Textile electronic circuits based on organic fibrous transistors

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25.1 Introduction

E-textiles and wearable electronics have been the focus of a growing body of investigation in the field of smart textiles for several decades. Fiber-based clothing systems are explored as a promising platform and substrate for wearable electronics because of their softness, deformability, and durability (Mattila, 2006; Tao, 2005). Within the four-layer structure (fiber-yarn-fabric-product), the e-textile is suitable for the fabrication of wearable electronics. With the development of materials sciences, especially in the nanosciences and conductive polymers, the clothing is endowed with different electronic functions with the integration of different sensors, such as electrocardiogram sensors (Coosemans et al., 2006; Ulbrich et al., 2014), electromyography sensors (Linz et al., 2007), strain sensors (Yi et al., 2012; Trifigny et al., 2013), pressure sensors (Meyer et al., 2010; Xu et al., 2013; Lee et al., 2015), optical sensors (Liang et al., 2005; De Jonckheere et al., 2008; Carmo et al., 2012), and chemical sensors (Dickinson et al., 1996; Windmiller and Wang, 2013). The rapid development of the miniaturization process of electronic devices promises the seamless integration of electronic devices into clothing for human interface design and control (Brun et al., 2009; Hyejung et al., 2008, 2009), such as electrochemical display (Moretti et al., 2013), organic light-emitting device (OLED); Janietz et al., 2012; Benito-Lopez et al., 2009), or radio-frequency identification (RFID) (Harrop and Das, 2014).

A study of e-textiles and wearable electronics is about studying the material in its first stage. Secondly, the study considers the method of integration by different technologies (Stoppa and Chiolerio, 2014). Among those technologies are embroidering, sewing, nonwoven textiles, knitting, weaving, spinning, braiding, coating/laminating, printing, and chemicals.

The transistor as a component of the e-textile plays a crucial role in the textile electronic circuit. The existing fibrous transistors can be divided into two categories: wire thin film transistors (WTFTs; Lee and Subramanian, 2003; Maccioni et al., 2006; Locci et al., 2007) and wire electrochemical transistors (WECTs; Hamedi et al., 2007; De Rossi, 2007; Tao et al., 2011). WTFT, also called WFET, is based on the field-effect transistor (FET) technology and WECT is based on electrochemical technology. With the help of these transistors, the textile electronic circuit can be achieved without loss of mechanical properties such as flexibility or softness.
This chapter reviews the current status of the fibrous transistor development and textile electronic circuit. It covers semiconducting materials, fibrous transistors, and textile electronic circuits. Section 25.2 will discuss the materials employed in semiconductor manufacturing, especially in fibrous transistors. Section 25.3 will present traditional and fibrous transistors. Textile electronic circuits are discussed in Section 25.4. The different methodologies of use will be compared. And finally, the conclusion and perspectives will be discussed.

25.2 Materials

A study about fibrous transistors is at this first stage reduced to a study of semiconducting materials. Over the past decade, many novel materials have been discovered and exploited to realize semiconductor components. Some of them are being employed in the smart textile applications. For fabricating the transistors, these materials can be divided into categories: inorganic and organic. In this part of the chapter, both categories of materials will be presented and their semiconductor proprieties will be explained.

25.2.1 Inorganic materials

Inorganic materials were used in the first transistor in 1947 at Bell Labs. The best way to get an overview of the different class of inorganic semiconducting materials is to examine the periodic table of elements. Table 25.1 shows a part of the periodic table that is associated with many elemental and compound semiconductors.

Most of the inorganic semiconductors are in group IV, carbon (C) in the form of diamond, silicon (Si), germanium (Ge), and tin (Sn). The crystal structure of all these semiconductors is shown as diamond. The difference between them is in the conducting properties between metals and insulators. Diamond behaves much more like an insulator; meanwhile tin is much like a metal. Between them silicon and germanium perform as two typical semiconductors. Nowadays, they are the dominant materials in microelectronics and the most important materials in all modern communication

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technology. Besides the pure elemental semiconductors Si and Ge, alloys of both materials also have semiconducting properties, such as SiGe or Si$_{1-x}$Ge$_x$, where $x$ represents the mole fraction of the alloy components.

The common feature of the elements of the main group IV of the periodic table is that there are four electrons in the outer shell of their electron clouds, the so-called valence shell. They can be doped with different types and concentrations of impurities to vary their conductivity. This variation of conductivity can be considered as one of the most important properties of a semiconductor.

Fig. 25.1 shows three basic bond representations of a semiconductor. Fig. 25.1(a) shows the intrinsic silicon, which is very pure and contains a negligibly small amount of impurities. Each silicon atom shares its four outermost electrons with its four neighbor atoms, forming four covalent bonds. Fig. 25.1(b) shows n-type silicon, where a substitutional phosphorous atom with five outermost electrons has replaced a silicon atom. As a result, a negative-charged electron is donated to the lattice in the conduction band. Fig. 25.1(c) shows that when a boron atom with three outermost electrons substitutes for a silicon atom, a positive charged hole is created in the valence band and an additional electron will be accepted to form four covalent bonds around the boron. This is p-type silicon.

Besides group IV, the compounds by the atoms in groups III-V are also semiconductors, such as BN, BP, Bas, AlN, AlP, AlAs, AlSb, GaN, GaP, GaAs, GaSb, InN, InP, InAs, and InSb. Except for the nitrides, all of these compounds crystallize into the zincblende structure. The nitrides are stable in the wurtzite structure. Meanwhile, the mixture crystals made of binary III-V compounds also have semiconducting properties, such as (Ga,Al)As, Ga(As,P),(In,Ga)As, and (In,Ga)(As,P).

The compounds by the atoms in the groups II-VI like ZnS, ZnSe, ZnTe, CdTe, HgSe, HgTe, CdS, CdSe, and MgTe also possess semiconductor proprieties. As in the case of the III-V compounds a large number of semiconducting alloys may also be realized from the II-IV compounds such as (Hg,Cd)Te, Zn(S,Se), Cd(S,Se), etc.

Although inorganic materials ensure the fabricated device with the best performance in the semiconductor application, their crystal structure prevents them from being employed in wearable textile applications. These materials cannot be deposited on a flexible substrate, such as a sheet, film, or yarn, with a satisfactory adhesion property.

**Figure 25.1** Three basic bond pictures of a semiconductor. (a) Intrinsic Si without impurity; (b) n-type Si with donor (phosphorus). (c) p-type Si with acceptor (boron).
because they are brittle and fragile and sensitive to the impurities in the manufacturing condition. The high-temperature requirement for their deposition is also a barrier to their application on textile substrates. The most common textile materials cannot support temperatures higher than 300°C, which impedes the traditional deposit technologies applied on textile substrates, such as sputtering deposit (Carlston et al., 1965). However, this inconvenience is conquered by using amorphous silicon (a-Si) (Madan, 2006).

The work on a-Si using plasma-enhanced chemical vapor deposition (PECVD) in silane gas (SiH₄) was pioneered by Sterling and his coworkers at Standard Telecommunication Laboratories starting in 1965 (Sterling and Swann, 1965). Nowadays, it has become the basis of a multibillion-dollar market in diverse applications such as field-effect devices (Le Comber et al., 1979), active-matrix liquid crystal displays (Rose, 2012), electrophotography (Schein, 1988), image sensors, solar cells (Rech and Wagner, 1999), etc. Its disordered atomic structure is the main feature that distinguishes amorphous from crystalline materials. Although there is a word amorphous for a-Si, it is not completely amorphous since a-Si keeps the covalent bonds between the silicon atoms in the same way in the crystalline silicon, with the same number of neighbors and the same average bond lengths and bond angles. The disorder is represented by the atom pair distribution function. The amorphous silicon has the same short-range order as the crystal but lacks the long-range order. However, there are still some defects, so-called dangling bonds, due to the disordered nature of the material.

Unlike the traditional silicon-based transistor, which normally requires a high-temperature process greater than 800°C, the great advantage of amorphous silicon is that it can be deposited in thin film at low temperature onto a variety of substrates. This gives a huge number of opportunities for use in textile applications. However, the carrier mobility of amorphous silicon is limited to the order of $1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, which is lower by two or three orders of magnitude than that of single-crystalline Si ($\approx 200 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for carrier concentration $\approx 10^{19} \text{ cm}^3$) (Nomura et al., 2004). In fact, because of the roughness of the textile surface and impurities, the actual linear mobility will be lower than the ideal value.

### 25.2.2 Organic materials

At the beginning of the twenty-first century, a new electronics revolution became possible due to the development and understanding of a new class of materials known as organic semiconductors. Since the 1970s the successful synthesis and controlled doping of conjugated polymers propelled the organic semiconductors development, which was honored with the Nobel Prize in Chemistry in the year 2000 (Chiang et al., 1977).

In the organic semiconductor family there are two major classes: small molecular weight materials and polymers. Both of them have the common property of a conjugated π-electron system that is formed by the pz-orbital of sp²-hybridized carbon atom (Fig. 25.2).

The important difference between these two classes of materials lies in the formation of thin films. The small molecular weight materials are usually deposited from the gas phase by sublimation or evaporation; meanwhile polymers form the film from
solution processing, e.g., spin-coating, dip-coating. Besides, the small molecular weight materials can be grown as single crystals allowing intrinsic electronic properties in order to obtain relatively high electron mobility (Pope and Swenberg, 1999; Farchioni and Grosso, 2001).

Different from covalently bonded inorganic semiconductor materials, organic materials are Van der Waals bonded solids, which makes weaker intermolecular bonding. As a result, organic materials possess decreased hardness and lower melting point in mechanical and thermodynamic properties. Especially, the delocalization of electronic wave functions among neighboring molecules is much weaker. In organic materials, the highest energy level of $\pi$ bonding in energy levels is called highest occupied molecular orbital (HOMO) and the lowest energy level of $\pi^*$ bonding is called lowest unoccupied molecular orbital (LUMO). The HOMO corresponds to the conduction band in the inorganic semiconductor materials, and the LUMO can be considered as a valence band in the inorganic semiconductor materials.

The pure intrinsic organic semiconductor can be considered as an insulator. However, there are several methods to increase the carrier density to make them as extrinsic semiconductors, in most cases this is the p-type doping, such as chemical doping (Pron and Rannou, 2002; Fedorko et al., 2001), electrochemical doping (Miomandre et al., 2005), photogeneration of carriers (Sun and Sariciftci, 2005), injection of carriers from contact (Bürgi et al., 2003), and field-effect doping.

Several models can explain the carrier transport in organic semiconductors. However, none of them can be independently employed to explain the carrier transport phenomena and the mechanism at the same time. Among the theoretical models, the most often used models are the band transport model (Warta and Karl, 1985; Pernstich et al., 2008; Karl et al., 1991), polaron transport model (Holstein, 1959; Emin and Holstein, 1969; Marcus, 1960), hopping transport model (Vissenberg and Matters, 1998), and multiple trapping and release model (Horowitz et al., 1995; Le Comber and Spear, 1970).

### 25.2.2.1 Small molecular semiconductor materials

Small molecular semiconductor materials can be deposited by physical vapor thermal technique in vacuum (Sadaharu et al., 2014) or by solution processing (Kim and Jeon, 2001).
Besides the crystalline systems, some small molecular semiconductors can be prepared by organic molecular beam deposition, such as Alq3 and TPD.

Pentacene (Fig. 25.3) is a typically studied small molecular material since the charge transport properties were reported to be excellent (Farchioni and Grosso, 2001). As its important feature, pentacene can form the well-ordered thin film on oxidized silicon. The study shows that the smallest stable island consists of four molecules in monolayer films (Ruiz et al., 2003). The single-crystal grain can be achieved under appropriate growth conditions (Meyer zu Heringdorf et al., 2001). It also can be deposited on aluminum oxide and metal. Brinkmann et al. have shown that pentacene can be deposited onto polymer film (Brinkmann et al., 2003).

Besides pentacene, some other small molecular organic semiconductors can also be rendered solution processable by attachment of flexible side chains. But they are no longer still used for realizing fibrous transistors. For more detailed information see (Sirringhaus, 2005).

**25.2.2.2 Polymers**

Polymer semiconductor materials (Fig. 25.4) were studied by Koezuka et al. for fabricating the organic thin film transistor (OTFT; Koezuka et al., 1987). Since that first demonstration, organic thin films have proven useful in a number of applications, some of them now reaching the consumer market such as color displays, which can be considered as the most successful case by using the OLED. Besides OLEDs, organic thin film transistors and low cost and efficient organic solar cells are other important applications for polymer semiconductor materials.

The typical semiconducting polymer is polythiophene. Since pure polythiophene is not soluble and therefore it is difficult to form a thin film, its derivate is used, such as poly(3-hexylthiophene) (P3HT), which has excellent solubility in a variety of organic solvents (Assadi et al., 1988) and can form the thin film by different types of solution processing, such as spin-coating, dip-coating, drop-coating, screen printing, or inkjet printing. The carrier mobility of P3HT varies from $10^{-5}$ cm$^2$ V$^{-1}$ s$^{-1}$ to $10^{-1}$ cm$^2$ V$^{-1}$ s$^{-1}$ in function of the self-organization of molecules. In regioregular P3HT, crystalline lamellas in the microstructure of molecules are advantageous to the intermolecular orbital overlap and charge transfer. The formation of regioregular P3HT depends on the degree of regioregularity, molecular weight, and deposition conditions. Besides, the carrier mobility of P3HT is influenced by the orientation of the regioregular lamellar, which is influenced by the substrate surface (Sirringhaus et al., 1999) and the interconnectivity between the individual lamellar domains (Kline et al., 2005).

![Figure 25.3 Chemical structure of some popular small molecular organic semiconductors.](image-url)
In spite of the advantage of P3HT for the low-temperature condition and solution processing, it is still limited for the fibrous transistor because of the processing conditions. Normally, in order to guarantee the purity of material, the substrate should be perfectly cleaned. Sometimes, the aqua regia is used to clean the substrate. However, the textile substrate cannot support such a strong solvent. Meanwhile, the solvent of P3HT might dissolve or destroy the organic insulator of fibrous transistor. At the very least, these solvents will attack the polymer surface and make it rough, which is important to the molecular organization and influences the mobility as a result.

Thirdly, the processing condition should be in vacuum in order to avoid the degradation of P3TH, which is not compatible with the mass production of textiles.

Another successful polythiophene derivative is poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) (Fig. 25.4) developed in the 1980s by Bayer AG Germany. Since David Nilsson et al. realized electrochemical organic transistors by using PEDOT:PSS in 2002 (Nilsson et al., 2002), PEDOT:PSS has become the most widely used material in flexible and printing organic electronics (Andersson et al., 2007; Invernale et al., 2010).

The doped state of PEDOT is almost transparent as the polaron bands absorb in the infrared (IR) region. The de-doped form of PEDOT is dark blue with an absorption maximum located slightly above 600 nm. As PEDOT is highly conducting in pristine state, it cannot be used as channel material in depletion mode OFETs. Instead, the good ion mobility of PEDOT:PSS and other PEDOT analogues makes this material ideal for
use in electrochemical devices. PEDOT:PSS and its derivatives are employed to realize electrochemical transistors (ECTs) for applications in transduction, sensor signal amplification, chemical and biological sensing, etc. (Kumar and Sinha, 2008; Berggren et al., 2008). More detailed information can be found in the review by (Groenendaal et al., 2000).

25.3 Fibrous transistors

25.3.1 Planar transistors

Transistors as the basic and crucial component for electronic circuits have been vigorously studied since 1947. The essential function of a transistor comes from its ability to control a larger signal by an applied small signal between one pair of its terminals. This property makes the transistor as an amplifier or switch. According to the mechanism of the generation of carriers in the channel, transistors can be divided into three categories: bipolar junction transistor, field-effect transistor, and electrochemical transistor. In electronic textile applications, the FET and ECT are employed to realize fibrous transistors.

25.3.1.1 Field-effect transistor

A field-effect transistor (organic or inorganic) consists of a thin semiconducting layer, source and drain electrodes, a gate electrode, and an insulating gate dielectric. The distance between source and drain electrodes is called channel length $L$. The width of source and drain electrodes is called channel width $W$. The gate electrode in the case of an organic FET can be a metal or a conducting polymer. As gate dielectrics, inorganic insulators, such as SiO$_2$, or polymeric insulators, such as poly(methyl methacrylate) (PMMA) or poly(4-vinylphenol) (PVP), are commonly used according to the transistor structure. The source and drain electrodes, which inject charges into the semiconductor, are usually high work function metals such as gold, but conducting polymers (eg, PEDOT:PSS, PANI), which can be printed, are used as well (Fig. 25.5).

According to the need of the nature of semiconductors and dielectrics or the different assemblage technologies, there are four different device structures that can show very different transistor behavior. They are (in relation to the semiconductor and gate dielectric) the bottom contact/top gate (BC/TG, Fig. 25.6(a)), bottom contact/bottom gate (BC/BG, Fig. 25.6(b)), top contact/bottom gate (TC/BG, Fig. 25.6(c)) structures, and top contact/top gate (TC/TG Fig. 25.6(d)) structures. Transistors with the same components but different geometries can show very dissimilar behavior.

The gate electrode is applied a voltage $V_g$ and the drain electrode is applied a voltage $V_d$. Normally, the source electrode is connected to ground, $V_s = 0$. The potential difference between the source and the drain is called the source-drain voltage $V_{ds}$. The operating regimes of transistors can be considered as two regimes: linear and saturation.
First, when the gate electrode is applied a voltage $V_g$, charges will be induced at the insulator/semiconductor interface (Fig. 25.7(a)). The number of accumulated charges is proportional to $V_g$ and the capacitance $C_i$ of the insulator. If a small voltage $V_{ds}$ is applied, then the movement of carriers between source and drain will create a current $I_{ds}$. The field-effect transistor works in linear regime (Fig. 25.7(b)). However, not all induced charges are mobile and will thus contribute to the current in a field-effect transistor. Some of them will fill the deep traps first before the additionally induced charges can be mobile. When the traps are all filled, the gate voltage is called threshold voltage $V_{th}$. Hence, in order to accumulate carriers, the gate voltage has to be applied higher than the threshold voltage ($V_g > V_{th}$).

When the source-drain voltage is further increased until $V_{ds}$ equals $V_g - V_{th}$, the channel is “pinched off” (Fig. 25.7(c)). That means a depletion region forms next to the drain because the difference between the local potential $V(x)$ and the gate voltage is now below the threshold voltage. A space-charge-limited saturation current $I_{ds,sat}$...
can flow across this narrow depletion zone. From this moment, the field-effect transistor works in saturation regime. Further increasing the source-drain voltage will not substantially increase the current because the potential at the pinch-off point remains \( V_g - V_{th} \) and thus the potential drop between that point and the source electrode stays approximately the same, and the current saturates at a level \( I_{ds,sat} \) (Fig. 25.7(d)).

Because there are two operation regimes, the current—voltage characteristics have to be described separately. For different gate voltages, with the increase of source-drain voltage \( V_{ds} \), the current \( I_{ds} \) comprises the linear and saturation regimes (Fig. 25.8(a)). In the transfer characteristics, at first the \( I_{ds} \) increases linearly with the voltage \( V_g \) when the gate voltage overcomes the \( V_{th} \) (Fig. 25.8(b)). When the transistor is in the saturation regime, the square root of the saturation current is directly proportional to the gate voltage (Fig. 25.8(c)). The mobility of charges depends on the ratio of \( I_{ds} \) and \( (V_g - V_{th})^2 \).

The traditional OFET is based on thin film transistor (TFT), which requires a precise control of thickness of gate dielectric. However, this precise control is not suitable for textile substrates in consideration of the roughness of textile surface. Hence, another field-effect transistor with electrolyte instead of gate dielectric has been developed (Fig. 25.9) (Panzer and Frisbie, 2008). In this kind of transistor, the charge carrier channel is induced by the bulk of electrolyte. When the gate is negatively biased, cations are attracted in the gate side inside of electrolyte. The gate/electrolyte interface is formed, whose electric capacity is very high (on the order of 10 \( \mu F cm^{-2} \)) because of the small distance between the gate electrode and cumulated cations in the electrolyte.
At the same time, anions are repelled to semiconductor side and another interface of electrolyte/semiconductor with high electric capacity is achieved. The double-layer capacitor induces the charge carrier in the semiconductor. The switch rate is lower than TFT because the accumulation of carriers in the semiconductor layer comes from the migration of ions in electrolyte, which is not instantaneous. Moreover, the electrolyte is in sol–gel form whose aging is still a problem in the case of no encapsulation. However, the easy processing condition is a huge advantage for fabrication of fibrous transistors.

25.3.1.2 Electrochemical transistors

The operation of electrochemical transistors is based on the switch of neutral and conducting states of materials. For the organic electrochemical transistor, as the oxidation
state of the conjugated polymer is altered the number of free charge carriers is controlled within the polymer bulk. Based on this electronic control of the fundamental properties of the polymer, conjugated polymers have been studied and employed as the active material in organic electrochemical transistors (OECTs). In 2002, Nilsson et al. reported an OECT using PEDOT:PSS as the active layer. They proposed two different structures of OECT. In these structures the PFEDOT:PSS is used as active material in the charge channel. An electrolyte gel is employed to oxide and to reduce the active material in the control of the gate voltage. According to the position of the gate electrode, Khan proposed two configurations of OECT: lateral electrochemical transistor (LECT) and vertical electrochemical transistor (VECT; Khan, 2009). The study shows that the position of electrolyte is not an important factor to the performance of OECT.

The mechanism of operation of this OECT is as follows: the gate and drain electrodes are negatively biased (Fig. 25.10(a)). When gate voltage $V_g$ equals to zero, the source-drain current is linear at the beginning and saturated when the drain side PEDOT is reduced because of the migration of cations from source via the electrolyte (Fig. 25.10(c)). If gate voltage is applied, the saturation will happen earlier because of the migration of cations from the gate electrode (Fig. 25.10(b)), and as a result the saturation source-drain current will be lower. A typical output characteristic is shown in Fig. 25.11.

Unlike the OFET whose charge carriers are induced by the field effect, which can be considered as an instantaneous operation, the switch of states of active material in OECT is induced by redox action via the electrolyte, which strongly depends on the nature of active material and ability of movement of ions in the electrolyte. Hence, the switch speed of OECT is much lower than that of OFET. Besides, the ON/OFF ratio of the OECT depends on the number of available oxidation sites of the gate electrode. In order to achieve a high ON/OFF ratio, this number should be much higher than that of the channel by making the volume of the gate electrode 10 times larger than the channel (Berggren et al., 2008).

![Figure 25.10 Principle of function of PEDOT:PSS-based organic electrochemical transistor.](image-url)
On the contrary, the processing condition of OECT is much simpler than that of OFET. The active material, gate, drain, and source use the same material. They can be deposited by solution processing in ambient temperature. The control of dimension of electrolyte is not highly required. The shape and thickness of electrolyte greatly vary because the speed of movement of ions in electrolyte is not influenced by the shape and thickness of electrolyte but the size of the ion and the sol–gel microstructure.

25.3.2 Fibrous field-effect transistors

The first study on fibrous transistors was published in 2003 by Josephine B. Lee and Vivek Subramanian (2003). They used an aluminum wire with the diameter of 250 and 500 μm as gate electrode and deposited 150–250 nm of low-temperature oxide gate dielectric to encapsulate the gate. An oxygen-rich chemistry (14:1 O₂:SiH₄) was used to ensure good step coverage and mechanical robustness. Ninety nanometers pentacene channel material was evaporated. Then, source-drain top contacts were patterned using orthogonal overwoven 50-μm-diameter wires. These served as channel masks; a transistor was formed at every intersection. One hundred nanometers of gold was evaporated to form source-drain contact pads. The output characteristics are similar to the TFT but there is an important leakage from the gate electrode. This is due to the poor quality of gate dielectric because of the roughness of the wire surface (Fig. 25.12). The device failure at a radius of curvature of 7.9 cm was found because of the breakdown of the dielectric. They found that the density of dielectric defects is 10 times higher than the planar silicon substrate.

The same authors improved their fibrous transistor by using stainless wire as the gate electrode in order to ameliorate the interface quality between gate and dielectric.

Figure 25.11 Output characteristics of PEDOT:PSS-based OECT.
(Lee and Subramanian, 2005). At the same time, they tried to use a PVP polymer as dielectric by solution processing. The average thickness of film PVP was assumed to be 1μm and the mobility was calculated to be 0.5 cm² V⁻¹ s⁻¹. However, the leakage problem was still observed.

In 2004 another team of researchers developed a fibrous transistor by using Kapton fiber as the textile substrate shown in Fig. 25.13 (Bonderover and Wagner, 2004). The silicon nitride and amorphous silicon were deposited by conventional processing techniques, including conventional photolithography, at temperatures up to 150°C on the Kapton sheet. Then the sheet was sliced into the fibers. The threshold voltage was reported to be 7.5 V and the linear electron mobility was 0.13 cm² V⁻¹ s⁻¹. However, the output characteristics were not shown in the report. We cannot know if there is leakage for this fibrous transistor.

In 2005 Bonfiglio et al. developed another prototype of fibrous transistor by using PFEDOT:PSS-coated Mylar ribbon as gate electrode and dielectric shown in Fig. 25.14. This was the first time that the gate electrode was deposed by solution processing for the fibrous transistor. They used three different semiconductors (regioregular poly-3-exil-thiophene, regioregular 3.3-didocel-2,2:5, 2-terthiophene in the solvent of chloroform and chlorobenzene and pentacene by vacuum evaporation) and showed the electric characteristics of the pentacene-based one.

In 2006 Maccioni et al. developed another fibrous transistor by using stainless wire as gate and polyimide as dielectric. The novelty of this prototype is in the fact that they rotated the wire when they deposited the semiconductor (pentacene). As a result, the channel width was doubled and the semiconductor layer was more homogeneous, and the leakage of gate was tremendously improved. Besides, they used “soft lithography” by using PDMS stamp to realize the source and drain electrodes by PEDOT:PSS.
The same research team published their theoretical modeling for the cylindrical OFET in 2007 (Locci et al., 2007). They considered the field-effect fibrous transistor as thin film transistor (Fig. 25.15) and reduced the source-drain current in linear and saturation regimes as Eqs. [3.1] and [3.2]:

\[
I_{\text{dlin}} = \frac{2\pi \varepsilon_i \mu}{L \ln \left( \frac{r_i}{r_g} \right)} \left[ (V_g - V_t)(V_{ds} - R_s I_d) - \left( \frac{V_d - R_s I_d}{2} \right)^2 \right]
\]  

[3.1]

\[
I_{\text{dsat}} = \frac{Z}{L} \mu C_i \left( \frac{V_g^2}{2} - V_t V_g \right) + \frac{Z}{L} \mu C_i \frac{V_p V_t}{2}
\]

\[
+ \frac{q \mu n_0 \pi}{L} \left( -V_p d_s r_i - V_p \frac{d_s^2}{2} - \frac{q N d_s^3 r_i}{6 \varepsilon_s} \right)
\]  

[3.2]

where \( \varepsilon_i \) is insulator permittivity, \( \mu \) carrier mobility, \( L \) channel length, \( r_i \) dielectric outer radius, \( r_g \) gate outer radius, \( R_s \) contact resistance, \( Z \) channel width that equals \( 2\pi r_i \), \( C_i \) dielectric capacity, \( V_p \) pinch-off voltage, \( q \) elemental charge, \( n_0 \) density of free carriers, \( d_s \) thickness of dielectric, and \( \varepsilon_s \) dielectric permittivity.

**Figure 25.14** Schematic for fibrous transistor by using Mylar as insulator, published in (Bonfiglio et al., 2005).

**Figure 25.15** Structure of the cylindrical OFET.
Under the hypotheses that \( n_0 = N \) and \( r_i \gg d_s \), the threshold voltage is equal to the pinch-off voltage \( V_p = V_{th} \), and all the terms in the second row of Eq. [3.2] can be neglected to obtain Eq. [3.3]. In this case, the field-effect fibrous transistor can be considered as a planar thin film FET.

\[
I_{dsat} = \frac{Z}{2L} \mu C_i (V_g - V_t)^2
\]  

[3.3]

Among the fibrous FET studies, semiconducting and insulator materials were deposited either by vapor thermal technology or by PECVD. Only in (Bonfiglio et al., 2005) was the derivate of polythiophene as semiconducting material deposited by solution processing. Unfortunately, its electric characteristics were not reported. The thermal or chemical evaporation deposit technologies require a vacuum environment, which is difficult to be compatible with mass industrial textile fabrication. Even if the PECVD is called “low temperature,” the real work temperature is about 250–350°C, which is still too high to be applied in the traditional textile material.

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![Figure 25.16](image)

**Figure 25.16** Schematics of electrolyte-based WFET.
Moreover, the source and drain electrodes were realized through mask or PDMS stamp, which are not suitable for continuous fabrication requirements.

With the contemporary technology, the quantity of deposited thin film remains an evident obstacle that prevents the development of WFET. In order to avoid this problem, the electrolyte-based OFET was transferred to realize WFET (Hamedi et al., 2009). The electrolyte replaced the gate dielectric. The semiconducting material P3HT is coated by solution processing. However, the spacing gap between source and drain should still be well controlled, and the electrodes were deposited by evaporation (Fig. 25.16).

### 25.3.3 Fibrous electrochemical transistors

In order to overcome the inconvenience of fibrous FET, electrolyte-based fibrous ECT began to be developed in 2007. The first fibrous ECT was published by Hamedi et al. (2007). A comparative study between WFET and WECT was published by Danilo De Rossi (2007).

A WECT is based on two PEDOT:PSS-coated Kevlar monofilament and polyester in cross-junction configuration with an electrolyte sol–gel between them (Fig. 25.17(a)). One of the filaments was considered as source-drain electrodes and another was considered as gate electrode. The coating was carried out using a vertical flow of the PEDOT:PSS fluid in the form of drops, under the influence of gravity. Since the geometry of the system is symmetric, the source-drain filament can be considered as gate filament and vice versa. The configuration of WECT was similar to VECT. The WECT worked as OECT and gave an ON/OFF ratio by $10^3$ (Fig. 25.17(b)).

In 2011 Tao et al. developed the similar WECT by using multifilament Kevlar. Besides the cross-junction configuration, they proposed a parallel configuration (Fig. 25.18). The Kevlar multifilament was coated by PEDOT:PSS by a roll-to-roll

![Figure 25.17](image.png) (a) Schematic picture of a wire ECT. (b) Output characteristics of the WECT with 10 μm fibers for both channel and gate.

machine, which is compatible to mass fabrication. This material was coated around the multifilament and penetrated interstices among filaments as well. The thickness of the PEDOT:PSS layer is about 3–5 μm observed by scanning electron microscope (SEM). The repeated $I_{ds} - V_g$ sweep of WECTs was carried out in order to check hysteresis behavior. The hysteresis behavior was stable in the first 10 cycles. Then the $I_{off}$ increased and the $I_{on}$ decreased. The On/Off ratio decreased and stabilized to 10$^2$.

In the same year, Müller et al. developed the cross-junction configured WECT on silk fibers (Müller et al., 2011). They submerged the fibers in PEDOT-S aqueous solution for 1 h and used smaller ionic liquid-polymer mixture electrolyte. They showed the possibility of rinsing the WECT with distilled water without any noticeable deterioration of device performance. The ON/OFF ratio and switch speed are similar to that of (Tao et al., 2011).

### 25.4 Textile electronic circuits

As humans we prefer to wear comfortable textiles rather than hard, rigid boxes, and in order to add advanced functions first efforts have been made to use the textiles themselves as a substrate for electronic functions (Post et al., 2000). Hence, the electronic circuit plays an important role in the development of textile electronic functionalization. The electronic components and their interconnections are preferred to be intrinsic or less visible to the fabric. As a result, the textile electronic circuit can be considered as the platform for the application of textile sensors and actuators.

From the application standpoint, textile electronic circuits can be used for stretch sensor, pressure sensor, electrochemical sensor, electrocardiogram sensor, electromyography sensor, electroencephalography sensor, temperature sensor, energy harvesting, wearable antenna, etc.

Structurally, textile electronic circuits can be classified into two categories: conventional electronic component implemented on fabric-based flexible planar circuit board (PCB) and intrinsic functional fiber/yarn-based circuit.
25.4.1 Textile circuit with traditional electronic components

Conventional components are implemented into a textile substrate, e.g., flexible planar circuit board. These conventional components could be sensors, OLEDs, and actuators. The circuit can be achieved by three methods: (1) weaving conducting wire, (2) sewing and embroidery technique, and (3) screen print and inkjet.

Conducting wires can be implemented into woven fabric to realize the circuit as weft or warp. These conducting wires could be metal wire, twisted metal wire, metal fibers, metal-coated wire, or conducting polymer filament. They are used to connect the components. For example, a plain-woven textile structure consisting of polyester monofilament yarn with diameter of 42 μm and copper alloy wires with diameter 50 ± 8 μm (AWG 461). Each copper wire itself is coated with a polyurethane varnish as electrical insulation (Locher, 2006). Cuts must be done with laser at specific locations in the wiring in order to avoid short circuits between copper wires. The interconnect is made by adding a drop of conductive adhesive. Finally, the epoxy resin is deposited on the circuit to enhance the mechanical and electrical protection. However, because of the irregular shape of the woven fabric, the repeatability of the position of the interconnect point between the conductive fibers is impossible to be achieved. Sabine et al. have developed a three-layered textile RFID tag with conducting warp threads in the top layer and conducting weft threads in the layer underneath (Gimpel et al., 2004). They also developed the textile keyboard and electroluminescent weaving by using the same technology.

For the sewing and embroidery, Post et al. (2000) used embroidery of conductive yarn to interconnect and directly attach electronic components to textiles. They discussed different types of conductive yarn, though all of them have resistances in the range of 100 Ω/m. They were the first to propose a way of stitching patterns that can define circuit traces, component connection pads, or sensing surfaces designed with traditional Computer Aided Design (CAD) tools for circuit layout. Linz et al. (2005) mounted flexible PCBs on fabric and sewed metal-plated multifilament yarn as the interconnection between PCBs. Conductive thread and yarn embroidery can be realized on fabric or can be quickly applied on different types of textile and apparel products, which is easy and efficient compared to a knitting or weaving approach.

Screen printing is another technique used for realizing a textile electronic circuit. It is appropriate for realizing electrics and electronics due to its ability to produce patterned, thick layers from paste-like materials. Paul et al. (2014) have developed a screen-printed network of electrodes and associated conductive tracks on textiles for medical applications. A polyurethane paste is screen printed onto a woven textile to create a smooth, high surface energy interface layer and a silver paste is subsequently printed on top of this interface layer to provide a conductive track (Fig. 25.19). Merritt et al. (2005) and Karaguzel et al. (2009) have screen-printed conductive structures on nonwoven textiles. They have measured variants of transmission lines and specified their electrical parameters such as DC resistance and line impedance before and after washing.
Inkjets are flexible and versatile and can be set up with relatively low effort. However, there are some specifics for the ink. It should have high electrical conductivity and resistance to oxidation. It should be able to dry out without clogging the nozzle during printing and have good adhesion to the substrate. The lower particle aggregation and suitable viscosity and surface tension are important for selection of ink. There are some inconveniences for inkjets. The most conductive inks and pastes are based on silver filler and suffer from brittleness. To achieve a satisfactory conductivity, several passes should be applied. As a result, the thickness of paste will be augmented, which influences the flexibility and elasticity of the textile substrate.

25.4.2 Intrinsic functional fiber/yarn-based circuit

The intrinsic functional fiber/yarn-based circuit is the flexible textile circuit whose electronic component is realized by fiber or yarn instead of conventional miniature electronic devices. These electronic components have only simple functions, eg, logic gate, mechanical sensor (Zou et al., 2012). The scale of components is about 100 μm to 10 cm.

When Lee and Subramanian invented the first fibrous transistor (Lee and Subramanian, 2003), they did not use it to develop a textile circuit. The reason may be in the rigidity, stability, and reproducibility of the fibrous transistor. The wire was in aluminum. It was difficult to insert it into woven fabric as a normal textile filament. Moreover, its evaporated semiconductor and source-drain electrodes were delicate. They would be easily destroyed during the assembly process. Besides, the source-drain electrodes were only in one side of the wire. The alignment with other conductive yarns was a problem in the source-drain position. Even if this kind of fibrous transistor was ameliorated by using stainless wire as gate and depositing the source-drain around the whole wire (Lee and Subramanian, 2005; Maccioni et al., 2006), there still was no laboratory prototype of a fibrous transistor-based electronic circuit published. Because the deposition should be carried out in vacuum, it became impossible to exploit series manufacturing for
realizing several fibrous transistors in a long wire. This impossibility hindered using them in real conditions.

At the same time, the fibrous OFET transistors that used ribbon or sheet as substrate were successfully used to realize electronic circuits. Bonderover and Wagner (2004)
used their transistors to develop an inverter. The flexibility of fabric was kept by using Kapton sheets and series manufacturing became possible. Bonfiglio et al. (2005) used the same idea to propose a theoretical ring oscillator structure. Unfortunately, they did not produce a real prototype.

As for the electrolyte-based transistor, they are easier to use to produce a textile circuit because the semiconducting material is deposited by solution processing and the interconnect between the semiconducting material and conductive material is made by electrolyte, which does not need precise alignment and size control.

Hamedi et al. (2007) developed the first textile circuit by using WECT shown in Fig. 25.20. They have demonstrated universal logic operations by constructing an

![Figure 25.21](image_url)

inverter on the basis of a voltage-shifting logic design, comprising three resistors and a depletion p-type transistor. A possible translation of the inverter circuit diagram into a real textile circuit is shown in Fig. 25.20(b) by manually creating a fiber crossbar from coated monofilaments with an electrolyte sol–gel at the crossbar junctions. The dynamic switching characteristic of the inverter is shown in Fig. 25.20(c). The inverter operates at 1–2 V, which is more than an order of magnitude lower than logic on the basis of conventional OFETs. Moreover, they realized a binary tree multiplexer with two address lines and four channel lines as shown in Fig. 25.21(a). Its dynamic operation characteristics in Fig. 25.21(b) showed that each of the four channel lines was uniquely addressed using the four possible binary combinations as inputs to the two address lines.

Hamedi et al. (2009) have developed a Boolean AND logic circuit by using two electrolyte-based transistors. These two transistors were inserted into tulle in Fig. 25.22(a). The input–output curves in Fig. 25.22(b) show a Boolean AND operation, with two inputs corresponding to gate voltages $V_{G1,2}$ and the output signal measured as output current $I_{out}$.

Tao et al. (2011, 2012) have developed a NOR-gated logic circuit by using WECT. They embroider the PEDOT:PSS-coated yarn into a cotton fabric as transistor. The resistance was realized by the black carbon—coated yarn. They used parallel configuration (Fig. 25.23(a)) and cross-junction configuration (Fig. 25.23(b)). The electrolyte was absorbed into fabric and after drying they became sol–gel. These electrolytes influenced a little hand feeling of fabric and left spots on the fabric. The aging of circuit and work rate were discussed. Apart from numeric logic circuit, they developed a simple amplifier with gain of five by using WECT.

![Figure 25.22](image-url) *(a) Microscopy image of AND logic circuit in a tulle by two transistors created along the horizontal fiber. (b) Input voltages and output currents measured on an AND circuit. Reproduced with permission from (Hamedi, M., Herlogsson, L., Crispin, X., Marcilla, R., Berggren, M., Inganäs, O., 2009. Fiber-embedded electrolyte-gated field-effect transistors for e-textiles. Advanced Materials 21, 573–577), Copyright 2009, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.*
Conclusions and perspectives

Wearable technologies have become extremely developed over the years in the textiles industries (Microsoft, 2015; CNET, 2015; Samsung, 2015). Most of them focus on the development of wearable equipment such as watches and glasses to help wearers to communicate and acquire data. The world is aware of the importance of wearable devices and their huge market and business value. Portability, invisibility, flexibility, and feasibility have become the trends of electronic devices. In the apparel industries, research has started to integrate miniaturized electronic components into textile fabrics (Google, 2015). Google and Levi Strauss have started a special project called “Project Jacquard” with the industries to fabricate jeans that can connect with a computer, tablet, or telephone.

The objective is to seamlessly integrate electronic devices into textiles. All efforts are being made to realize that objective in the fields of new materials, nanotechnology, and miniaturized electronic components. The ultimate aim is to let users accept electronically functionalized products without feeling a difference in the mechanical properties and hand feel of the materials.

There are two approaches to achieve this aim. With the development of the electronic device, the conductive material, and electronic manufacture technology,
miniaturized electronic components can be implemented on the flexible planar circuit board into textiles, eg, planar fashion circuit board (Hyejung et al., 2009). This kind of flexible planar circuit board has the same mechanical properties as the fabric. As a result they can be easily processed into the various items such as clothing, a bag, and a pillow as a normal textile and the electronic devices such as planar fabric sensors, LED display, fabric chip package. As well, this kind of circuit can be directly screen printed on fabric (Yongsang et al., 2010). Apart from the print technology, with development of textile compatible electronic control devices, eg, LilyPad and Adafruit FLORA, the control system can be easily integrated into textiles connected with embroidered conductive thread. The wireless control by using XBee protocol even becomes possible. These kinds of devices are washable by hand.

On the other hand, the fibrous transistor-based circuit takes advantage of this miniature size and pure textile nature. Particularly for the WECT, they can be used to develop a basic digital or analogical circuit. The technical difficulties reside in the low work rate and flexibility. By using smaller ion-based electrolytes, the WECT will obtain a higher work rate. Meanwhile, the aging of sol–gel of electrolytes should be investigated.

References


