Review on PEDOT:PSS-Based Conductive Fabric

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ABSTRACT: This article reviews conductive fabrics made with the conductive polymer poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), their fabrication techniques, and their applications. PEDOT:PSS has attracted interest in smart textile technology due to its relatively high electrical conductivity, water dispersibility, ease of manufacturing, environmental stability, and commercial availability. Several methods apply PEDOT:PSS to textiles. They include polymerization of the monomer, coating, dyeing, and printing methods. In addition, several studies have shown the conductivity of fabrics with the addition of PEDOT:PSS. The electrical properties of conductive textiles with a certain sheet resistance can be reduced by several orders of magnitude using PEDOT:PSS and polar solvents as secondary dopants. In addition, several studies have shown that the flexibility and durability of textiles coated with PEDOT:PSS can be improved by creating a composite with other polymers, such as polyurethane, which has high flexibility and extensibility. This improvement is due to the stronger bonding of PEDOT:PSS to the fabrics. Sensors, actuators, antennas, interconnectors, energy harvesting, and storage devices have been developed with PEDOT:PSS-based conductive fabrics.

1. INTRODUCTION

1.1. Electronic Textiles. Electronic textiles, often known as smart textiles, are fibers that are capable of sensing heat, communicating, and transmitting information. Research into “smart textiles” is currently a growing topic of scientific interest due to their diverse applications and environmentally friendly properties. Conductive fabrics, which are used in the smart textile area, have broad applications, such as sensors,7−3 photovoltaic devices, heating textiles, devices for electrotherapy,10 wearable computers, actuators,13 and electrostatic discharge clothing.14 Another application of smart textiles can be found in various wearable electrodes,35 heat storage,16−17 and thermoregulated clothing.18−19 Base fabric materials, including cotton, wool, polyester, and nylon, are used as substrates for fabricating conductive fabrics.20−27 These substrates can be made conductive by coating or implanting the fibers or the fabric with conductive materials such as gold,28−29 copper,30 titanium,31 nickel,32 and silver.33 Conductive polymers,34−36 carbon black,21,37 carbon nanotubes,38−40 graphite,41 and graphene41,42 are other conductive materials used to manufacture conductive fabrics.

2. METAL-BASED CONDUCTIVE FABRICS

2.1. Advantages and Disadvantages of Metallic Fabrics. Conductive metallic fabrics can be made by adding metallic nanoparticles and metal fibers to the fabrics, which give the material high conductivity,28−33 improve its strength,43 give high heat resistance since metals have a high melting point, and are less likely to degrade under elevated temperatures. Furthermore, conductive metallic fabrics have a high interference electromagnetic shielding effect.44 However, their low flexibility, high cost, and incompatibility with other materials limit their textile applications. Metallic materials can also irritate the skin and affect comfort. In addition, the surface energy of metals is high, which leads to rapid oxidation. Metals are not suited for crafting highly complex fabric geometries or shapes. Table 1 shows the advantages and disadvantages of the various methods of manufacturing metal-based conductive fabrics.

2.2. Literature Review on Metallic Fabrics. Xue et al.45 fabricated superhydrophobic and conductive cotton fabrics by coating fibers in situ with silver nanoparticles followed by hydrophobization. The two-point probe method was used to measure the resistance of the modified hydrophobic cotton fabric. The results show that cotton fabrics have antibacterial

Received: March 25, 2022
Accepted: September 27, 2022
Published: September 30, 2022
properties with a low resistance of 37.0 Ω ± 1.8 Ω. Recently, Zhu et al. fabricated conductive polypropylene fabrics with copper nanoparticles by a simple spray method. The superhydrophobicity of the fabric was achieved after 4 h of vacuum drying without any surface modifiers. The conductive fabric has a minimum sheet resistance of about 0.92 Ω/□ with excellent superhydrophobicity. El-Shamy designed a nanocomposite of PEDOT:PSS and carbon dot films by using sulfuric acid via a casting technique for thermoelectric applications. Because of the formation of conductive pathways within the films and the improvement in both carrier mobility and carrier concentration, the through-plane conductivity (σ⊥) and in-plane conductivity (σ//) values increased with increasing nanodots to σ⊥ = 165.3 ± 5 S/cm and σ// = 254.9 ± 10 S/cm (3 wt % nanodots). Babaahmadi et al. prepared a conductive, durable, and flexible polyethylene terephthalate (PET) fabric by coating silver nanoparticles and reduced graphene oxide on a PET surface via thermal annealing at relatively low temperatures. The results show that the electrical conductivity and durability were significantly improved after thermal treatment due to the sintering of the silver nanoparticles between the layers of reduced graphene oxide and the PET fibers. The electrical conductivity reached the maximum value of 0.26 S cm−1 using a four-point method to measure the sheet resistance. Ahmad et al. investigated the electrical conductivity and durability of cotton, polyester, and nylon fabrics after coating each type with different concentrations of silver nanoparticles, using the dipping and drying process to deposit silver nanoparticles to the surface of the fabric. The concentration of silver nanoparticles and the type of substrate affect the electrical conductivity and durability. Nylon fabrics showed the best performance compared to cotton and polyester fabrics, as they had the highest conductivity value at a certain concentration of silver nanoparticles. Moreover, the conductivity of the fabrics increases with the concentration of silver nanoparticles and decreases after washing, and the maximum conductivity was 208 × 10−5 S/cm. Ali et al. prepared two electrically metallic cotton fabrics by depositing gold and silver nanoparticles. Then, a thin layer of gold was added to the two samples using the electrosless plating method. The surface resistivity of the cotton fabrics was 620 Ω and 756 Ω for the gold and silver nanoparticles deposited on the fabrics, respectively. After electrosless gold plating of the fabric with gold and silver nanoparticles, a surface resistivity of 20 Ω and 27 Ω, respectively, was obtained. Furthermore, the samples with modified electrosless plating showed longer durability. Gao et al. fabricated conductive, flexible, superhydrophobic, antibacterial, and ultrahigh electromagnetic shielding cotton fabrics. Polydopamine was formed by first immersing cotton fabrics in a dopamine hydrochloride solution for 24 h and then washing them with ethanol and DI and drying them (self-polymerization) (see Figure 1). Second, the cotton fabrics were soaked in silver ammonia solution to obtain silver nanoparticles on the surface of the sample. Polydopamine connects silver nanoparticles and cotton fibers. Finally, the sample was coated with thin-layer polydimethylsiloxane (see Figure 1) or polyimide to fabricate superhydrophobic surfaces. The EMI shielding efficiency reached a maximum of 110 dB at a deposition time of 90 min, while the electrical conductivity of the sample was 1000 S/cm. Furthermore, conductive cotton fabrics exhibit adequate durability and antibacterial properties against Staphylococcus aureus and Escherichia coli.

3. CONDUCTIVE POLYMERS

Conductive polymers (CPs) have attracted great interest mainly because of their special structure. Their backbone consists of single and double bonds that alternate with each other (see Figure 2). Doping can increase their electrical conductivity by several orders of magnitude through the formation and movement of charge defects (polaron, bipolaron, and soliton) through the polymer backbone. CPs can store and transfer charge in the electrical double layer because they contain functional groups that have pseudocapacitance properties. Therefore, CPs have a high capacitance. CPs are used in the manufacture of conductive textiles because they give the fabric the feel of cloth and are lightweight, and the mechanical properties of the fabric are not affected by a thin coating of CP. They have also been used in applications such as thin-film transistors, sensors, displays, electrochromic devices, supercapacitors, light-emitting diodes, and field-effect transistors and in wide applications in energy conversion, storage devices, and solar cells.

4. PEDOT:PSS

Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) is an organic conductor that is receiving attention in electronics and smart textiles. It is a doped p-type semiconductor in which sulfonate anions in the PSS chains

Table 1. Advantages and Disadvantages of Different Fabrication Methods of Metal-Based Conductive Materials

| Method         | Advantages                                           | Disadvantages                                      | Ref |
|----------------|------------------------------------------------------|----------------------------------------------------|-----|
| Spraying       | Low cost, direct deposition. Simple process and no vacuum required. Metallic and organic particles can be deposited. | Multiple process steps and hard-to-scale production and annealing are required. | 45  |
| Casting        |                                                      |                                                    | 46  |
| Coating        |                                                      |                                                    | 47  |
| Dip and dry    |                                                      |                                                    | 48  |
| Deposition     |                                                      |                                                    | 49  |
| Spraying       |                                                      |                                                    | 50  |
chains were found to affect the electrical conductivity of counterions that balance the positive charge in PEDOT:PSS films. PEDOT:PSS can be deposited on a substrate by various methods, such as dip coating, inkjet printing, spin coating, and spray coating. Recently, a new technique for making conductive polymer films has become available, called sequential solution polymerization. This technique can be used to produce conductive films for large-scale applications. PEDOT:PSS films by spin coating PEDOT:PSS on a silver nanowire substrate and PDMS. The sheet resistance and elongation of the hybrid materials PEDOT:PSS and polydimethylsiloxane (PDMS) by the drop-casting method. Ethylene glycol was used as a secondary dopant, and Triton X-100 was used to improve the solubility between PEDOT:PSS and PDMS. The sheet resistance and elongation of the hybrid films were investigated as a function of the concentration of ethylene glycol and Triton X-100 in the films. It was found that the ratio of ethylene glycol and Triton X-100 affected the sheet resistance of the films and their elongation. The sheet resistance of the hybrid films with 7 wt % EG and 10 wt % Triton X-100 reached a minimum value of 20 Ω/sq, and the elongation at break was approximately 82%. This improvement in conductivity was attributed to the effect of ethylene glycol as a secondary dopant, which leads to high charge carrier mobility, and Triton X-100 decreases the ionic interaction between PEDOT and PSS. Moreover, the addition of Triton X-100 improved the mechanical compliance.

5. PEDOT:PSS-BASED CONDUCTIVE FILMS

PEDOT:PSS films can be deposited on a substrate by various methods, such as dip coating, inkjet printing, spin coating, and spray coating. Recently, a new technique for making conductive polymer film fabrics has become available, called sequential solution polymerization. This technique can be used to produce conductive films for large-scale applications. PEDOT:PSS films by spin coating PEDOT:PSS on a silver nanowire substrate and PDMS. The sheet resistance and elongation of the hybrid materials PEDOT:PSS and polydimethylsiloxane (PDMS) by the drop-casting method. Ethylene glycol was used as a secondary dopant, and Triton X-100 was used to improve the solubility between PEDOT:PSS and PDMS. The sheet resistance and elongation of the hybrid films were investigated as a function of the concentration of ethylene glycol and Triton X-100 in the films. It was found that the ratio of ethylene glycol and Triton X-100 affected the sheet resistance of the films and their elongation. The sheet resistance of the hybrid films with 7 wt % EG and 10 wt % Triton X-100 reached a minimum value of 20 Ω/sq, and the elongation at break was approximately 82%. This improvement in conductivity was attributed to the effect of ethylene glycol as a secondary dopant, which leads to high charge carrier mobility, and Triton X-100 decreases the ionic interaction between PEDOT and PSS. Moreover, the addition of Triton X-100 improved the mechanical compliance.

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fabricated graphene/PEDOT:PSS composite films on a polyethylene terephthalate substrate by spin and blade coating methods. The effects of graphene concentration and ultrasonic vibrations on the transparency and sheet resistance of the composite films were investigated. The transmittance of the composite films decreased with increasing graphene concentration because graphene absorbs more photons at high wavelengths. In addition, the transmittance decreased with increasing vibration of the substrate due to the transmission of ultrasonic energy to the substrate. It was also found that the sheet resistance of the composite films depended on the graphene content and ultrasonic vibration. The sheet resistance of the composite films decreased by 3 to 4 orders of magnitude compared to that of the PEDOT:PSS films. In addition, the single-layer composite films prepared with substrate vibration exhibited lower sheet resistance, which was attributed to the improvement in film homogeneity and the prevention of agglomeration of graphene. In contrast, the sheet resistance of the two-layer composite films did not decrease because the film was more uniform. In another study, conductive PEDOT:PSS films were prepared by spin-coating PEDOT:PSS with an optimal 5 wt % DMSO solution on glass substrates, followed by a drying process in which the doped films were heated to 100 °C for approximately 1 h to evaporate the solvent. Then, the resulting films were exposed to DMSO vapor for different times. The results showed that a considerable improvement in electrical conductivity occurred after the films were exposed to DMSO vapor and that this depended on the duration of the vaporization of DMSO. The electrical conductivity of the films increased from 673.4 S/cm (before exposure to DMSO vapor) to 900 S/cm (after 20 min of exposure to DMSO vapor) and then slowly increased to 979 S/cm until 60 min. In addition, the thermal properties of the films also improved after exposure to DMSO vapor, with the Seebeck coefficient increasing from 13.41 μV/K at 0 min to 14.72 μV/K at 20 min and 15.85 μV/K at 60 min. The tremendous improvement in thermoelectrical properties suggests a change in the morphology and conformation of the PEDOT:PSS film by the addition of DMSO, which may improve the molecular arrangement and further increase the mobility of charge carriers. In a recent study, hydrothermal treatment was used instead of organic solvents to improve the electrical conductivity of PEDOT:PSS films. In this treatment, the relative humidity and temperature were greater than 80% and 61 °C, respectively. The electrical conductivity increased from 0.495 S cm−1 (for untreated films) to 125.367 S cm−1 (for the hydrothermally treated films). The improvement in conductivity is due to the reduction in the Coulombic attraction between the positively charged PEDOT chains and the negatively charged PSS chains, which leads to structural rearrangement of PEDOT:PSS. In a recent study, Raman et al. prepared thin nanocomposite films of indium tin oxide nanoparticles and PEDOT:PSS using the bar coating method on a polyethylene terephthalate substrate (PET). The films were annealed at low temperatures in plasma by exposing them to O2 plasma after posttreatment with H2SO4. A decrease in sheet resistance from 1105 Ω/□ to 535 Ω/□ and an increase in optical transmission at 550 nm from 85.91% to 89.71% for unannealed and annealed films, respectively, were observed. This improvement was attributed to the transfer of plasma energy to the lattice of the films, which led to a change in the crystallinity of the composites.

Xia et al.105 prepared PEDOT:PSS films on a glass substrate by spin coating after treating PEDOT:PSS with dilute sulfuric acid. The maximum conductivity of the PEDOT:PSS films reached 3065 Ω cm−1 by multiple treatments with H2SO4. Moreover, the sheet resistance and transparency (at 550 nm) of the PEDOT:PSS films were 39 Ω/sq and 80%, respectively. The cosolvent treatment of PEDOT:PSS films was used to prepare a buffer layer in polymer solar cells, using hydrophilic methanol and hydrophobic 1,2-dichlorobenzene as cosolvents.106 The conductivity increased from 10−3 S cm−1 to 1 S cm−1, and the photovoltaic efficiency also improved from 3.98% to 4.31%. Methanesulfonic acid treatment of PEDOT:PSS films was used to fabricate transparent electrodes on glass and PET substrates for perovskite solar cells.107 The conductivity of the treated PEDOT:PSS films exhibited high transparency with a maximum conductivity of more than 2000 S cm−1. The optimum power conversion efficiency is 11.0% for the rigid perovskite solar cells with glass substrates and 8.6% for the flexible PSCs with PET substrates. In another study, chloroplatinic acid added to an aqueous PEDOT:PSS solution was used to prepare a conductive, transparent, and flexible film on a glass substrate with an optimum sheet resistance of 41 Ω/sq and a transparency (at 550 nm) of 85%. This improvement was attributed to the reduction of the Coulomb force between PEDOT and PSS. It was also observed that the films did not lose their conductivity at a bending radius of 3.5 mm for 1000 times. Wang et al.108 presented a new approach to fabricate conductive PEDOT:PSS films with a maximum conductivity of 1996 S cm−1 and a maximum power factor of 203.1 μW m−1 K−2 to be used as flexible thermoelectric generators. In this approach, the films were prepared from PEDOT:PSS doped with sulfonic acids. DMSO and hydrazine were then dropped onto the films to adjust the degree of oxidation. A series of mineral acids were added as dopants to PEDOT:PSS to produce PEDOT:PSS films.110 The resulting conductivity was found to depend on the nature and concentration of the acids, with the highest conductivity obtained at 2244 S cm−1 for 0.08 M H2SO4. The increase in conductivity was attributed to the phase separation between PEDOT and PSS and also to the increase in the concentration of the polaron or bipolaron in PEDOT.

6. PEDOT:PSS-BASED CONDUCTIVE FABRICS

This review focuses on the development of conductive fabrics using PEDOT:PSS. PEDOT:PSS has been used in a variety of textile applications. One of the simplest processes is to coat the fibers or fabric with PEDOT:PSS by soaking,111 dipping,112–114 drop-casting,115–119 spraying,120,121,122 immersing,123–125 drying, and/or annealing to form a film. These processes have the advantage of resulting in flexible, lightweight textiles with high conductivity. Textiles such as polyethylene terephthalate (PET) (see Figure 4), woven Spandex fibers, cotton, and polyurethane nonwoven fibers can benefit from these processes. In addition, chemical vapor deposition126 and

Figure 4. Chemical structure of polyethylene terephthalate (PET).
plasma treatment techniques have been used to develop uniform layers of conductive polymers on the fiber surface. Another method to create uniform layers of conductive polymers on the fiber surface is in situ polymerization of conjugated polymer systems on the surface of the textile fiber. Similar to the methods listed below, this technique can be used to produce flexible and lightweight fabrics with good conductivity. Some of the disadvantages of these methods are the complex manufacturing processes, difficult scalability of production, and inevitable degradation of the natural properties of the textiles. For this reason, printing techniques such as screen printing and inkjet printing have been developed to produce conductive patterns on textiles and washable conductive fabrics at a low production cost and large scale. The only limitation with these techniques is the durability of the fabrics produced. The advantages and disadvantages of the different manufacturing techniques for conductive fabrics with PEDOT:PSS are summarized in Table 2.

Ding et al. prepared a conductive Spandex fabric with an electrical conductivity of 0.1 S/cm by immersing it in an aqueous PEDOT:PSS solution containing 2 wt % of D-sorbitol and then air-drying it. It was found that the electrical conductivity increased linearly by repeating the immersion process and reached a maximum value of 1.71 S/cm. The stability of the PEDOT:PSS films was also reported, with the conductivity decreasing with increasing storage time. In addition, the conductivity increased when the Spandex fabric was stretched, as the orientation of the polymer caused the particles to approach each other, facilitating charge hopping. Otely et al. fabricated conductive PET nonwoven fabrics with silica nanoparticles using PEDOT:PSS and DMSO as organic conductors and secondary dopants, respectively, and the drop-casting method. The sheet resistance decreased exponentially with the amount of polymer up to 0.3 wt % and then decreased slowly. The sheet resistance reached a minimum value of 3.2 Ω/sq at a high current capacity of 1.09 A mm⁻² for nonwoven fabrics containing 5.7 wt % of PEDOT:PSS. This is due to the phase separation caused by the covalent bonding between polystyrene sulfonic acid and silica nanoparticles on the surface of PET nonwoven fabric during annealing. In addition, DC voltage up to 8 V was applied to the fabrics; the temperature was recorded; and it was found that the temperature change increased linearly with increasing input power, reaching a maximum temperature of 150 °C at a maximum power of 8.6 W. This sample was stable for 10 min and then degraded. Moreover, the conductive fabric applied with a voltage of 7 V was stable at a temperature of 131 °C for several hours, indicating that this sample is suitable for resistance heating applications.

Yeon et al. investigated the effects of using combinations of PEDOT:PSS and the ionic agent sodium dodecyl sulfate (SDS) (see Figure 5) on the electrical conductivity and mechanical stability of polyurethane fabrics and cotton fabrics using the mixing method followed by the dipping method. A fixed amount of SDS ranging from 0 to 40 mM was added to the PEDOT:PSS solution and applied to the fabrics using a poly(1,1,2,2-tetrafluoroethylene) filter (mixing method). Then, the fabrics were impregnated with the PEDOT:PSS solution and immersed in SDS solution (dipping method). The sheet resistance of cotton fabrics (24 Ω/sq) was lower than the sheet resistance of polyurethane fabrics (48 Ω/sq) because 1.6 mg cm⁻² of PEDOT:PSS coated the cotton, while 0.7 mg cm⁻² of PEDOT coated the polyurethane. In addition, it was observed that the sheet resistance of the fabrics decreased as the number of coatings increased. The achievement of low sheet resistance was attributed to the nature of the bond, porosity, and hydrophilicity of the fabrics. In addition, the effect of tensile strain (ε) on the normalized sheet resistance of conductive cotton and polyurethane fabrics was also investigated. The normalized sheet resistance increased with increasing tensile strain of both samples. The values of normalized sheet resistance were consistent and different from the calculated values at ε ≤ 20 and ε > 20, respectively. A flexible heater using conductive cotton with a sheet resistance of 24 Ω/sq was also designed, as an application of stretchable conductive fabrics. The conductive cotton heater exhibited reversible electrical behavior with a heat capacity of 2 J K⁻¹, a convective heat transfer coefficient of 30 W m⁻² K⁻¹, and a tensile strain of more than 80%.

![Figure 5. Chemical structure of sodium dodecyl sulfate (SDS).](http://pubs.acs.org/journal/acsodf)

| Technique          | Advantages                                                                 | Disadvantages                                                                 | Ref  |
|--------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------------|------|
| Soaking Dipping    | Simple process, no vacuum required, low cost. Good conductivity and other electrical properties are obtained. Conservation of the original fiber properties such as density, flexibility, and handiness and durability. | Multiprocess steps, slow process, and difficult to scale production.          | 111  |
| Drop-casting       |                                                                          |                                                                               | 112  |
| Spraying           |                                                                          |                                                                               | 113  |
| Immersing          |                                                                          |                                                                               | 114  |
| Inkjet printing    | Possibility of a large-scale production and low cost. Good conductivity and other electrical properties are obtained as a pattern. | Durability of printed patterns.                                               | 115  |
| Screen printing    |                                                                          |                                                                               | 116  |

Table 2. Advantages and Disadvantages of Different Manufacturing Techniques for Conductive Fabrics with PEDOT:PSS
Moraes et al.\textsuperscript{114} coated a polyamide nylon fabric (see Figure 6) with glycerol-doped PEDOT:PSS after treating the fabric with an atmospheric double barrier dielectric plasma. The electrical properties of the coated fabrics were compared with the addition of glycerol and/or the plasma treatment. It was found that the electrical resistivity of the conductive fabrics reached the minimum value of 0.14 ± 0.03 \(\Omega\) cm when they were coated with 5-layer glycerol-doped PEDOT:PSS and plasma treatment. The improvement in the conductivity of PEDOT:PSS after plasma treatment is due to the changes in the chemical and morphological properties of the fiber surface. In addition, glycerol enables the PEDOT:PSS grains to reorient in the direction of elongation, which makes them easily withstand tensile deformation and improves the uniform electrical conductivity. The effect of applied voltage on the current density of plasma-treated samples coated with 1 layer and 5 layers of PEDOT:PSS was also investigated, with and without glycerol doping. The results showed that the Joule heating power of the fabrics depended on the thickness of the layer, which in turn was affected by the applied voltage. It was also observed that the doped 5-layer sample reduced the operating voltage to 7.5 V and caused a temperature change up to 38 °C above human body temperature with good stability for up to one hour. These fabrics are suitable as heating elements for applications such as clothing and car seats.

Conductive PET fabrics were prepared using PEDOT:PSS and the secondary dopant DMSO by the spray-dry method.\textsuperscript{120} The electrochemical properties and thermal performance were investigated at different coating amounts. The sheet resistance of the conductive fabrics decreased from 76.50 \(\Omega/\square\) to 12.10 \(\Omega/\square\) by increasing the number of coatings from 2 to 8 layers. The lower value of sheet resistance was attributed to the increase in the thickness of the PEDOT:PSS layers and the formation of conductive paths. Moreover, the surface temperature of PEDOT:PSS-coated PET fabric changed from 38.0 to 56.2 °C when the applied AC voltage was changed from 1 to 7 V. Guo et al.\textsuperscript{75} fabricated 5 mm wide wires from conductive nonwoven PET using sponge stencils, injection printing techniques, and PEDOT:PSS. The most important result of their work was that the wire fabricated from the sponge stencil had the lowest sheet resistance of 2.7 \(\Omega/\square\) with 1.59 mg of PEDOT:PSS, compared to 3185.7 \(\Omega/\square\) for the wire fabricated by inkjet printing with 0.15 mg of PEDOT:PSS. It was also shown that printed PEDOT:PSS DC wires can sufficiently transmit at small currents with a small amount of PEDOT:PSS. An electrical circuit consisting of printed wires representing both resistance and conductive connections between different resistors was also constructed. PEDOT:PSS fabric wires were manufactured using the screen-printing method.\textsuperscript{129} This fabric wire was used as an electrode for monitoring electrocardiography (ECG) signals without using a hydrogel around it. The initial results of this study showed that the sheet resistance of fabric wire depended on the number of screen-printed PEDOT:PSS layers, i.e., the amount of PEDOT:PSS in the wire. As the number of PEDOT:PSS layers increased, the sheet resistance of the fabric decreased and reached a minimum value of 5.6 \(\Omega/\square\) at five PEDOT:PSS layers. In addition, ECG signals were recorded for PEDOT:PSS and copper electrodes on Ag/AgCl attached to the chest. The amplitude of the first wire was 2% lower than the amplitude of the second wire with an average sheet resistance of 5 \(\Omega/\square\). It was found that the PEDOT:PSS wire can be used to measure the ECG signal when the temperature varies between 0 and 50 °C under real-time conditions.

Another method,\textsuperscript{115,116} different from most conventional methods, was the fabrication of highly electrically conductive PEDOT:PSS cotton fabrics with a wide range of sheet resistances from M\(\Omega/\square\) to 1.58 \(\Omega/\square\) without using metal, carbon, and/or silica nanoparticles. This method was based on increasing the concentration of DMSO-doped PEDOT:PSS on cotton fabrics. Low sheet resistance could be achieved in two ways: by drop-casting a small amount of PEDOT:PSS, drying, and then repeating this procedure several times or by drop-casting a large amount of PEDOT:PSS and then drying in one or two trials. A remarkable decrease in sheet resistance by 9 orders of magnitude from 3.75 \(\times\) 10\(^{12}\) \(\Omega/\square\) to 69.06 \(\Omega/\square\) was observed for untreated cotton and for cotton treated with 0.2 wt % of PEDOT:PSS. At low concentration values, the sheet resistance showed nonlinear behavior as a function of concentration since the electrical paths were not continuous. However, at high concentration values, the sheet resistance showed linear behavior since the paths were continuous due to the overlap of the PEDOT:PSS domains. At a saturation concentration of 21.7 wt %, the sheet resistance reached a minimum value of 1.58 \(\Omega/\square\), which can be attributed to the high degree of crystallinity of PEDOT:PSS at this concentration. The resistance of the conductive cotton fabrics as a function of temperature in the range of 30 to 100 °C showed that the fabrics exhibit semiconductor-metal behavior. This behavior was also observed over a frequency range from 10 Hz to 13 MHz. In addition, this study mimicked the actual circuit in which conductive cotton was used to construct a circuit with a 32 W light bulb directly connected to the building power supply (220 V), and the light bulb was operated at full intensity.

Alamer et al.\textsuperscript{117} investigated the effect of the type of cotton fabric on its electrical properties after doping with the aqueous solution PEDOT:PSS with DMSO. Three types of cotton were used, including dental cotton, textile cotton, and gauze cotton, which have the same area of 1 in. × 1 in. The electrical stability of the conductive cotton was also investigated over a period of three months. The results showed that the electrical properties depended on the type of cotton, with dental cotton having the lowest value for sheet resistance (0.0615 \(\Omega/\square\)) compared to textile cotton (0.5061 \(\Omega/\square\)) and gauze cotton (1.2159 \(\Omega/\square\)). The relationship between sheet resistance of the conductive fabric and PEDOT:PSS concentration was also investigated. It was found that the sheet resistance of dental cotton and cotton gauze was inversely proportional to the PEDOT:PSS concentration at low concentrations and then decreased sharply at high concentrations because the fabric could no longer absorb the polymer. In contrast, the sheet resistance of textile cotton was only inversely proportional to the PEDOT:PSS concentration. It was also observed that these conductive substances exhibited good electrical stability with metallic behavior over a period of three months. An electrical circuit was constructed using conductive dental cotton, a 12 W light bulb, and a power supply, and the light bulb was operated...
at full intensity for approximately an hour without damaging the conductive cotton.

PEDOT:PSS and polyethylene glycol (PEG 400)\textsuperscript{112} were used to produce conductive cotton fabrics by a simple dipping and drying process. The DC conductivity of the conductive cotton depended on the number of dip-coating cycles as the coating thickness increased and the void fraction decreased, which contributed to unique electrical transport. The high DC conductivity of 52.02 S/cm after 20 dip cycles results from the formation of a three-dimensional network of conductive PEDOT:PSS particles as the distance between them decreases due to the effect of PEG on the PSS depletion layer. In addition, the electromagnetic interference (EMI) shielding of the PEDOT:PSS/PEG cotton fabrics was investigated over a range of 1 cycle to 25 cycles. The EMI shielding increased with an increasing number of dip-coating cycles and reached the maximum value of 65.6 dB at 25 dip cycles, which was attributed to the increased deposition of PEDOT domains on the surface of the fabric, causing the hopping phenomenon.

Tadesse et al.\textsuperscript{121} presented a new idea for the preparation of conductive PET fabrics by first coating PET fabrics with PEDOT:PSS, drying them, and then immersing them in three additives: polyethylene glycol, ethylene glycol, and methanol (see Figure 7a). The purpose of the immersion was to reduce contamination by water, remove the additives after curing, and reduce surface tension. The samples prepared by this method were electrically conductive and less hydrophilic. The results showed that the sheet resistance values decreased due to the partial removal of the insulating PSS chain from the PEDOT:PSS film. It was also observed that the sheet resistance was independent of the immersion time, indicating that the reaction between PEDOT:PSS and the additives takes little time, and of the type of drying conditions. In addition, the hydrophilic behavior of the conductive PET fabrics was investigated by measuring the contact angle. Different contact angle values were found for the samples with additives compared to those without additives, indicating that all samples were hydrophilic. This is attributed to the partial removal of the hydrophilic PSS when the PEDOT:PSS-coated fabric is immersed in the additives.

Coating and immersion processes\textsuperscript{122} were used to prepare conductive polyamide/lycra knitted fabrics using a composite of PEDOT:PSS, 0.1 wt % of zonyl surfactant, and 5 wt % of DMSO with different types of polyurethane (PU) dispersions at different concentrations (see Figure 7b). PU was used to improve the durability, elasticity, and softness of the conductive fabrics. In the coating method, a rheology modifier was added to the previous composite to obtain a homogeneous conductive paste. Their results compared the electromechanical properties of polyamide/lycra fabrics prepared by coating...
and dipping. The sheet resistance of treated fabrics prepared by the immersion method was lower than the sheet resistance of treated fabrics prepared by the coating method at the same concentration of PU because PEDOT:PSS diffuses easily and penetrates the structure of the fabric as well as into the fiber in the immersion method. For example, at 50 wt % of PU, the sheet resistance was 3.7 Ω/□ and 12.6 Ω/□ for the immersion and coating methods, respectively. Coated and dipped fabrics have quite different surfaces. Substances treated by dipping have a more uniform and smoother appearance, while those treated by coating have nonuniform aggregation due to the rheology modifier. This study also found that the relative resistance of polyamide/lycra fabrics increased only slightly when the fabric was stretched up to 100% for both the immersion and coating methods. However, the relative resistance of the coating sample increased 2-fold compared to the relative resistance of the immersion sample when the stretch increased above 100%. This increase in resistivity at higher strain is due to the lower amount of PEDOT:PSS, causing disruption of the interconnecting pathways for charge carriers.

Tseghai et al.\textsuperscript{131} used a screen-printing technique to fabricate conductive and stretchable cotton fabrics with a composite of PEDOT:PSS and poly(dimethylsiloxane-\textemdash ethylene oxide) (see Figures 8 and 9). The hydrophobic effect of the cotton was first enhanced by using water-repellent fabrics to prevent the composite absorbed into the fabric. The sheet resistance of the conductive cotton fabrics was calculated at different concentrations of poly(dimethylsiloxane-\textemdash ethylene oxide) with a fixed amount of PEDOT:PSS on different surfaces. The resistance increased with increasing surface area for each concentration. It was also observed that the resistance decreased with increasing concentration of poly-(dimethylsiloxane-\textemdash ethylene oxide). Moreover, these treated cotton materials were used to fabricate various types of electrodes: strain electrodes, moisture electrodes, electrocardiography electrodes, and electroencephalography electrodes.

In an interesting study,\textsuperscript{132} conductive nylon nanofibers treated with PEDOT:PSS were used to construct textile-based transmission lines. As shown in Figure 10, the conductive nanofibers were prepared as follows: PEDOT:PSS was dropped on the nanofibers, dried, coated with doped PEDOT:PSS in DMSO, dried, dipped in DMSO, and dried again. Their results showed that the sheet resistance of nanofibers depends on the number of PEDOT:PSS coatings. The minimum sheet resistance was 6.56 Ω/□ for the sample coated with four layers of PEDOT:PSS with a thickness of 7.11 μm. This was attributed to the interconnection between the PEDOT domains, leading to enhanced charge transport.

Figure 8. Chemical structure of poly(dimethylsiloxane-\textemdash ethylene oxide).

Figure 9. Schematic representation of the specimen produced by the screen-printing process, based on ref 131.

Figure 10. Schematic diagram of sample preparation (adapted with permission from ref 132).
Furthermore, the waveforms between the input and output signals of the conductive PEDOT:PSS nanofibers were studied and compared with copper wire. The results showed that the amplitude and phase of the input signal waveform were similar to those of the output signal. The waveforms of the conductive nanofibers and the copper wire were also the same.

Åkerfeldt et al. fabricated conductive PET fibers from the hybrid material PEDOT:PSS and polyurethane. Ethylene glycol (EG) and a rheology modifier were used as secondary dopants to improve the electrical conductivity and hydrophobically modified ethoxylated urethane, respectively. The surface resistance of the conductive fibers was found to depend on the concentrations of PEDOT:PSS, polyurethane, EG, and a rheology modifier. The minimum surface resistance was 12.7 Ω/□ for the sample with formulation of 80 wt % of PEDOT:PSS, 4 wt % of polyurethane, 8 wt % of EG, and 8 wt % of a rheology modifier. In addition, this sample was more ductile due to the increase in the proportion of PEDOT:PSS and EG in the composite, and the tensile strength and flexural stiffness of this formulation were ≥61.4 N and 0.4 gf × cm²/cm, respectively.

Abraitiéné et al. developed a conductive fabric to protect the human body from the effects of electromagnetic fields using PEDOT:PSS as a coating material. Three types of fabrics were used and coated with PEDOT:PSS by the knife-roll method. It was found that the shielding of electromagnetic radiation depended on the concentration of PEDOT:PSS and the structure of the fabric. The resistance of the coated fabrics was also improved by two methods: atmospheric plasma treatment and chemical modification.

7. PEDOT:PSS-BASED CONDUCTIVE FIBERS

PEDOT:PSS conductive fibers have relatively high electrical conductivity, stability, and charge storage, which is why they are used for many high-tech applications, such as smart textiles, flexible electrodes, sensors, and actuators. PEDOT:PSS can be spun into a conductive fiber or filament or can be produced during wet spinning or electrospinning of fibers.

Zhang et al. fabricated highly electrically conductive PEDOT:PSS fibers using the wet-spinning method, as shown in Figure 11. H₂SO₄ was used as the treatment agent, which enabled low fiber density. It was found that the electrical conductivity of the fibers increased with decreasing fiber diameter, reaching a maximum value of 3828 S/cm for fibers with a diameter of approximately 15 μm. The increase in conductivity was attributed to the removal of the insulating PSS component from the polymer and the improvement in the alignment of the PEDOT chains. These conductive fibers can be used in versatile applications, such as touch sensors, supercapacitors, and body moisture monitoring. Zhang et al. fabricated ultrafine conductive nanofibers with an average

![Figure 11. Process of fiber spinning: (a) wet spinning of PEDOT:PSS fibers (adapted with permission from ref 148) and (b) schematic diagram of the electrospinning system (adapted with permission from ref 149).](https://pubs.acs.org/doi/10.1021/acsomega.2c01834)
The electrochemical properties of this conductive approach to fabricate conductive fabrics. Ahmed et al. prepared conductive cotton fabrics using a hybrid of reduced graphene nanoplatelets was also used to prepare conductive cotton fabrics. The results showed that the mechanical and electrical properties of the fabrics were improved, with 20 wt % of graphene nanoplatelets in PEDOT:PSS giving the best values for elastic modulus and maximum elongation. The minimum sheet resistance of the conductive fabrics was 25 Ω/□ after doping the graphene nanoplatelets with dimethyl sulfoxide. Li et al. fabricated conductive fabrics using graphene nanosheets and PEDOT:PSS by a spray-coating method. The conductive fabrics showed an enhanced specific surface capacitance of 245.5 mF/cm², which can be used as flexible textile supercapacitors. Kumar et al. fabricated a supercapacitor on a large scale using reduced graphene oxide, PEDOT:PSS, and carbon cloth. The treated fabrics exhibited a specific capacitance of about 170 F/g at 10 mV/s with an energy of 2880 W/kg and a power density of 4460 W/kg. The supercapacitor with an area of 25 cm² had a capacitance of about 5.5 F per electrode at a mass loading of 2.4 mg/cm².

### Table 3. List of Graphene-PEDOT:PSS-Based Fabrics, Indicating Their Manufacturing Technology, Properties, and Proposed Applications

| PEDOT:PSS composite          | Manufacturing method | Sheet resistance/resistivity | Proposed application                  | Ref |
|------------------------------|----------------------|------------------------------|---------------------------------------|-----|
| PEDOT:PSS/graphene nanoplatelets | Dip-coating drying | 25 Ω/□                       | Biosensors                            | 158 |
| rGO/PEDOT:PSS                | Exhaust drying       | 120 Ω/□                      | Electrocardiogram electrodes          | 159 |
| 3D graphene/PEDOT:PSS        | Coating              | 0.042 Ω/cm                   | Stretchable electronics               | 160 |

The results showed that the sheet resistance of the samples increased with increasing number of washing cycles. It was found that the polyester sample remained conductive after 20 wash cycles, while the cotton sample became insulating. Tadesse et al. improved the durability of PEDOT:PSS fabrics by using different grades of water-based polyurethanes. They found that the wash stability of the polyurethane-treated sample improved after 10 wash cycles compared to the untreated sample because the polyurethanes firmly bonded PEDOT:PSS to the fiber and increased its ability to resist the effects of washing. Islam et al. prepared a conductive fabric with a sheet resistance of 278 Ω/□ by treating the cotton with polydopamine and then coating it with PEDOT:PSS doped with ethylene glycol. They compared the wash resistance between the untreated and treated cotton fabrics and found that the treated cotton was more durable compared to the untreated cotton.

### 9. DURABILITY OF PEDOT:PSS-COATED FABRICS

This section addresses the durability, particularly the wash resistance, of PEDOT:PSS-coated fabrics and PEDOT:PSS composites with other materials for wearable applications. Rubezienė et al. investigated the electromagnetic properties and durability of PEDOT:PSS-coated fabrics. They found that the durability of PEDOT:PSS-coated fabrics improves after plasma treatment because the strength between the PE-DOT:PSS coating and the fibers increases. Ojštrček and Gorgiev fabricated conductive cotton and polyester fabrics using PEDOT:PSS and screen-printing techniques to improve the durability of the fabrics. The sheet resistance of the two types of fabrics was studied as a function of washing cycles. The results showed that the sheet resistance of the samples increased with increasing number of washing cycles. It was found that the polyester sample remained conductive after 20 wash cycles, while the cotton sample became insulating.

### 8. GRAPHEME–PEDOT:PSS-BASED CONDUCTIVE FABRICS

The use of graphene–PEDOT:PSS systems is another approach to fabricate conductive fabrics. Ahmed et al. prepared conductive cotton fabrics using a hybrid of reduced graphene oxide and PEDOT:PSS by the dip-coating drying method. The electrochemical properties of this conductive fabric were improved by excellent stable heating up to 60% strain. The dispersed PEDOT:PSS with graphene nanoplatelets were improved by excellent stable heating up to 60% by treating the cotton with polydopamine and then coating it with PEDOT:PSS doped with ethylene glycol. They compared the wash resistance between the untreated and treated cotton fabrics and found that the treated cotton was more durable compared to the untreated cotton.
untreated cotton after 10 wash cycles because the polydopamine increased the adhesion between the cotton and PEDOT:PSS. Guo et al. developed wash-resistant PEDOT:PSS on nonwoven polyethylene terephthalate using patterning techniques with a minimum sheet resistance of 1.6 Ω. They found that the sheet resistance changed by 6.2% after 3 washing and drying cycles with detergent. In another study, the sheet resistance of the conductive composite cotton containing PEDOT:PSS and rGO was investigated after 1 to 15 washing cycles. The result showed that the sheet resistance of the sample slightly increased after 5 washing cycles, which was due to the fact that part of the conductive composite was removed from the surface of the sample. Further increase of washing cycles to 10 and 15 resulted in an increase of sheet resistance due to the surface damage of the coated layers caused by the strong agitation during washing.

■ CONCLUSION

Finally, the fabrication of conductive fabrics using PEDOT:PSS was reviewed. Several techniques were investigated to incorporate PEDOT:PSS into textiles. One of the simplest methods is to coat the fibers or fabric with PEDOT:PSS by dipping, drop-casting, soaking, drying, and/or annealing to form a film. The advantages of these techniques are that they produce flexible and lightweight fabrics with good conductivity. These techniques are applicable to textiles such as polyethylene terephthalate (PET), woven Spandex fibers, cotton, and nonwoven polyurethane fabrics. The electrical properties of the conductive fabrics were improved by several orders of magnitude with the addition of polar solvents to PEDOT:PSS. In addition, the composites of PEDOT:PSS and other polymers improved the mechanical properties of the conductive fabrics. The main objective of all studies is to achieve sufficient electrical conductivity with the least amount of PEDOT:PSS and to preserve the properties of PEDOT:PSS. Therefore, conductive fabrics based on PEDOT:PSS have been used for various applications, such as strain sensors, ECG electrodes, OLEDs, portable electronic Joule heaters, and other applications. The electrical conductivity and mechanical stability of fabrics coated with PEDOT:PSS need to be further improved. This can be achieved by changing the synthesis method of PEDOT:PSS, using nanoparticles or combining different polymers.

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Notes
The authors declare no competing financial interest.

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