industrial products where performance is sought in conjunction with weight saving. Composites reinforced with carbon fibrous and particulate fillers have been proposed as alternatives to metals in applications such as electrostatic dissipation and electromagnetic shielding [103–105].

Carbon fibers offer a range of electrical conductivity levels depending on the precursor and processing conditions. Compared to PAN carbon fibers, which are commonly used in the industry, pitch-based carbon exhibits better electrical conductivity [106]. According to Minus et al. [107], pitch-based carbon fibers have the potential for electrical conductivities as high as 10^4 S/cm. Using pitch precursors, Park et al. [106] prepared carbon fiber webs by electrospinning followed by stabilization and carbonization of the fiber mat. The electrical conductivity of the fiber web ranged from 63 to 83 S/cm depending on the carbonization temperature. This conductivity is about 10 times higher than the other polymer-based carbonized fibers, such as PAN, polyimide, and polyimidazole.

Another commonly used technique to produce conductive fibrous materials is to homogeneously disperse conductive nanofillers within a polymer matrix. Carbon-based nanomaterials have been widely used to achieve conductivity. Thus, conductive polymer nanocomposites were developed using insulating polymers matrices and conductive nanofiller reinforcements, including carbon nanofibers [108,109], carbon black [110], and carbon nanotubes [111–114]. Graphene and graphene oxide (GO) have also been cited in research aimed at imparting conductivity to textiles and to developing textile sensors and capacitors [19,39,115,116]. Using a method adapted from traditional yarn winding and twisting processes, Ko et al. [112] electrospun continuous polylactic acid (PLA)/PAN yarns filled with CNTs. In another study by Rosca et al. [114], the researchers synthesized bucky papers made of multiwalled CNT webs in epoxy resin and reported conductivities ranging from 13.68 to 36.29 S/cm.

Conductive carbon-filled composites have been spun into fibers using various synthetic and natural polymers. Regenerated cellulose fibers were solution-spun by Lee et al. [117] with multi-walled carbon nanotube (MWNTs) reinforcement. The authors reported an electrical conductivity of 2.7 S/cm achieved with a MWNT loading of 30 wt%. Also using MWNTs as reinforcement, Bilotti et al. [118] melt-spun thermoplastic polyurethane nanocomposite fibers with varied conductivity levels depending on processing condition.

Other polymers reinforced with carbon fillers to impart conductivity include polyamide [119,120] and polyamide/polypropylene composite [121]. Notably, Ra et al. [122] used MWNTs as a reinforcement in PAN prior to carbonization, thus creating a MWNT/PAN-based carbon nanofiber composite structure. Under optimal carbonization conditions and orientation of the MWNT fillers, the material exhibited a conductivity of up to 35 S/cm with 10 wt% loading of MWNT [122].

Using an ionic liquid solvent, 1-methyl-3-methylimidazolium acetate ([EMIM][Ac]), Miyauchi et al. [123] electrospun a core-sheath fiber structure with MWNT in the core, and cellulose constituting the sheath. The fibers had diameters ranging from several hundreds of nanometers to several micrometers. The electrospun MWNT-cellulose fiber mats exhibited a conductive pathway of bundled MWNTs. Fiber mat conductivity increased with an increasing ratio of MWNT in the fibers; however, the maximum conductivity obtained at 45 wt% MWNT loading was only 0.107 S/cm, which is in the EMI shielding range [124]. Sekitani et al. [125] developed a highly conductive elastic film by dispersing single-walled carbon nanotubes (SWNTs) in a vinylidene fluoride-hexafluoropropylene (PVDF-HFP) copolymer matrix, followed by coating with dimethylsiloxane–based rubber. The conductivity level achieved in this research was 57 S/cm [125]. Dalton et al. [126] used a coagulation-based SWNT/polyvinyl alcohol (PVA) spinning method to produce composite fibers with high SWNT content (60% by weight), and exceptional mechanical and electrical properties [126].

In addition to nanocomposite structures, another approach to imparting electrical conductivity using carbon-based additives consists of coating the target textile structures [116,127]. For instance, Shim et al. [127] coated cotton yarns with both SWNTs and MWNTs using a polyelectrolyte base for the binding. Not unlike the results obtained using the nanocomposite approach, SWNT-coated cotton yarns exhibited a higher conductivity (approximately 4×10^{-2} S/cm) compared with MWNT samples [127].

Xiang et al. [116] coated Kevlar fibers with three types of carbon materials: graphene nanoribbons (GNRs), MWNTs, and SWNTs. The carbon structures were affixed to the fiber surface through layer-by-layer spray-coating using polyurethane as an interlayer binder, which provided strong adherence on the fiber [116] (Figure 9). The authors found that among the three types of carbon materials, SWNTs coatings produced the best results with a durable conductivity of 65 S/cm. Using GO in a succession of dip-coating and infra-red baking on a polyester fabric substrate, Yang et al. [39] achieved a conductive structure with piezoresistive properties useable as a strain sensor. With an analogous dipping and drying process of cotton fabric in a SWNT ink, Hu et al. [18] produced a highly flexible and stretchable conductive fabric with a conductivity of 125 S/cm.

Based on the review discussed above, carbon-based fibrous materials appear to offer the potential for higher conductivity than the previous approach using conductive polymers. Representative conductivity results reported with carbon coatings, nanofibers, and nanofillers are summarized in Figure 10.

3.3. Metal Nanocomposite and Nano-Enhanced Conductive Materials

Other than the widely used carbon fillers discussed above, textile structures with metal nano-additives have also been extensively documented with a broad range of applications depending on the conductivity performance. For instance, conductivity levels in the electrostatic charge dissipation range were achieved by Zhou et al. [128] by incorporating zinc oxide whiskers in polyurethane, PVA, and natural rubber. Xue et al. [129] coated woven cotton fabric with silver nanoparticles and generated a multifunctional fabric combining biocidal and conductive performance.

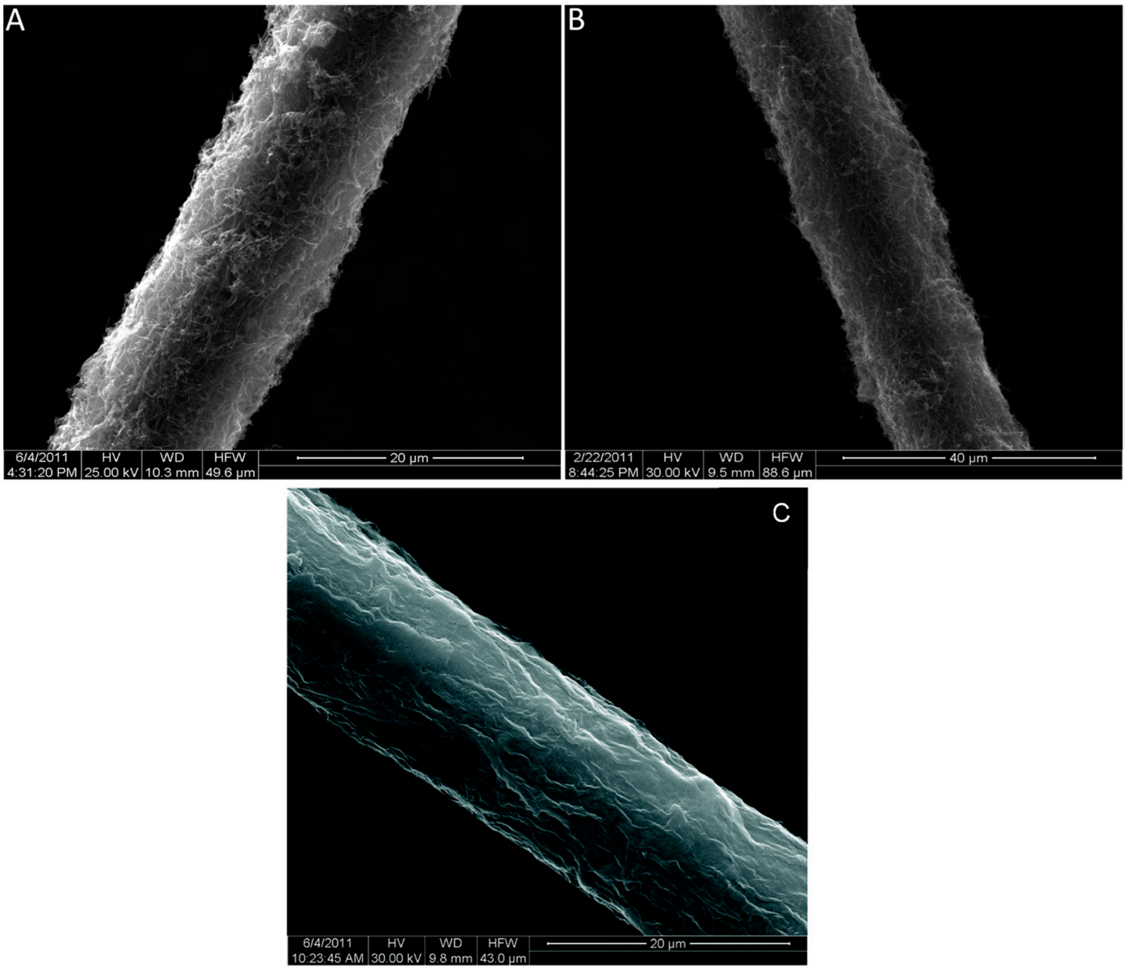

Figure 9. SEM images of (**A**) GNR-coated Kevlar fiber; the scale bar is 20 µm, (**B**) A MWCNT-coated Kevlar fiber; the scale bar is 40 µm; (**C**) SWCNT-coated Kevlar fiber, scale bar is 20 µm. Adapted with permission from [116]. Copyright 2011 American Chemical Society.

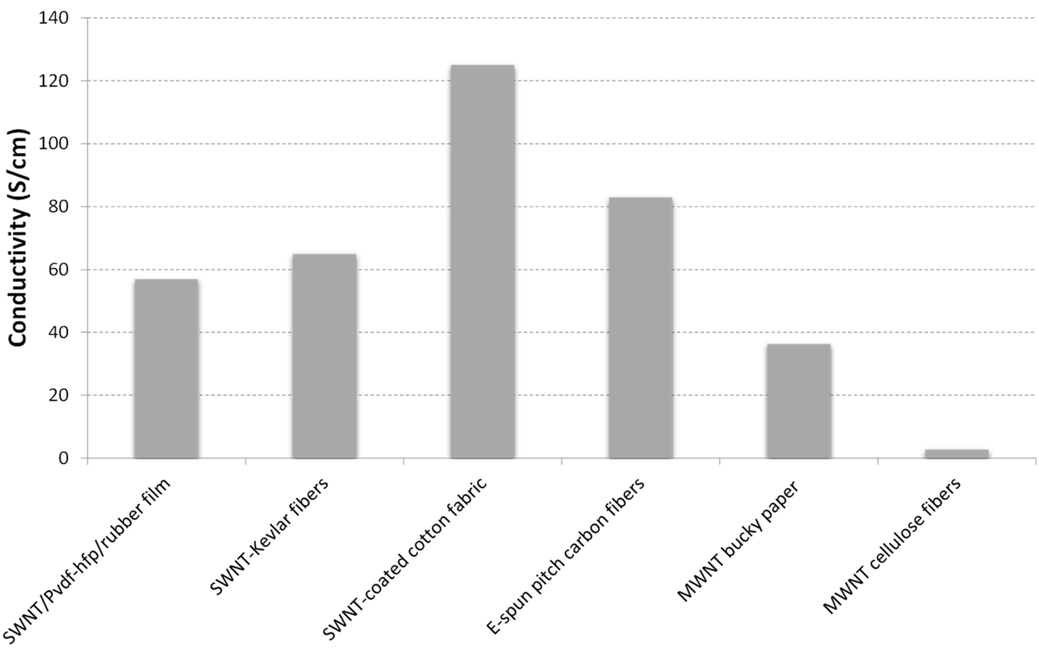

Figure 10. Example conductivity levels of carbon-based materials reported in the literature.

Nickel is another metal that has been reported in research to impart electrical conductivity to textile structures using both coating and nano-filling approaches [130–135]. As a nano-filler, nickel has been commercialized in the form of nanostrands (NiNs) with a branched 3D structure (Figure 11) generated by chemical vapor deposition [132,136–138]. The branched 3D structure has been cited as an advantage of NiNs over other nanofillers (including carbon and metals) in terms of electrical conductivity because it enables more interconnects and thus more conductive pathways within the polymer matrix [136,139–141]. NiNs have been reported as nanofillers with electrical conductivity in polymers such as nylon [132], as well as epoxy, thermoplastic polyurethane, and polyimide [137–140].

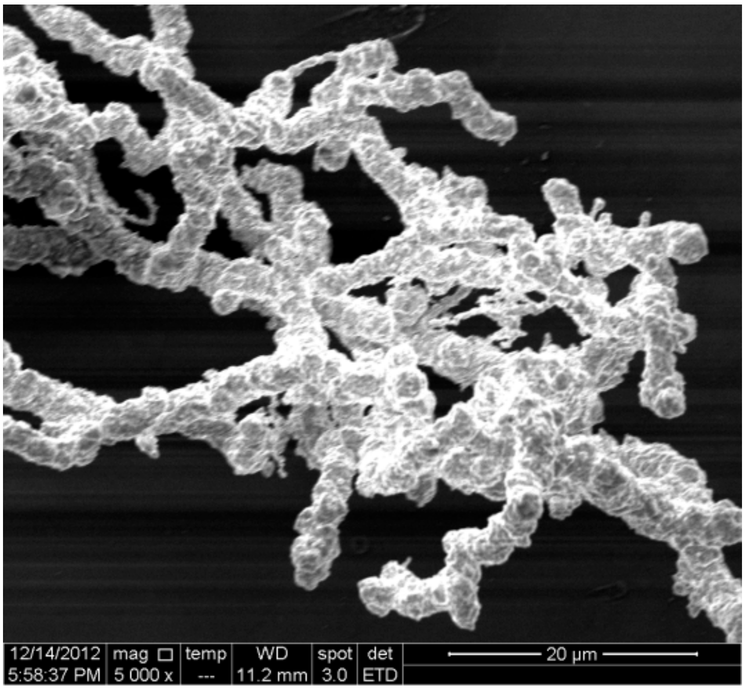

Figure 11. Three-dimensional branched structure of nickel nanostrands [132].

Attempts were also made to incorporate NiNS in inherently conductive polymers such as PEDOT:PSS and yielded a significant two-orders-of-magnitude improvement in conductivity [132]. The investigation of the electrical properties of nanocomposites made from intrinsically conductive polymers has been of interest. Gangopadhyay and De [142] discussed the use of various inorganic nanoparticles, such as SiO_2, SnO_2, TiO_2, and Fe_2O_3, in reinforcing several intrinsically conductive polymers including PPy, PANi, and PEDOT.

In terms of coating approaches, Guo et al. [130] deposited a nickel layer on polyester fabric using electroless plating and succeeded in reaching conductivity levels with effective EMI shielding. More recently, Moazzenchi and Montazer [131] used a similar electroless plating method to synthetize nickel nanoparticles onto polyester fabric, yielding superior EMI shielding performance.

Recently, there has been growing interest in bimetallic layered double hydroxide (LDH) nanostructures, with metals such as nickel, cobalt, and aluminum as important components [133–135]. For instance, Nagaraju et al. [133] grew nickel-cobalt layered double hydroxide (Ni-Co LDH) nanosheets on conductive fabrics useable for energy storage. Similarly, Lu et al. [135] electrodeposited nickel-aluminum layered double hydroxide (Ni-Al LDH) onto cotton fabrics and reported a superior conductivity of 143 S/cm.

Another recent innovation in developing stretchable and highly conductive textile structures was reported by Zheng et al. [46]. The researchers aimed to circumvent the potential for deterioration of conductivity in e-textiles due to mechanical strain and used a coaxial wet spinning process to generate liquid metal sheath-core microfibers with a conductivity of 435 S/cm that remains stable within a 4% range at strains of up to 200% [46]. The liquid metal core used in this research consists of eutectic gallium indium (EGaIn) alloy, which is liquid at room temperature, and offers high electrical conductivity (3.4×10^4 S/cm) that is maintained under mechanical deformation [46,143]. Poly(vinylidene fluoride-hexafluoropropylene-tetrafluoroethylene)/poly(ethylene glycol) diacrylate (PVDF-HFP-TFE/PEGDA) was used as the solution in the sheath channel of the coaxial spinneret [46].

Overall, the different approaches discussed above led to the development of a broad range of flexible, stretchable, and conformal textile structures with conductivity levels that range from antistatic to fully conductive performance. Current challenges remain in ensuring consistent performance while withstanding the mechanical stresses endured during wear and fabric care. For instance, resistance to washing is considered one of the primary challenges to the marketability of e-textiles [144–147]. One of the problems highlighted by Rotzler et al. [144] is the absence of standardized methods for testing the washability of e-textiles, leading to inconsistent washability data. Another review by the same authors [145] presents a comprehensive summary of challenges related to the washability of e-textiles, and the various failure modes caused by washing and impacting reliability. Because of the growing awareness of those challenges, washability and robust performance after laundering have come to the forefront of concerns in recent research aimed at developing e-textiles [146–149]. Recent developments such as metal-based nanostructures and liquid metal core-sheath filaments offer promising solutions toward durable and stable conductivity levels that can withstand wear and wash.

4. Summary

Flexible smart fabrics and conformal textile-based electronic devices are a critical component in the development of body-centric sensing and information communication systems. In the concept of the Internet of Things (IoT), smart clothing is viewed as the interface connecting humans to the numerous and more and more ubiquitous objects with digital functionalities. This paper reviews some representative textile applications for information acquisition and transmission, i.e., textile-based sensors and antennas. In both categories, research has evolved from reliance on metallic structures with limitations in flexibility and drape, to more and more flexible and conformal all-textile structures with effective performance. To achieve this goal, textiles with a range of electrical conductivity have been developed using various approaches, including inherently conductive polymers, carbon-based conductors, and nano-enhanced fibers and fibrous structures. Conductivities achieved in these structures ranged from the antistatic and dissipative bands using inherently conductive polymers, to the semi-conductor and conductor bands achieved with carbon fibrous structures and nanofillers, and other innovations such as Ni-Al LDH coating and liquid-metal core-sheath fibers and filaments.

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