Fabrication Processes of Conductive Textiles

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Wearable electronics are gaining popularity as a platform for the next generation of human-friendly electronic devices. Therefore, a new class of devices with various functionality and amenability for the human body is essential. Traditional textile materials, such as fiber, yarn, and fabric, are non-conductive. Innovative methods and novel processing technologies have been introduced to impart conductivity in textile materials to solve this issue. Coating, printing, deposition, and in situ polymerization are common techniques for this purpose. Here, the newly developed methods with significant potential are summarized, which includes their conductivity level in different applications, such as batteries, displays, and sensors.

Keywords: wearable electronics ; conductive textiles ; vapor deposition ; conductive coating ; 3D printing

1. Deposition Method

The deposition is an effective way of applying a thin coating on textile substrates. Metals or non-metals and intrinsically conductive polymers (ICPs) can be deposited on a suitable substrate by following three steps: (a) scatter or vapor deposition, (b) employing sol precursor, and (c) sintering the substrate to start a sol-to-gel transformation [1].

1.1. Vapor Deposition

Highly pure and high-performing solid materials, such as metal, nanotubes, and ICP, are deposited as thin films of one or several layers [2]. The deposition of thin perovskites is a thin film based on organo-inorganic materials, such as $CH_3NH_3PbX_3$ (X = I−, Br−, Cl−), which has fascinating optical and electronic properties [3]. A film of solid and liquid through vapor deposition without solvent has been investigated. In vapor deposition, vapor can be condensed by two processes: (a) physical condensation or (b) chemical reaction; furthermore, depending on these two processes, vapor deposition is classified by: (i) physical vapor deposition (PVD) and (ii) chemical vapor deposition (CVD) [4].

1.1.1. Physical Vapor Deposition (PVD)

PVD was developed to address the capacity to create a layer with continuous electrical conductivity and the ability to create an element with a specific geometry and dimensions, which is not possible in conventional layering technology such as printing, dipping and so on. [5]. PVD is a process of applying a fine coating of conductive materials on the textile substrate by the vaporization process. PVD comprises four steps: (a) production of vapor phase by evaporation of target materials, (b) transportation of the vapor to the substrate, (c) reaction between the metal atoms and the appropriate reactive gas, and (d) condensing vapor on the surface of the substrate [6][7][8]. PVD can be deposited in almost all materials, such as pure metal, metal, and organic material mixtures such as glasses, alloys, compounds, and layer systems [9]. Silva et al. studied the PVD of aluminium on bare Kapton and when it was coated with PVC/PU [10]. The PVC-coated substrate was the best among the samples for making flexible electronics. Depending on the deposition technique, PVD can be classified by evaporation techniques (vacuum thermal evaporation, electron beam evaporation, laser beam evaporation, pulsed electron deposition, arc evaporation, molecular beam epitaxy, ion plating evaporation) [11] and the sputtering technique [12][13][14]. A silver coating was deposited on cotton fabric using PVD (vacuum thermal evaporation) with a Flexicoat 850 coating apparatus to impart conductivity [15]. The same process was used to deposit a nano-coating of Al and Zn on cotton fabric, with Zn coating having a greater EMI shielding performance than Al-coated cotton fabric [16].

Sputtering is a non-thermal physical vapor deposition technique where molecules move from the surface of the material through the knocking of high energy particles. Molecules that emerge from the target material by the shell firing of high energy particles on the material are condensed on the surface of the substrate to deposit a thin film of the target material [17]. Park et al. investigated DC magnetron sputtering of an Ni-Fe/Cu multi-layer (500 nm Ni-Fe/500 nm Cu) thin film to impart conductivity and led to an EMI shielding effect in the range of 0.7 GHz–6 GHz, which is a better EMI shielding

effect than a pure Ni-Fe and Cu layer [18]. Sputtering deposition of Cu metal is used to make ECG electrodes for biomonitoring smart wear [19]. Wang et al. reported the very first PVD of amorphous carbon-coated 3D $NiCo_2O_4$ on carbon cloth to make a binder-free flexible electrode with high dimensional and cyclic stability (535.47 mAhm^{-1} at 500 mA g^{-1} for 100 cycles) capacity and electrochemical performances [20]. A better electrochemical performance was found for $NiCo_2O_4$/NiO/C composites on carbon cloth obtained by magnetron sputtering PVD of $NiCo_2O_4$ nanowires/NiO nanoflakes with cyclic stability (1051 mAh g^{-1} for 100 cycles at 100 mA g^{-1}) [21].

1.1.2. Chemical Vapor Deposition (CVD)

CVD refers to the segregation or chemical reactions of gaseous reactants near a heated substrate surface in an activated situation (heat, light, plasma), which will finally form a stable solid product [22]. Its history goes back to 1893 when De Lodyguine (an electrical engineer and inventor) deposited tungsten onto carbon lamp filaments through the reduction of tungsten hexachloride (WCl_6) by hydrogen (H_2). This initiated the pedestal of the industrial utilization of CVD [23]. Typically, the CVD method is applied to deposit conductive polymers on the textile substrate (fiber, yarn, fabric) [24]. The fundamental concept of CVD is a chemical reaction that forms a layer on the substrate from the vapor of the reagents, leaving the by-products in a volatile form.

Researchers experiment with different kinds of materials by using the CVD method to make textile materials conductive. $FeCl_3$-coated cotton yarns were exposed to pyrrole vapor, thereby producing a coated layer of PPy on cotton yarns [25]. The CVD method is adopted for PPy deposition in various fabrics such as viscose, cupro, lyocell, nylon, PET and so on. [26][27][28].

The CVD process is a recognized technique for making highly conductive polymeric layers on different substrates [29]. To get high conductivity and a uniform polymeric layer on a flexible and rigid substrate, a novel method called Oxidative Chemical Vapor Deposition (OCVD) was implemented [30]. OCVD is a solvent-free technique that results in more homogenous, thin, and highly conductive polymer layers on different substrates. The steps for OCVD of PEDOT include: (i) First, fiber penetration with oxidant ($FeCl_3$) solution and sub-drying; (ii) then, oxidant-enriched fibers were exposed to EDOT monomer vapor; and last, (iii) PEDOT-coated fiber doping. It is reported that the CVD technique could successfully coat PET fabrics with PEDOT, but PEDOT-coated PET fabrics showed reduced conductivity due to poor fiber contact [31]. PEDOT-coated PET yarn fibers with good electrical and mechanical characteristics were developed, which could be converted into woven structures with good electrical properties. Furthermore, viscose yarn was tested in both the CVD and OCVD processes. Although the OCVD process found a high conductivity level of 14.2 Scm^{-1}, fewer mechanical properties were obtained at 15 wt% oxidant concentration on viscose yarn [32].

1.2. Layer-by-Layer Deposition (LbLD)

LbLD is a new and simple method of developing a thin film on the substrate at normal temperature and pressure. Alternate deposition occurs using a poly-ion layer on solid substrates by dipping into an oppositely charged solution and washing between each depositing layer. The alternation of the surface charge results in polyelectrolytic layers on the solid. Charged particles are bound by the electrostatic and Van der Waals bond [33][34][35][36]. The LbLD process has already been applied to impart conductivity to textile materials in many applications [37][38]. Electromagnetic interference shielding of cotton fabric by layer-by-layer (LbL) assembly of positive and negative charge MWCNTs and nickel ferrite ($NiFe_2O_4$) nanoparticles with a PDMS covering to keep the layer stable was reported [34]. A cationic surfactant is employed to create positively charged MWCNT, and EDTA is used to functionalize $NiFe_2O_4$, which is controlled by the ionization of both catalysts [34]. The vacuum-assisted spray-LbLD process can deposit MWCNT without any binder, thereby producing a high degree of binding sites and resulting in better sensing capabilities [39]. Poly(ethylenimine)/CNTs and ammonium polyphosphate layer nanocomposite coating were placed LbL on cotton fabrics to generate superior hydrophobic conductive cotton fabric, and PDMS coating imparted an identical energy density throughout the surface [40]. LbL deposited Chitosan–graphene cation and PSS anion layers one after the other on cotton fabric, resulting in an electrical conductivity of 1.67×10^3 Sm^{-1} for 10 layers [41]. V_2O_5-nanostructured supercapacitors show low energy density and electrical conductivity. Deposition of graphene layers between V_2O_5-coated MWCNT films prevents congregation and improves the energy density (96 Whkg^{-1}). The graphene layer acts as a barrier and improves the durability and capacitance of the device [42]. An LbLD process featuring a pad-dry-cure method for developing an electrically conductive Ag nanoparticles–carboxymethyl cellulose composite was reported [43].

1.3. Electrochemical Deposition

The electrochemical deposition, or the electrodeposition process, is used to deposit (composite/single) thick, stiff coats of conductive materials onto textiles, especially metal particles, with the help of an electric field [44]. In this process, metal

ions turn into solid metal and deposit on the cathode surface [45]. Electrochemical deposition has become so popular due to its versatile application for the deposition of different kinds of materials such as metal, metal alloys, composites, nanocoatings [46], ceramic and organo-ceramic materials [47], semiconductors (chalcogenide and oxides) [48], nanocrystalline and nanophase metallic materials [49], graphene-reinforced metal matrices [50], intrinsic conductive polymers (PANI, PPy, PEDOT, PEDOT: PSS) [51], carbon-based materials and their composites (CNTs, graphene, carbon/metal) [52], MnO_2–carbon-based materials [53], metal oxides [54], and so on.

Nickel was electrochemically deposited on linen and nylon fabric to produce wearable radar-visible fabrics. Electrodeposition assembly consisted of an electrolyte (nickel sulphate hexahydrate, nickel chloride, Boric acid) cathode and anode. The fabric was connected to the cathode by a platinum strip, and another platinum strip was used as an anode. Electrochemical deposition was done at 4 V for 15 min [55]. The Box–Behnken technique of electroless plating of nickel is reported [56]; they noticed that the deposition amount depended on the time and current applied, and Ni was electrodeposited on the Cu nanowires network to produce a transparent conductive film [57]. A process of targeted electrochemical deposition to produce microelectromechanical devices by employing a non-conductive mask between the anode and cathode and regulating the electrolyte with a pump was proposed [58]. Electroless plating on stretchable fabric aids in electrochemical deposition by providing conductivity to the fabric. Later, the electrochemical deposition of metal on every fiber with conductive material makes the fabric stable and provides optimum conductivity [59]. A simple one-step electrochemical deposition method to produce a metal-organic framework and PPy composite capacitor electrode with the help of dopamine with better conductivity than a virgin metal-organic framework was presented [60]. MnO_2-deposited capacitors have low electrical conductivity and have been investigated in many ways to increase this. MnO_2 is electrochemically deposited on CNTs to produce pseudocapacitors [61]. The electrochemical deposition of MnO_2 and PPy composite on carbon cloth produced a flexible electrode for supercapacitors with a capacitance of 325 Fg^{-1} and MnO_2-coated CNTs deposited on flexible graphene nanosheets produced electrodes for supercapacitors with a capacitance of 442.9 F/g [62]. MnO_2 deposited on activated carbon paper improves its capacitance (485.4 F/g) [63]. Kim et al. prepared a flexible photo sensor that deposits ZnO on Ni-Cu-Ni-coated PET fabric and copper deposited on silane molecules, which were polymerized with 2-(methacryloyloxy) ethyl trimethylammonium chloride (METAC)-coated recycled PET nanofibers [64]. Rosa-Ortiz et al. proposed a method of electrochemical deposition with the help of Hydrogen Evolution that improves the speed of copper coating and is directly fused to the wearable fabric, which eliminates the soldering machine [65].

1.4. Electroless Deposition

Electroless is an elegant and multipurpose process of conductive metal deposition on any surface. Apart from other deposition processes, electroless is an autocatalytic chemical reaction and is done without electrical energy. It can deposit both thickly and thinly coated films quickly and effectively. It can deposit metals such as silver [66], aluminum, copper [67], nickel, and iron, which are uniformly and smoothly deposited on the surface of the textile substrate [8][68]. The main principle uses a reducing agent in a solution for the chemical reduction of metal ions and deposits them on the substrate's surface, which imparts electrical conductivity to the textile substrate. The chemical reaction involved in this process is as follows [69]:

$$S = S^{n+} + ne^-$$

$$M^{n+} + ne^- = M$$
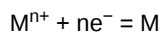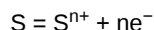
Electroless-deposition-produced conductive textiles, such as conductive woven cellulose fabric [70], PET fabric [71], and others, have a wide range of applications. Silver is deposited with the use of ultrasonics to create a shielding-effective PET fabric [72] treatment with silver nitrate and sodium hydroxide at 130 °C for 1 h, which increases the surface activity and eliminates the need for a catalyst that produces ethylene as a reducing agent, while ammonia treatment stabilizes the conductive layer [73]. Stretchable conductors are prepared by depositing silver through electroless plating on polyurethane filaments [74]. PVC is added to thermoplastic urethane during electroless plating, making the silver layer more adhesive and higher in conductivity.

The electroless deposition of Cu imparts a variety of features to the textile substrates. Cu is seeded with Ag and coated on cellulosic fabric to make it conductive for the manufacture of a light-emitting diode [70]. Lin et al. made ultra-stretchable conductors that deposit Cu on polydopamine-coated cotton fabric with a Pd^{2+} catalyst [75]. Guo et al. employed $AgNO_3$ instead of $PdCl_2$ to deposit Cu on PET textiles, resulting in a more uniform metal distribution and denser layer [76], and hydrazine monohydrate (80 wt%) treatment at 60 °C improved the interaction between PET and the Cu layer [77]. The addition of 3-mercaptopropyltriethoxysilane to PET textiles during a deposition improves the washing performance [78]. Paquin et al. described a three-step copper deposition on cotton using Pd or Ag as a catalyst [79]. Cotton fabric can also be activated by Ag and Cu nanoparticle deposition before the electroless plating of Cu [80]. Cu has been electroless

deposited on cotton fabric using $(NH_4)_2PdCl_4$ as a catalyst to create a highly conductive fabric [81]. Laser treatment on cotton fabric improves abrasion resistance [82].

2. In Situ Polymerization

In recent years, in situ polymerization has become a popular technology for creating conductive nanocomposite because of its varied and advantageous approach to polymerization that directly uses 90 mixtures of monomer and nanoparticles with various additives. Grothe et al. highlighted the differences between in situ polymerization and other surface modification approaches, such as nanoparticle fusing, and the benefits of in situ polymerization over other methods [83]. Due to the intense interaction between two side-by-side polymer chains, most conductive polymers are thermally unstable and not soluble in different solvents. However, in situ polymerization can polymerize in various ways depending on the conductive polymer for different applications, such as in situ chemical polymerization, in situ electrochemical polymerization, in situ vapor phase polymerization, and in situ polymerization in a supercritical fluid [84].

Liu et al. mentioned that in situ polymerization can reduce the impedance of the electrolyte interface and bring interfacial compatibility and stability to solid-state lithium batteries, thereby simplifying the process of polymerization [85]. Highly electrically conductive and thermally stable graphene/polyaniline (GN/PANI) nanocomposite was synthesized by in situ polymerization [86].

In situ polymerization, according to Park et al., aids in the efficient dispersion of carbon SWNTs in polymer composites in the presence of sonication, which was previously challenging due to the non-reactive surface of SWNTs [87]. The resulting nanocomposite is electrically conductive and optically transparent, with improved mechanical characteristics and thermal stability at low concentrations (0.1% of vol). Hong et al. used ferric p-toluenesulfonic acid (FepTS) and $FeCl_3$ as oxidants to investigate in situ polymerization of PEDOT on nylon 6, PET, and poly (trimethylene terephthalate) (PTT) fabrics and compared different properties of PEDOT/nylon-6, which has the best conductivity of all the nanocomposites; however, PTT/PEDOT is the most stable [88].

3. Coating

A textile conductive coating is a material layer that adheres to a textile structure (fiber, yarn, or fabrics). These coatings are used to make the textile material conductive or to add functionality to the textiles. Coating methods are industrial technologies used to adapt the properties of textiles to those required for technical and specialty applications. The variety of methods allows for good adaption to end-use requirements [89].

3.1. Dip Coating

Dip coating is a simple and cost-effective process commonly used in various industrial fields for depositing coating material onto any substrate, along with metallic and ceramic polymer film and textile materials. The process could be interpreted as depositing aqueous liquid phase coating solutions on the surface of any substrate [90][91][92]. Conductive materials are typically dissolved in solutions that are immediately deposited on the surface of the substrate, after which, to obtain the dry film, the sedimentary conductive wet coating has to be evaporated. The technique associates submerging the textile material in the solution of the conductive coating materials, ensuring that the textile material is completely penetrated and then withdrawn from the solution materials. Notably, this supposedly easy process of constructing film through dip coating comprises complex chemical and physical multi-variable norms. The thickness and morphology of depositing thin conductive films were determined by various criteria such as dipping time, withdrawal speed, dipping cycles, substrate (textile material) surface, density, viscosity, surface tension, and evaporation of the conductive coating solution [93][94][95]. Various modified dip coating techniques, such as solution dip coating, sol-gel dip coating, multi-layer dip coating, and vacuum-assisted dip coating, are significant to manufacture deposited films on the surface of textile materials.

Solution dip coating is the most straightforward technique of forming a film on textile materials' surfaces and is typically used in increasing production. Since it is the most commonly used method in textile manufacturing, dip coating is often referred to as starch finishing or sizing. Solution dip is a user-friendly process to operate and can increase the efficiency of production. However, on the opposite, the solution of dipping the uniformity of the coating is weak and the bonding state is relatively poor [95]. Cotton fabric containing high electrical conductivity has been confirmed to have been established by a two-step dipping and coating. The cotton fabric was immersed in an acetone solution and rinsed properly with deionized water after drying in an oven. Then, GO was coated onto the fabric surface by dipping the modified cotton fabric into GO

dispersed solution for two cycles. After that, a padding process was conducted to remove the excess material using a pair of rollers and high vacuum pressure [96]. The dipping process is shown in **Figure 1**.
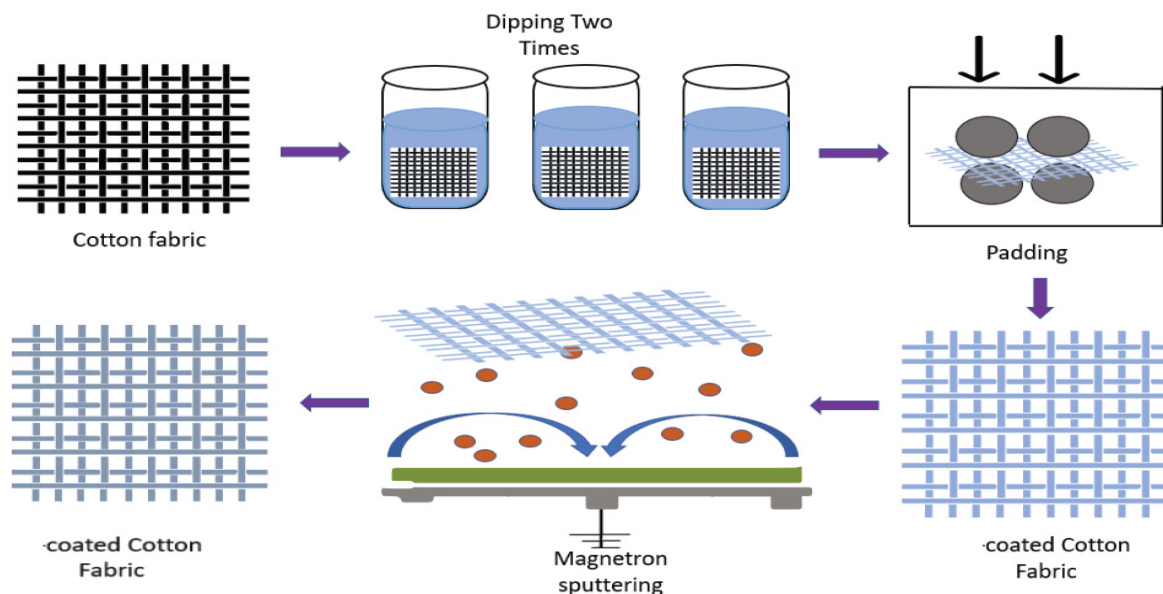

Figure 1. The preparation process of silver/graphene-coated cotton fabric, adapted from Ref. [96].

Sol-gel technology is a relatively novel method for endowing unique properties upon textiles and is affiliated with decreased ecological impacts [97]. Various functional characteristics such as antibacterial function [98], UV radiation protection [99], dye fastness [100], anti-wrinkle finishing [101], super-hydrophobicity [102], and biomolecule immobilization have been introduced by this method. MWCNTs for conductive purposes and methyltrimethoxy silane for hydrophobicity purposes were coated by the sol-gel process on cotton fabric [103]. The process involves Sol preparation, which is a mixture of methanol, distilled water, and MWCNTs of definite concentration and quantity. Following this, the Sol was mixed well by a magnetic mixer. Then, the cotton fabric was added to the Sol. After checking several parameters, the ultimate result was 40 kΩ cm^{-2} [103].

To improve the uniformity characteristics or thickness of the single dip coating film, the researchers investigated the multi-layer dip coating. A multi-layer dip coating was studied at a thickness of 90–100 nm and electrical resistance of <400 Ω mm^{-1} to increase the conductivity of the PEDOT:PSS-coated fibers, and the density and surface tension of the conductive coating solution were varied by altering the mixture ratio, by adding a fluorosurfactant, or by changing the withdrawing speed to achieve a significant, thick PEDOT:PSS layer [104]. Pu et al. organized a two-step dip coating method to establish Ag nanowire networks on the surface of PET materials [105]. The PET substrates were dipped into conductive Ag nanowire solutions and then dried; afterward, the substrate was coordinated vertically to operate the second-step dip coating. The Ag nanowire-coated PET substrates with an order-enhanced analog crisscross structure were prepared. Repeating the multi-layered dip coating method could increase the thickness, improve uniformity, and manufacture the coatings with desired features. Multi-layered dip coating of various coating solutions mainly achieves functional superposition by several deposited films. The fabrication is facile, and it is easy to achieve the multifunctional synergies of each deposited layer. Furthermore, this multi-layer dip coating process benefits broadening the applications of fibrous materials, such as supercapacitors, lithium-ion batteries, and electrode plates.

The vacuum-assisted dip coating method has been introduced to maintain the desired coverage of nanoparticles on the substrate surface with minimal defects, including metallic and ceramic fibers. Liu et al. demonstrated a vacuum-assisted LbL assembly technique to construct electrically conductive substances on textiles to develop multifunctional and flexible textiles with superb EMI shielding performances, super-hydrophobicity, and a highly sensitive humidity response [106]. Cotton fabric was coated with a GO nanosheet via the vacuum filtration deposition method [107]. The woven cotton fabric was treated with sodium hydroxide solution. Vacuum filtration deposition was used to disperse the GO nanosheet aqueous solution into the cotton fabric surface to fabricate GO–cotton fabric. Refluxed graphene and polyvinylidene fluoride (PVDF) were mixed and dissolved in absolute ethanol. This mixture was then forcibly deposited into the cotton fabric via a vacuum filtration deposition process, as shown in **Figure 2** [107][108].
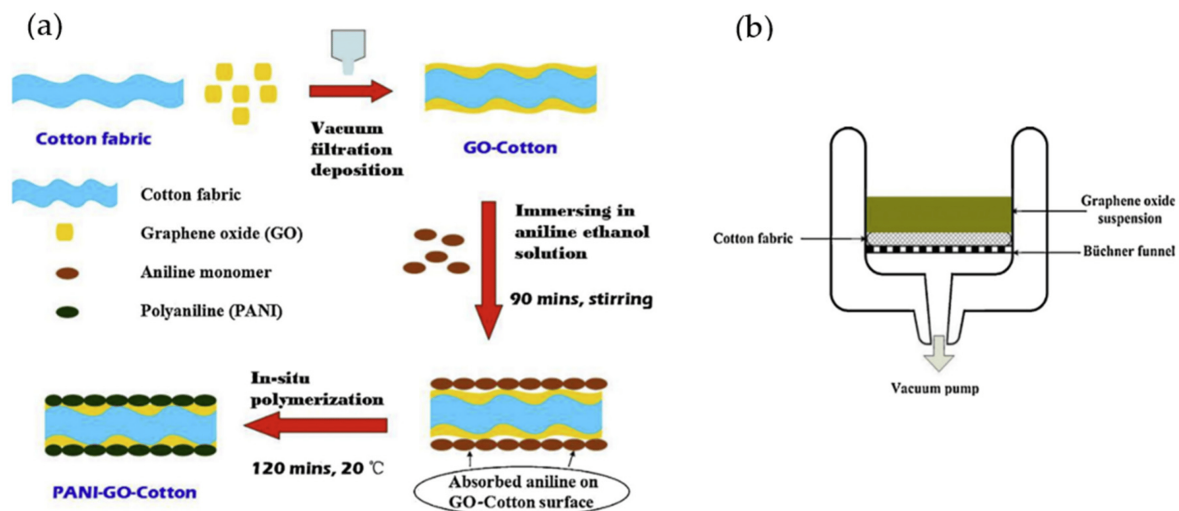
Figure 2. Schematic of (**a**) graphene oxide (GO)-coated cotton fabric fabricated by vacuum filtration deposition process, (**b**) PANI-GO-cotton fabric preparation procedure [107] (reprinted with permission from Elsevier).

The spray coating technique uses a spraying device (found on compressed air, such as with an airbrush or spray gun) to deposit conductive materials on the textile surface by the breeze. Any substrate can be coated by this simple, economic, fast, and scalable process, whether it be round or flat, or flexible or rigid [109]. Recently, it has been published that the spray coating approach that applies PEDOT:PSS conductive materials containing 5 wt% dimethyl sulfoxide (DMSO) made highly conductive and multifunctional PET fabrics. PET fabrics were coated with conductive PEDOT:PSS solutions that contain 5 wt% DMSO via spraying conductive material onto the surface of pre-treated PET fabrics [110].

3.2. Rod Coating

The rod coating process is easy and inexpensive to penetrate the conductive material on the textile substrate in a continuous and controlled manner (see **Figure 3**). This technique can affect the uniformity and condition of penetrated thin conductive thin coat by key parameters such as the rod's size, solvents, and conductive solution's viscosity. The concentration of the coating is influenced by the groove size in the wire-wound rod and depends on the rod's diameter. The solution flows through the grooves in the wire-wound rod, resulting in a thin film deposition at room temperature [109]. Zhang et al. reported a simple dry-Mayer-rod-coating method that fabricates the conductive sheath/core-structured graphite/silk fibers and indicates their application as wearable strain sensors [111]. A clip is used to align the bundle of silk fiber at one end of the flat plate. Then, graphite was put on the fixed end of the silk fiber and graphite flakes, which were then moved by a Mayer rod pressed onto the fibers [109].
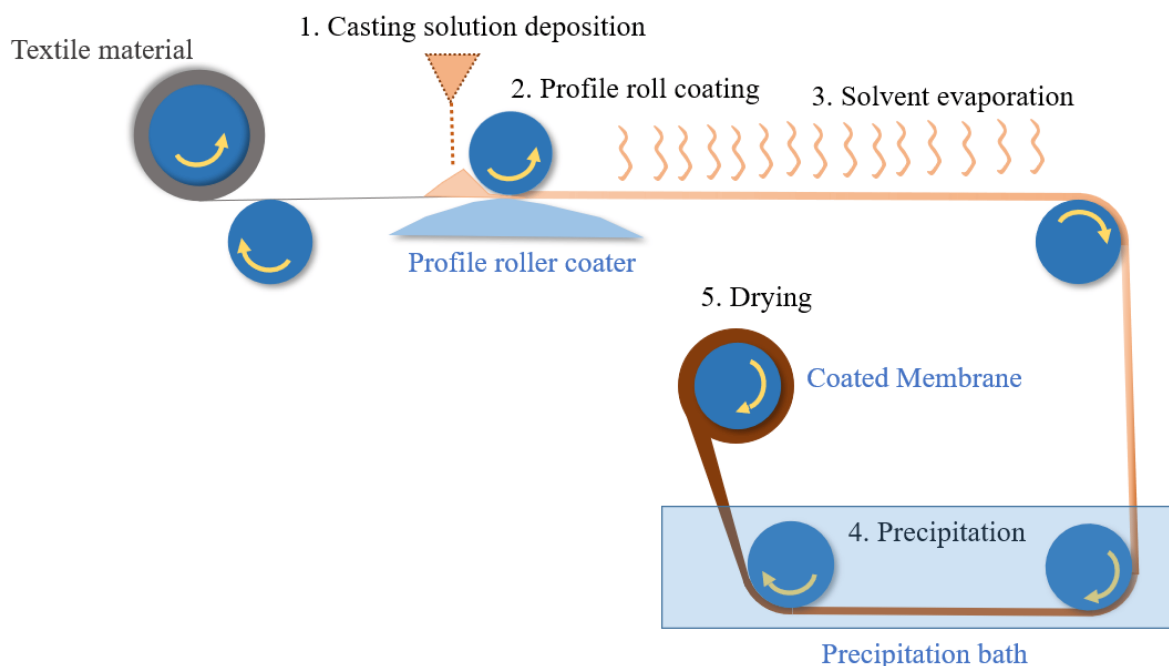

Figure 3. Fabrication of sheath/core-structured graphite/silk strain sensor through a dry-Mayer-rod-coating process, adapted from Ref. [111].

3.3. Roller Coating

The Spandex multifilament yarn was coated with thermoplastic polyurethane/carbon nanotube (TPU/CNT) conductive polymer composite (CPC) using the roller coating technique. The conductive mixture was placed into a bath; three rolls pushed the yarn. It was coated when it rolled over the second roll, which was explicitly immersed in the coating bath to pick up the conductive material; next, a glass tube entered with hot air moving through the glass, thereby acting as a drying oven, as shown in **Figure 4** [112].
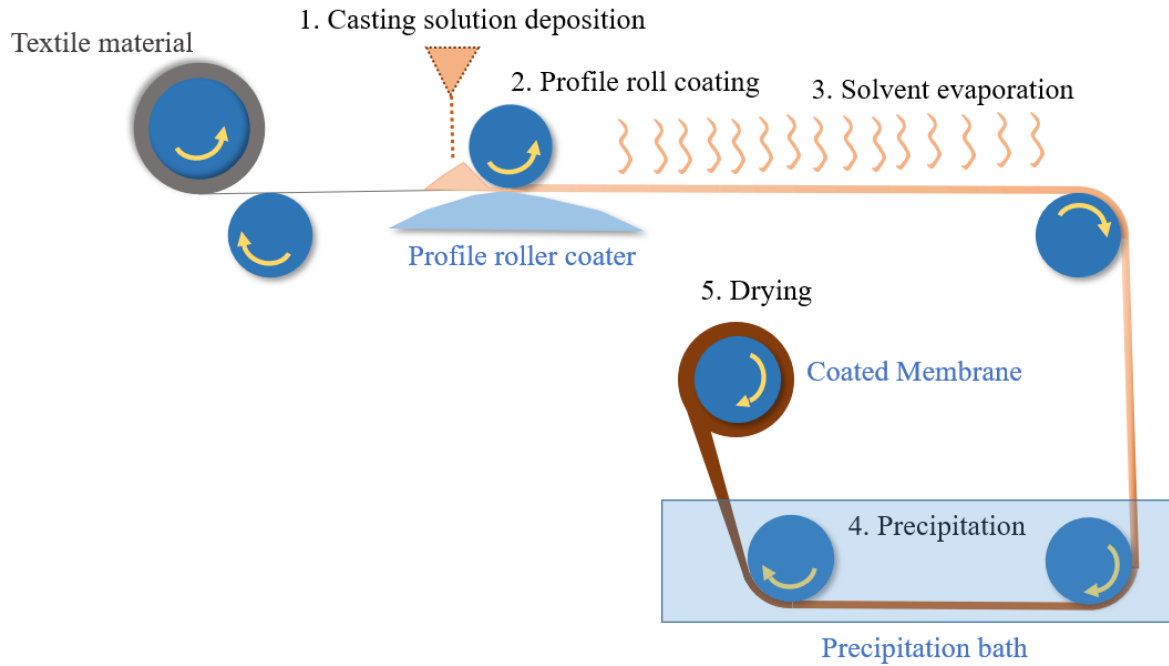

Figure 4. Roller coating process.

4. Printing

The printing process is a versatile manufacturing method that enhances and facilitates the field of flexible sensors by providing cost-effective processing routes [113]. Screen and stencil are the two broadly used printing methods for coating conductive materials to different substrates, including textiles [114].

4.1. Screen Printing

The first evolution of screen printing dates back to the beginning of the twentieth century. At the time of printing, there was no actual loss of coating solution. The method is shown in **Figure 5** and includes a screen of woven material (i.e., synthetic fiber or steel mesh) that has been attached to a tensioned frame. The pattern is generated by filling the screen with an emulsion that is impermeable to the coating solution in regions where no printing can occur. The region of the printed pattern remains open (without emulsion). The screen is then packed with a coating solution and brought close to the substrate. The squeegee is forced to the screen, bringing it into touch with the textile substrate and then linearly drawn across the screen, pushing the conductive coating solution through the open regions onto the textile substrate and thus reproducing the pattern [115].
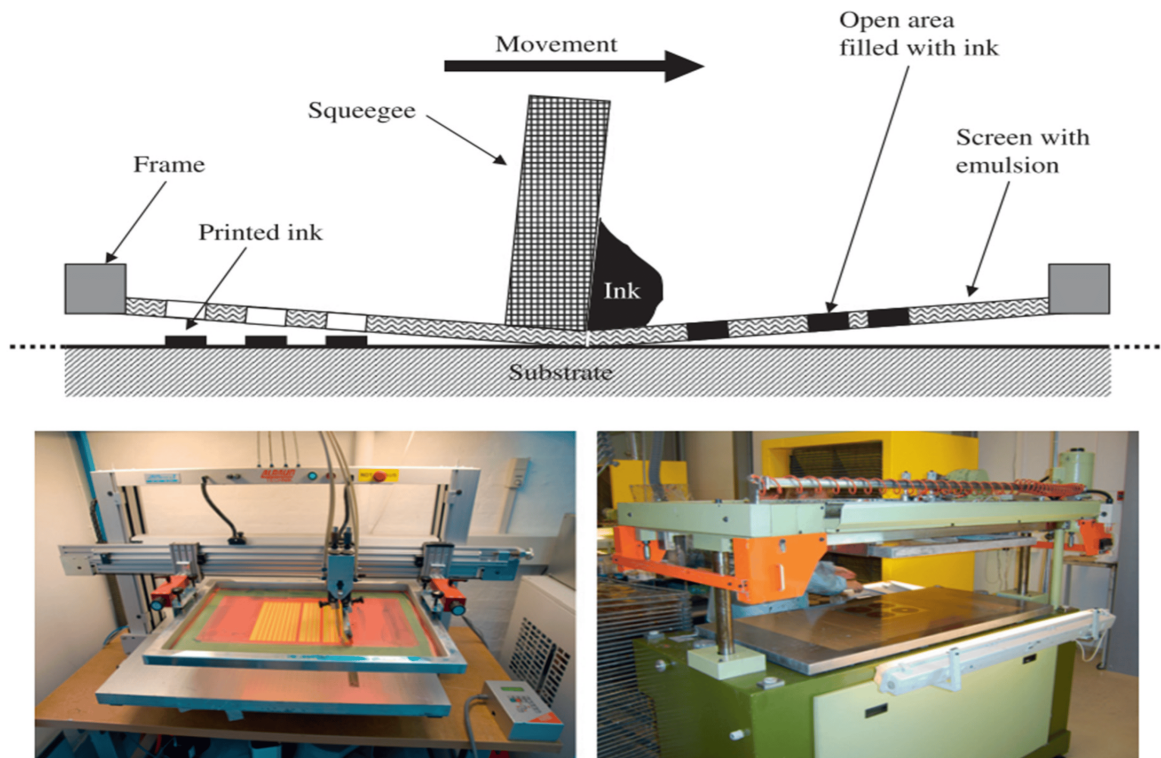
Figure 5. Illustration of the screen printing process (**above**) and examples of a laboratory screen printer (**bottom left**) and an industrial screen printer (**bottom right**) [115] (reprinted with permission from Elsevier).

Screen printing is cheap and is highly efficient in providing thick conductive film [116]. Conductive silver-based inks can be applied to various woven and non-woven textile substances using screen printing to track various vital signs [117]. Sadi et al. have developed a multifunctional weft-knitted cotton fabric through screen printing of CNT ink for wearable electronic devices, smart displays, and cold weather conditioners [118]. There are some difficulties and disadvantages of screen-printed conductive textiles, such as low abrasion resistance and drying out of the ink on the screen, which destroys the design of the screen [113]. The screen printing method is not ideal for single output compared to the direct write printing method [119].

4.2. Inkjet Printing

Digital or direct printing technology is a way of producing low cost and high quantity conductive materials [120]. Inkjet printing is a way of writing patterns directly to substrates. Inkjet printing is a simple term characterized by dye drops as ink is poured into specific positions to form a printed design on a textile substrate with a specified resolution [121]. In essence, the procedure involves the ejection of a fixed quantity of ink in a liquid-filled chamber in response to applying an external voltage. This abrupt reduction produces a shock wave in the liquid, which induces a drop in the liquid to eject from the nozzle [122]. The expelled drop comes under gravity and air resistance gained in motion, and the surface tension helps slow it along the surface [123]. Then, the drop will dry by solvent evaporation.

Kim et al. developed a knit structure printed with silver inks by inkjet printing, which had a resistance of 0.09 Ω/sq [124]. Low production costs, no masking, non-contact viability, lower material consumption, low temperature, and quick inkjet printing processing have gained interest in cost-effective manufacturing processes [125]. The design can be easily changed as no mask is used [122]. The major advantage of the inkjet printing process is that the conductive material can be deposited only in the required area on the substrate [126].

4.3. 3D Printing

Three-dimensional printing has gained major importance worldwide for its application in textiles and fashion [127]. Three-dimensional printing techniques have a profound impact on conductive textiles development with multifunctional purposes [128]. Nanocomposites with CNTs or graphene bases possess 3D conductive polymers [129]. The solvent-cast 3D printing method has been characterized by the application of scaffold microstructures (conductive nanocomposite) for its various properties, such as thickness, diameter, and interfilament spacing [130]. Three-dimensional printing of metallic substances enables it to be used for forging stainless steel electrodes with the help of a suitable laser melting machine and can also perform as a pH sensor [131]. Solvent-evaporation-assisted direct-wire (DW) 3D printing techniques have generated biocompatible polymers comprised of polylactic acid (PLA) and polyethylene adipate (PEA) with barium titanate

nanoparticles [129]. The Desktop 3D printing method has also enabled the use of CNTs or graphene as construction materials with electrical and thermal conductivity properties [132]. Boron nitride/polyvinyl alcohol has generated a higher thermal conductivity (1.56 and 2.22) than PVA fabrics and cotton fabrics when fabricated by 3D printing techniques, respectively [133]. The textile substrate can accommodate conductors and antennas with the 3D direct-wire (DW) dispensing method, which can provide more accurate data [134]. As no dye is required in this direct-wire (DW) method, the geometric shapes can be conveniently altered [129].

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