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REVIEW ARTICLE

Research progress of fiber-based organic electrochemical transistors

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ABSTRACT

Organic electrochemical transistors are flexible in design with characteristics such as miniaturization, biocompatibility and amplification and are one of the rapidly developing research topics in recent years. As an excellent flexible material, fiber has unparalleled advantages in weaving and compatibility with the human body. Combining fibers with organic electrochemical transistors is a promising research direction that has the high sensitivity of organic electrochemical transistor testing and the human body compatibility and flexibility of wearable electronic products. This paper introduces the relevant operating principles, working modes and commonly used channel materials of organic electrochemical transistors. Based on the basic device structure of organic electrochemical transistors, the development and changes of organic electrochemical transistors in recent years are discussed, and the research results of fiber-based electrochemical transistors by researchers focusing on the application of fiber-based organic electrochemical transistors in chemical sensing, bio-sensing and other application explorations are summarized. Finally, this paper visioned the future development trend of fiber-based organic electrochemical transistors.

Keywords: fiber; organic electrochemical transistor; flexibility; wearable

1. Introduction

Organic thin-film transistors are the core components of organic electronics, and their comprehensive properties are comparable to those of commercial amorphous silicon products. At the same time, the advantages of low cost and high function have shown broad development prospects and industrialization value[1].Organic electrochemical transistors (OECTs) are a kind of organic thin-film transistors, which were invented by White et al.[2] Organic electrochemical transistors have the advantages of flexible design, low operating voltage, and good biocompatibility. They also have dual functions of sensing and amplification and can be widely used in light sensing[3], artificial skin[4], environmental monitoring[5], food safety testing[6], drug release[7] and medical diagnosis[8].In previous studies, most of the reports on OECTs are based on planar structures, and there are few studies on flexible OECTs, so OECTs are often unable to adapt to complex curved environments in practical tests, and the application is limited. Fiber-based organic electrochemical transistors are a major emerging re-

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search direction in recent years. Fiber is a common material in daily production. It is closely related to people's lives and is also a popular material in scientific research. It has the advantages of lightweight, good flexibility, able to be weaved, and low cost. Many studies have been carried out to use it as a substrate to prepare electronic materials and devices. Fiber-based organic electrochemical transistors creatively combine the sensitivity of OECTs with the flexibility and weavability of fibers that can adapt to complex test environments while effectively testing, and have a wider range of applications such as wearable sensors. The broad development prospects have been acknowledged by the majority of scientific research workers. This paper discusses the working principle, mode and materials of OECTs device channel and briefly introduces the development of OECTs technology focusing on the recent development of fiber-based organic electrochemical transistors and their applications in biological and chemical sensing. The application of fiber-based electrochemical transistors and the future development direction of fiber-based electrochemical transistors are also reviewed.

2. The working principle, mode and material of OECTs

2.1. The working principle of OECTs

OECTs consist of an organic semiconductor channel in contact with the electrolyte and three electrodes, where the channel is between the source and the drain. The channel is covered by an electrolyte and the gate is an external electrode immersed in the electrolyte. The source and drain are in contact with the organic semiconductor film and define a channel for holes or electrons to flow from the source to the drain. It works as follows: The source is grounded, and a constant voltage bias on the drain drives a current through the semiconductor channel between the source and drain. This channel current is defined as the output current of OECTs, which is modulated by the input voltage on the gate electrode. This modulation is caused by the interaction between electrons and ionic carriers. Charge carriers (holes) carry channel currents in OECTs. On the other hand, ionic charge carriers provide charge balance for holes, thereby regulating the concentration of holes and thus the electron conductivity of the transistor channel. OECTs rely on the implantation of ions from an electrolyte into an organic thin film, thereby changing its doping state and thus its conductivity, controlled by the voltages applied to the gate (gate voltage, VG) and drain (drain voltage, VD). The VG controls the ion implantation channel and thus the doping state (i.e. redox state) of the organic film. The VD induces a current (drain current, ID), which is proportional to the amount of mobile holes or electrons in the channel, and this mechanism probes the doping state of organic thin films. Similar to organic thin-film transistors, OECTs work like switches, where the VG (input) controls the ID (output). They can also be thought of as amplifiers, where the power of the input signal is amplified on the way to the output.

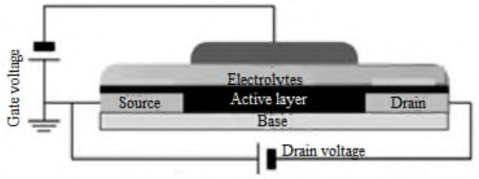
In contrast to the thin interfacial regions in field-effect transistors, the distinguishing feature of OECTs is that doping changes occur over the entire volume of the channel. Therefore, for low VGs, large modulation of the ID can be achieved, which makes OECTs efficient switches and powerful amplifiers[9]. At the same time, the use of electrolytes instead of metal oxide semiconductor dielectrics greatly enhances the flexibility of OECTs in terms of device architecture and integration with various substrates. The inherent tunability of organic conducting polymers can also improve ion and electron transport and the convenience of bio-functionalization. Due to these characteristics, OECTs are widely used in research, including neural interfaces[10], chemical and biosensors[11], printed circuits[12] and neuromorphic devices[13]. In addition to the advantages of organic thin-film transistors, OECTs also have the characteristics of simple structure, low operating voltage, and the ability to work in a solution environment. First, OECTs can work in an aqueous medium, and their low operating voltage can effectively prevent hydrolysis. Second, OECTs gate electrode and channel can be prepared separately, and the biochemical sensor can be prepared by special treatment of OECTs gate electrode. OECTs can be successfully used in biochemical detection[14] such as lactate[15], glucose[16], dopamine[17], DNA[18], ions[19], bacteria[20] and antigens[21].

2.2. The working mode of OECTs and their channel materials

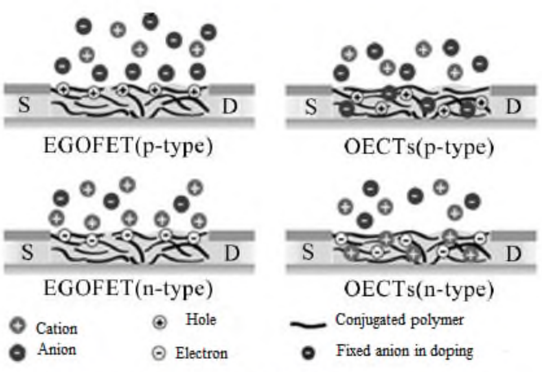
The working mode of OECTs depends on the doping level of the conjugated polymer in the original state, and its working modes are divided into depletion mode and accumulation mode. In depletion mode transistors, the current between the source and drain gradually decreases as the VG increases. For transistors operating in accumulation mode, the VG increases in correlation with the gradual increase of current between the source and the drain. Its working curve is shown in **Figure 1**[22]. In depletion mode, the conjugated polymer of OECTs is in the doped form in the pristine state and the device is turned on at zero gate bias. Applying positive gate bias results in the injection of cations or the expulsion of anions from the conjugated polymer network and shuts down the device. Most of the OECTs developed so far work in depletion mode because they are already present in the doped form when they are fabricated. The polyelectrolyte dissolves in the solvent and can ionize out ions that act as counterions to the positively charged formed in the backbone of the conjugated polymer upon doping. Therefore, the pristine conjugated polymer/polyelectrolyte exhibits high conductivity at zero gate bias. Taking the most common PEDOT—PSS as an example, when a positive gate bias is applied, the PEDOT is reduced to a neutral (non-conducting) state according to the following half-reaction PEDOT:

$$\mathrm{PEDOT:PSS} + \mathrm{M}^{+} + \mathrm{e}^{-} \rightleftharpoons \mathrm{PEDOT} + \mathrm{M:PSS}$$

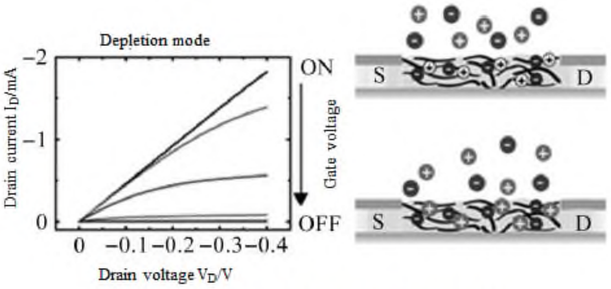
In the equation above, e^- is the electron, M^+ is the positively charged ion from the electrolyte. In accumulation mode OECTs, the conjugated polymer is in the de-doped semiconducting state in its original form, and the device is turned off at zero gate bias. Applying a negative gate bias causes the injection of anions from the active layer (or the expulsion of cations from the active layer), which turns the device on. Commonly used materials in OECTs channel are shown in **Figure 2**[22]—Semiconductor conjugated polymers, conjugated polymer composite materials and conjugated polyelectrolytes.



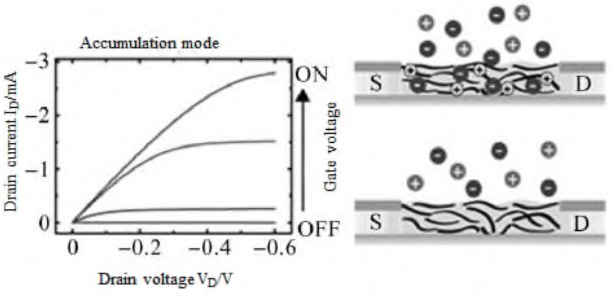
(a) Common structure of organic electrochemical body tube



(c) The working principle of field effect transistor and organic electrochemical transistor

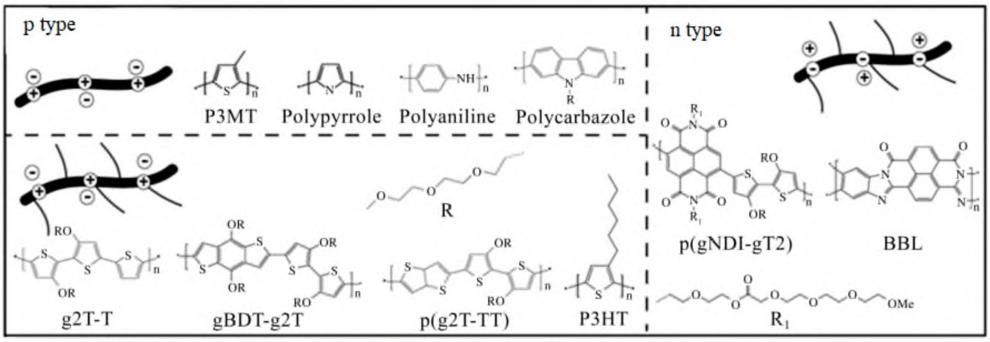


(b) Transistor operating in depletion mode

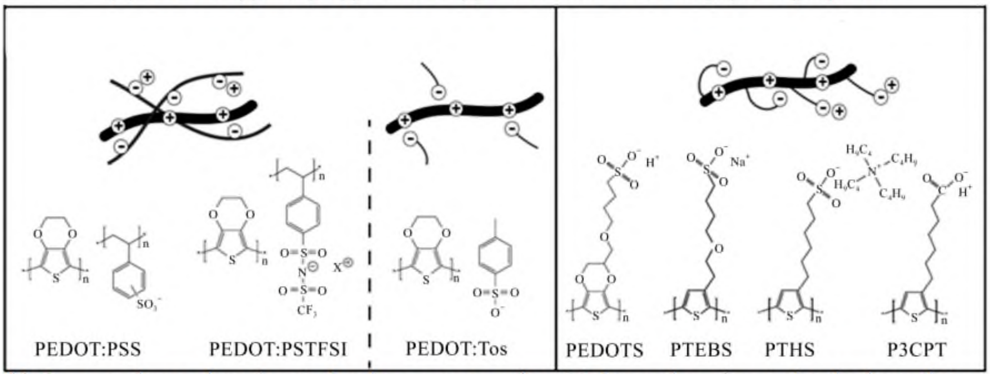


(d) Transistor operating in accumulation mode

Figure 1. The working principle of organic thin-film transistors.



(a) Several typical p-type and n-type semiconductor conjugated polymers



(b) Commonly used conjugated polymer composites (c) Several conjugated polyelectrolytes

Figure 2. Common materials for the channel of organic electrochemical transistors.

Most of the organic semiconductors used in OECTs show p-type characteristics in air, such as PPy, PANI, PEDOT:PSS, etc. Therefore, most of the research on OECTs done so far worked with the depletion mode. The channel materials required for transistors operating in accumulation modes, such as BBL and P3HT, are difficult and expensive to prepare. Hence, there are not many studies on this aspect.

3. Development of OECTs

3.1. Development of OECTs device structure

The basic structure of OECTs is shown in **Figure 1(a)**. It is mainly composed of three electrodes: Gate, source and drain, as well as a channel and electrolyte. The electrolyte is separated, and the electrolyte covers the three electrodes, thus constituting a basic OECTs device. The use of an electrolyte as the gate dielectric allows great flexibility in the design of OECTs in terms of the placement of the gate electrode relative to the channel. In addition, the "long channel" effect can also be addressed. In organic thin-film transistors (OTFTs), charges are transported along accumulated holes or electron sheets and reside at the semiconductor-gate dielectric interface. In long channels, this often results in very low currents, limiting the ability to use the OTFT as a power-hungry driver. On the contrary, in OECTs, the entire volume contributes to charge transport, therefore, higher currents can be delivered for the same given channel length. At the same time, OECTs can be flexibly designed concerning the gate, electrolyte, channel size and relative position. In addition, different deposition and patterning techniques on a variety of substrates including flexible and stretchable substrates can be applied, paving the way for a host of new device architectures and form factors.

Bartlett et al.[23] reported on the electrochemical transistors fabricated by printing technology. Carbon-based source and drain electrodes and dielectrics were screen-printed on polyvinyl chloride substrates. The obtained devices had a channel length and width of 20 μm and 4.5 mm, respectively and were used as a microelectrochemical enzymatic transistor for glucose and peroxide sensing. Meanwhile, Rani et al.[24] reported on OECTs with 1MKCl electrolyte, thick paper as carrier and polycarbazole as channel material with a channel length of 0.5 mm and studied the effect of device electrode spacing on the transfer performance of OECTs. This study provided a good idea for the electrode design of subsequent OECTs.

In the early 1990s, poly-3,4-ethylenedioxythiophene (PEDOT) was used as electronic inks and conductive coatings for various conductive, electronic, and electrochemical applications[25,26]. PEDOT shows good redox stability and high electronic conductivity when combined with the dopant sodium poly (p-styrene sulfonate) (PSS) and can be incorporated into OECTs structures using printing techniques, where PEDOT:PSS can be used both as an active channel as well as an electrode for the gate, drain and source electrodes. As such, PEDOT: PSS has become the most common material for the preparation of OECTs.

Anderson et al.[27] used PEDOT:PSS to fabricate channel materials on coated paper by printing technology and combined the prepared OECTs with vertical electrochromic display units to form the main smart pixel and display. Wan et al.[28] used a 3D porous sponge of PEDOT:PSS to prepare OECTs as a sensing scaffold. Paper and plastic films as extremely widely used flexible materials with their use as substrates to prepare OECTs have attracted great attention from scientists. Several standard and modified printing techniques have been explored to produce OECTs devices and circuits using these techniques such as screen printing[29] and inkjet printing[30], of which both are commonly used for the preparation of planar flexible OECTs. The advantages of these methods are low cost, simple and flexible design. The preparation of OECTs based on these two technologies can design different circuit structures on their substrates. Hütter et al.[31] developed full-screen printed OECTs logic circuits on a polyethylene terephthalate (PET) substrate by screen printing. Textiles are also good carriers for OECTs and the preparation of OECTs based on textile fabrics has potential applications in the field of wearable electronics. For example, PEDOT-based transistors have been fabricated on Gore-Tex as gas sensors on “breathable” substrates, and have also been screen-printed on common fabrics such as woven cotton and Lycra for wearable sensors that were used for biological fluid sensing such as sweat, saliva, and urine[33]. In addition, PEDOT:PSS combined with nano-fibrillated cellulose (NFC) was also investigated as a coating around the fibers. This combination provides a scalable technology for both stand-alone and large-scale OECTs integration systems such as the reconfigurable OECTs tagging platform[34].

3.2. Device structure of fiber-based organic electrochemical transistors

With the development of medical technology, real-time monitoring is becoming increasingly important for modern medicine and patient health. The OECTs device structure has also begun to be studied by various research groups. A review published in 2018 briefly summarizes the different device structures of OECTs (**Figure 3**)[35]. Compared with rigid planes, the flexibility and practicality of wearable devices and biosensors based on flexible OECTs have improved greatly, which makes real-time monitoring possible.

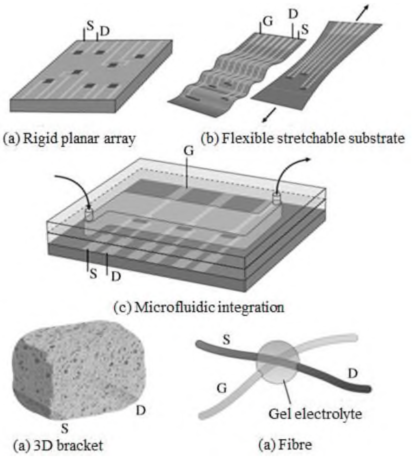


Figure 3. Different device structures of OECTs.

Fiber weaving technology, which has a history of thousands of years, provides a superior platform for the device development of OECTs. Integrating electronic functions within fabrics is an important approach to improve textile performance and extend functionality.

Fiber-based organic electrochemical transistors (FECTs) are a kind of smart material that has developed rapidly in recent years. Its advantage is that it can directly integrate electronic functions into ordinary fiber materials and achieve the design of integrated circuits on textile materials through weaving methods. The structure is simple to prepare and easy to weave into flexible fabrics. Fiber-based organic electrochemical transistors (FECTs) not only have the advantages of ordinary OECTs of low operating voltage, able to work in aqueous environments, good biocompatibility, high sensitivity, low production cost and simple preparation process, but also have the advantages of similar flexibility, bendability and weaving as fiber materials. Therefore, it can be applied to the fields of health care, biological intelligence monitoring and wearable sensing devices to effectively test human biomarkers[14]. Compared with other flexible platforms, textile fibers provide OECTs with superior flexibility, material diversity, and simple processability, enabling the efficient development of various designs. Due to the flexibility of fibers, the preparation method of fiber-based electrochemical transistors is very flexible where fibers are often used as carriers with conductive polymers attached to them. The methods of attaching conductive polymers include dip coating, in situpolymerisation, electrodeposition, and gas-phase polymerisation[36]. In addition, the gate preparation of OECTs is independent and the way of assembling and designing FECT devices is also very flexible and simple. The two most common assembly methods include the use of fiber coated with conductive polymer as the channel material as the source and drain, and the conductive fiber is used as the gate. The two fibers are separated by an electrolyte to form a cross (as shown in **Figure 4**)[37]. In another way, two fibers are placed in parallel at a certain interval[38], and the electrolyte is then dropped in the middle to coat the two fibers to prepare the OECTs. In addition to these two ways, there are many assembly ways to be explored.

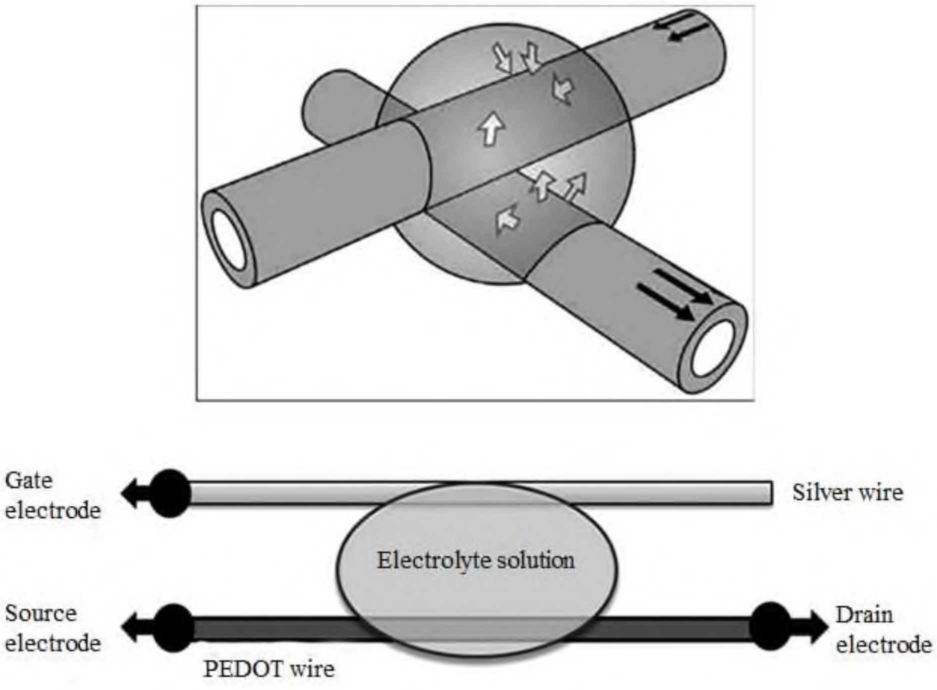


Figure 4. Two typical device structures of fiber-based organic electrochemical transistors.

4. Development process and application of fiber-based organic electrochemical transistors

In recent years, many researchers have begun to focus on the study of fiber-based organic electrochemical transistors. Since Hamediet al.[37] first reported fiber-based organic electrochemical transistors in 2008; many research groups have successively published relevant literature. Cotton, nylon and other fibers have been used as carriers to prepare various FECTs for different applications. In particular, in-depth research has been carried out on sensors based on FECTs. The sensing applications based on FECTs can be roughly divided into chemical sensing and biological sensing. This paper will introduce recent research on FECTs in these two fields. In addition, other researchers have explored and studied other properties and applications of FECTs, which will be briefly introduced below.

4.1. Application of fiber-based organic electrochemical transistors in ion sensing

Tarabellaet al.[38] used cotton fibers to functionalized cotton fibers by simply soaking them in a poly (3,4-ethylenedioxythiophene) (poly styrene sulfonate) (PEDOT:PSS) conductive polymer and directly used as channels for organic electrochemical transistors (OECTs) in contact with liquid electrolytes and silver wire gates (**Figure 5**). The prepared OECTs show stable and reproducible current modulation and demonstrate a very efficient electrochemical detection of sodium chloride concentration in water, which is simple and low-cost and has great potential in the development of wearable electronics in fitness and healthcare.

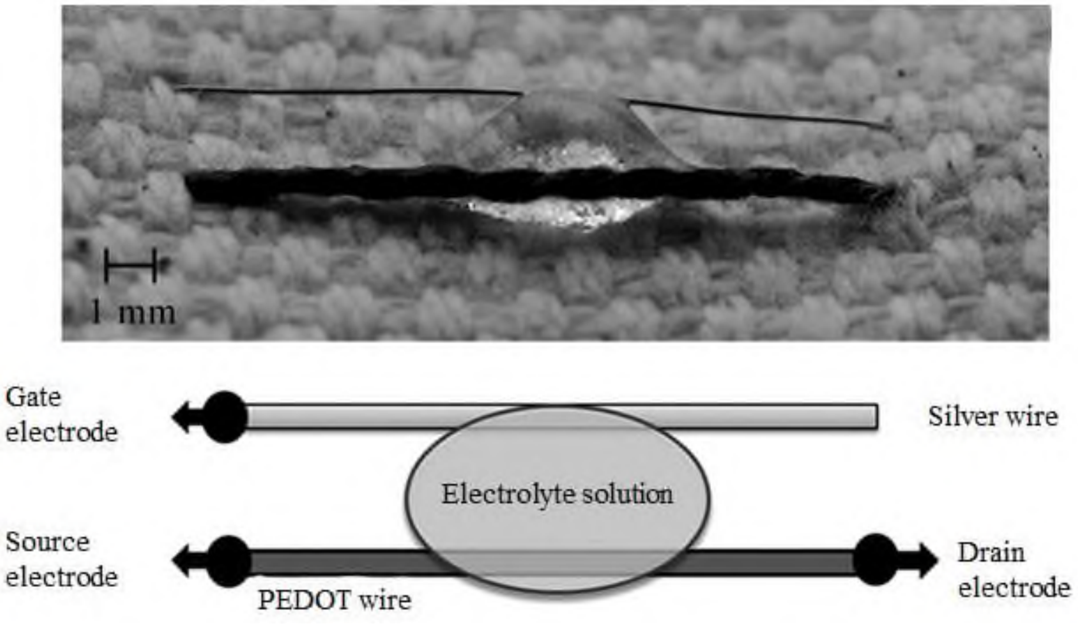
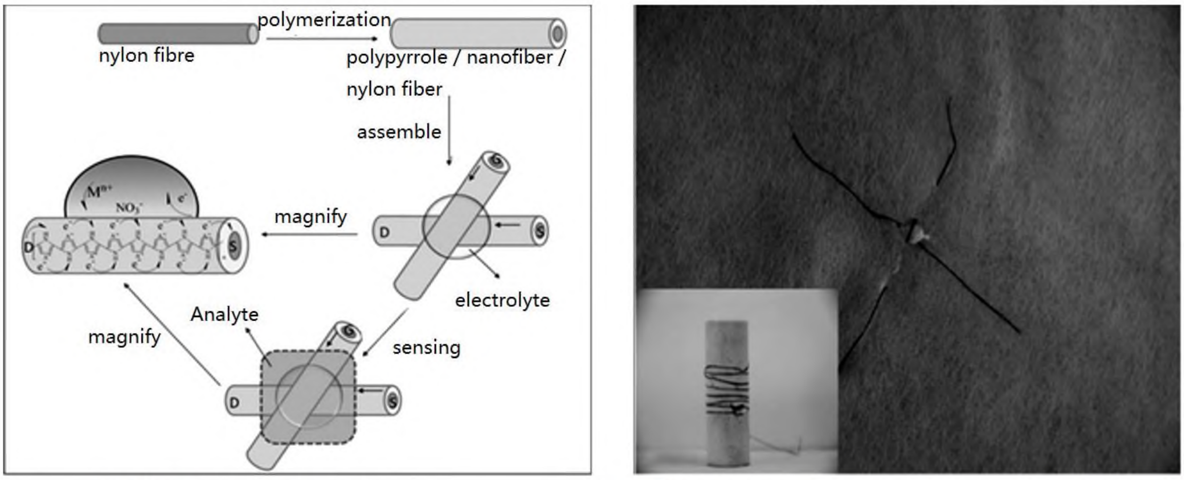


Figure 5. Optical photos and device assembly of FECTs devices.

Wang et al.[39] from Wuhan Textile University first prepared a fiber-based organic electrochemical transistor using polypyrrole and nanofiber materials in 2016, as shown in **Figure 6**. The FECTs exhibit excellent electrical performance with an on/off ratio as high as 100 and an operating voltage below 2 V. At the same time, the ion sensing behavior of FECTs was studied. The results showed that with the increase of cation concentration, the transfer curve of FECTs shifted to low gate voltage and the sensitivity reached 446 μA/dec in the range of 10^{-5} to 10^{-2} M lead ion concentration.

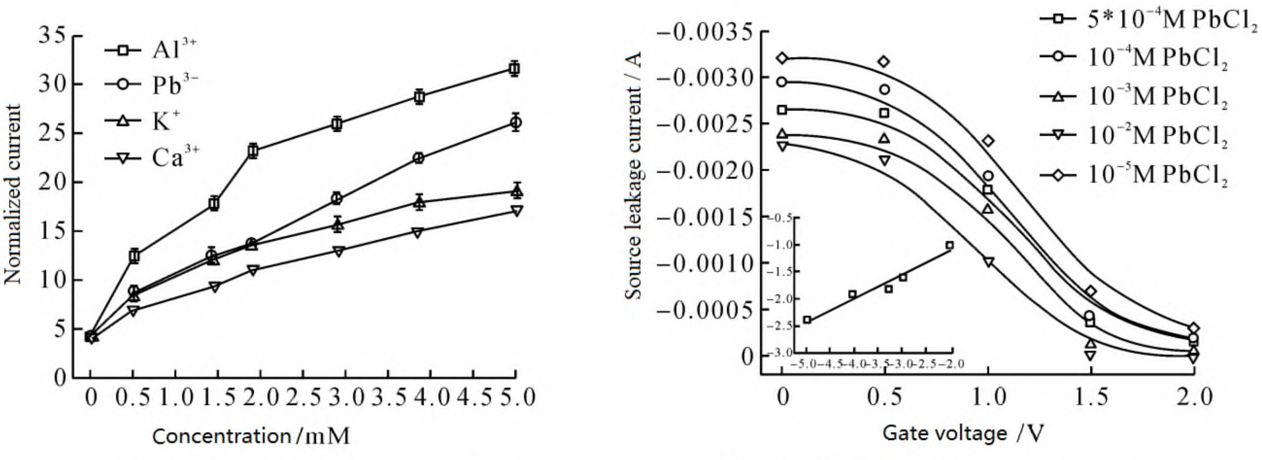
The ion-selective properties of FECTs were also systematically investigated (**Figure 7**) for the detection of potassium, calcium, aluminium, and lead ions. Devices with different cations show large differences in the response curves. Compared with other cations, transistor sensors are more suitable for selectively monitoring lead ions and are very efficient for lead ion electrochemical sensing, opening a path for wearable electronics in healthcare and biological applications.



(a) Effects sensor schematic

(b) Optical micrographs of organic electrochemical transistors

Figure 6. Assembly of nylon-based FECTs.

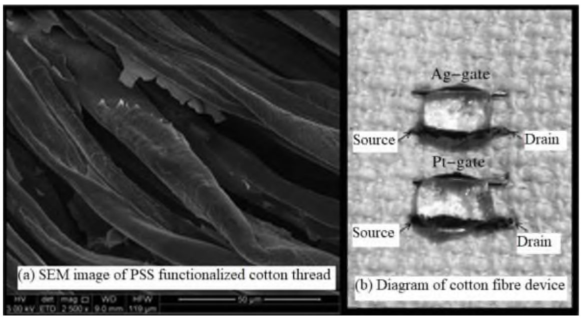


(a) Graph of transistor normalized response

(b) Output characteristics of FECTs at different Pb^{2+} concentrations illustration: Log (Pb^{2+}) logarithm relationship between I_{DS} and devices

Figure 7. Sensing performance of FECTs sensor.

Copped et al.[40] studied organic electrochemical transistors as electronic textile biosensors and fully integrated PEDOT:PSS on a single cotton yarn as a channel material. **Figure 8** demonstrates the two different transistors that were fabricated using silver (Ag) and platinum (Pt) wires as gate materials, respectively.



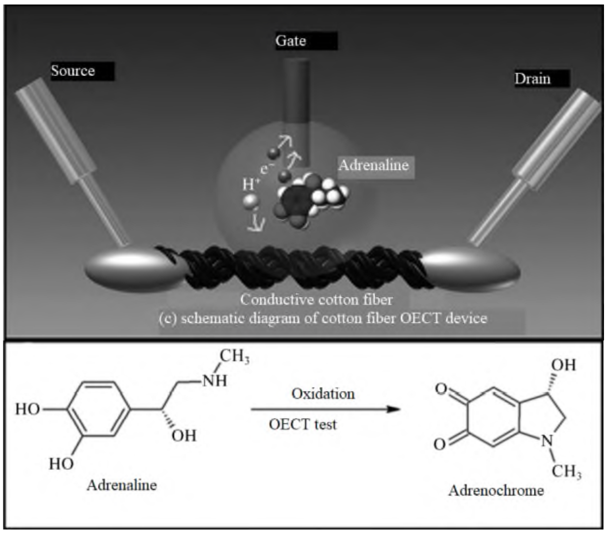
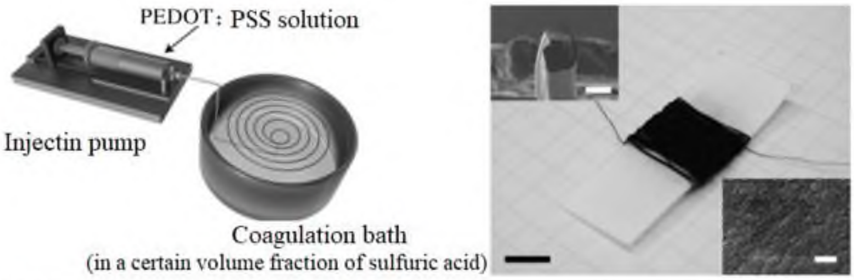


Figure 8. Assembly and sensing mechanism of cotton fiber-based OECTs.

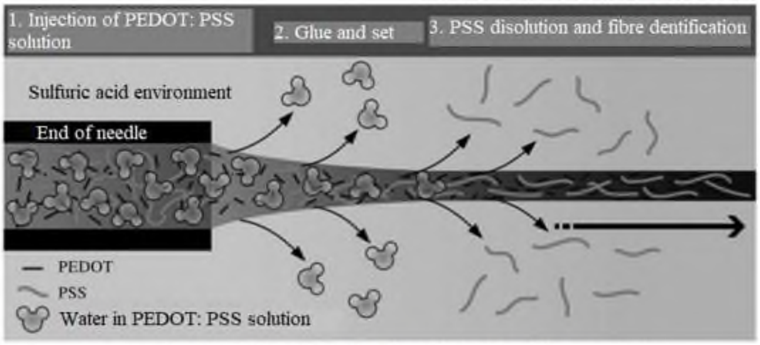
The difference between the fabricated sensors is in the use of different gate electrode materials to detect saline and epinephrine concentrations in human sweat, respectively. Measurements performed in real-time detection mode confirmed the complete independence of epinephrine detection from sodium chloride, thus guaranteeing specific monitoring of epinephrine. The oxidation of epinephrine at different electrodes was studied by absorption spectroscopy. The findings confirm that the oxidation reaction driven by the Pt electrode results in the accelerated formation of adrenochrome, whereas for the Ag electrode, the oxidation is similar to the spontaneous oxidation that occurs in the air. This research opens up new avenues for healthcare, fitness and job security.

Kim et al.[41] from Korea reported conductive polymer microfiber organic electrochemical transistors (OECTs) and their application in single-strand fiber-based wearable ion concentration sensors. As shown in **Figure 9**, they used a simple wet spinning process using aqueous sulfuric acid as a coagulation bath to form PEDOT:PSS microfibers with excellent electrical conductivity and examined their electrical/electrochemical properties thereby achieving the fabrication of combined substrateless PEDOT:PSS microfiber OECTs devices. The novel characterization method presented in this study demonstrates that the current rate of change can be a reliable method for evaluating device performance as well as detecting ion concentration, regardless of actual channel dimensions. Finally, by introducing a source-gate hybrid electrode, single-strand fiber-type skin-mountable OECTs were developed and the resulting microfiber sensor was demonstrated to perform real-time repeated measurements of ion concentrations in human sweat.



(a) Schematic diagram of wet spinning process of PEDOT: PSS microfiber

(b) The photo of the spooled microfiber in the paper roll is illustrated with an inclined microfiber cross section and a surface electron microscope



(c) PEDOT: PSS forms microfibrils in acidic coagulation

Figure 9. Spinning procedure and coagulation mechanism of PEDOT: PSS microfibers in a sulfuric acid environment.

4.2. Application of fiber-based organic electrochemical transistors in biosensing

In 2017, Wang *et al.*[42] used in situpolymerisation method to induce the generation of PPy nanowires on nylon fibers with reduced graphene oxide and prepared a new type of woven fiber organic electrochemical transistor (**Figure 10**). The experimental results showed that the introduction of rGO nanosheets can induce the growth of PPynanowires and increase their ratio. Moreover, it can enhance the conduction and electrical properties of the transistor. The fabricated transistors have a high on/off ratio, fast response time and long cycle stability. A glucose sensor based on fiber organic electrochemical transistors has also been studied, which has excellent sensitivity, a fast response time of 0.5 s, a linear range of 1 nM to 5 μM, low limit detection concentration and good repeatability.

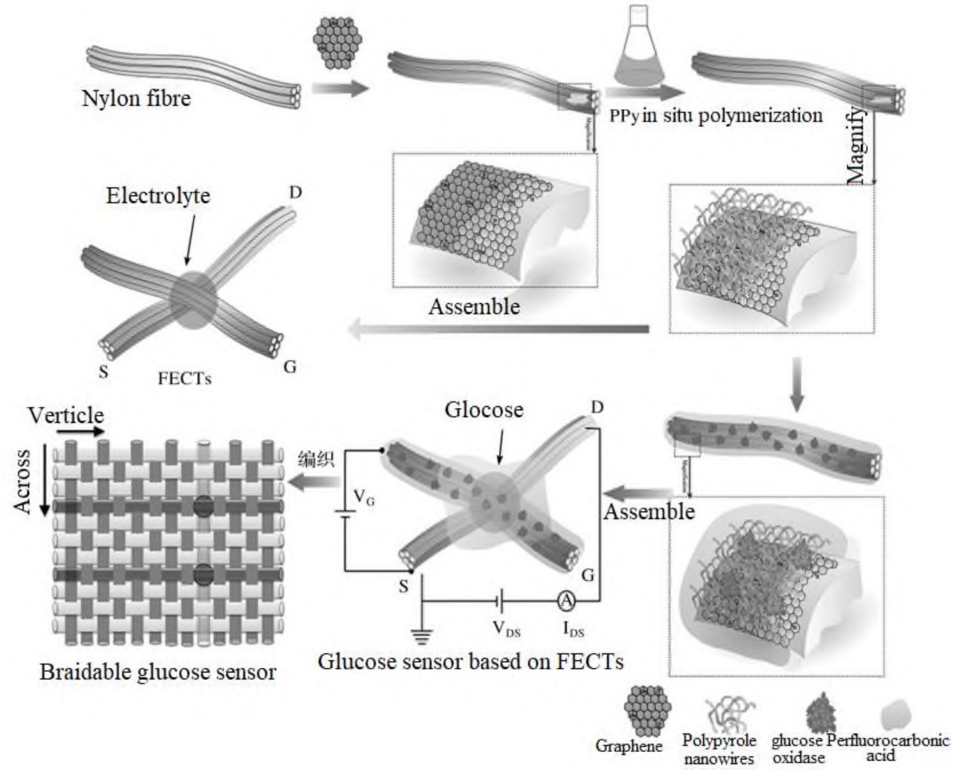


Figure 10. Schematic illustration of the glucose sensor of the fibrous organic electrochemical transistor.

In 2018, the research group[43] simultaneously fabricated another kind of fiber-based organic electrochemical transistors (FECTs), providing a new platform for achieving ultrafast and ultrasensitive biosensors. As shown in **Figure 11**, they pre-treated nylon fibers with PVA-co-PE nanofibers (NFs) to induce polypyrrole (PPy) nanofiber network on the fibers.

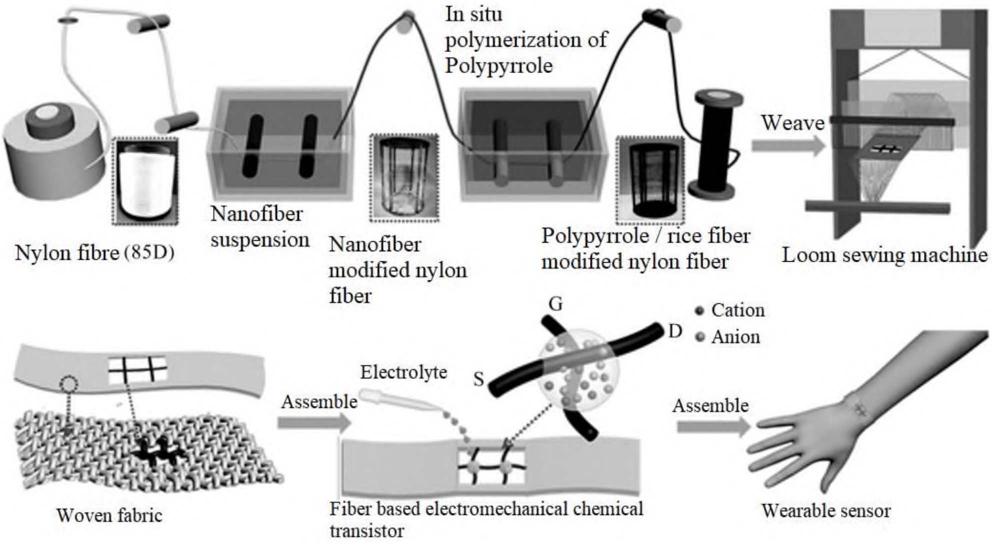
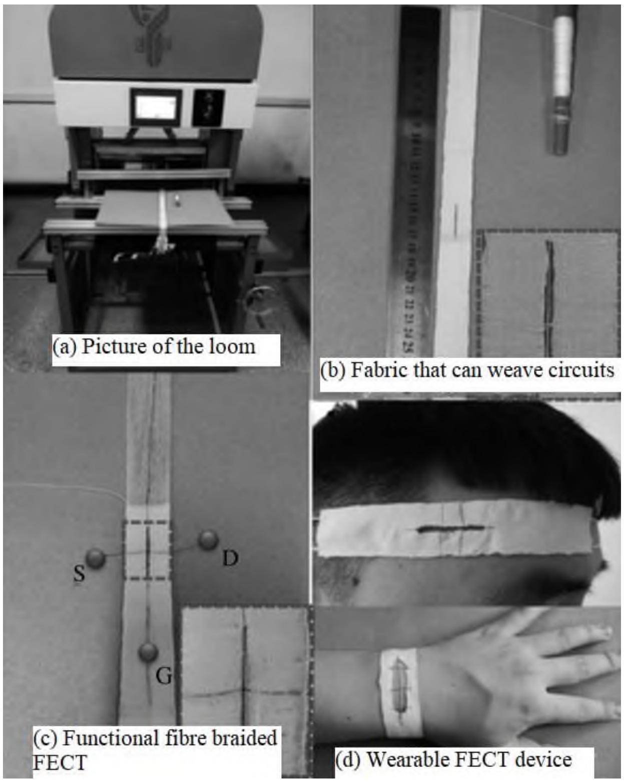


Figure 11. Fabrication and assembly of a wearable dopamine sensor based on FECTs.

The experimental results showed that the introduction of NFs significantly increased the specific surface area and hydrophilicity of nylon filaments, resulting in the formation of a large-area interwoven PPy nanofiber network. The PPy nanofiber network improved the electrical properties of the fibers and their electrical conductivity significantly. The device on/off ratio is as high as 100 with switching time between on and off states was as low as 0.34 s and exhibited good cycling stability. In addition, they also investigated the performance of FECTs-based dopamine sensors relying on different gate electrodes. The results showed that the fiber-based conductive polymer composite gate had the highest sensitivity while the device is highly selective and has excellent reproducibility in the presence of sodium chloride, uric acid, ascorbic acid, and glucose interferences. Moreover, it can also be woven into fabric products (**Figure 12**), which has strong application potential in wearable electronic sensors.



(a) Picture of the loom

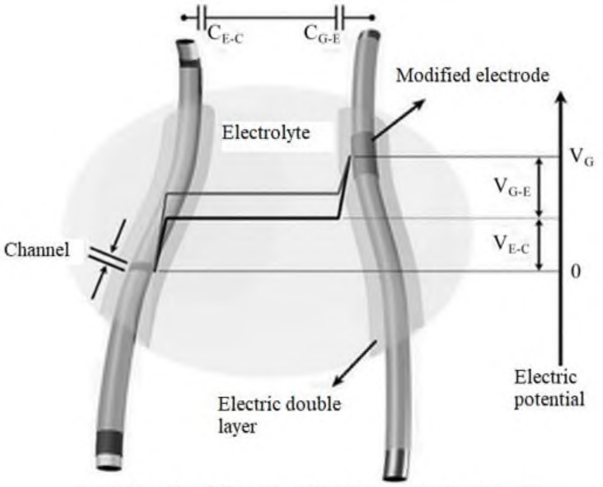
(b) Fabric that can weave circuits

(c) Functional fibre braided FECT

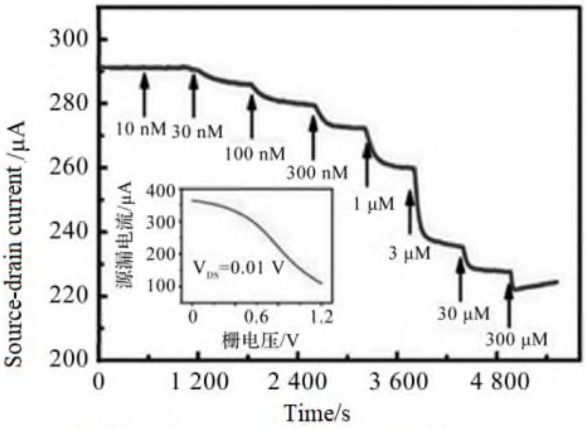
(d) Wearable FECT device

Figure 12. Practical weaving and wear of FECTs.

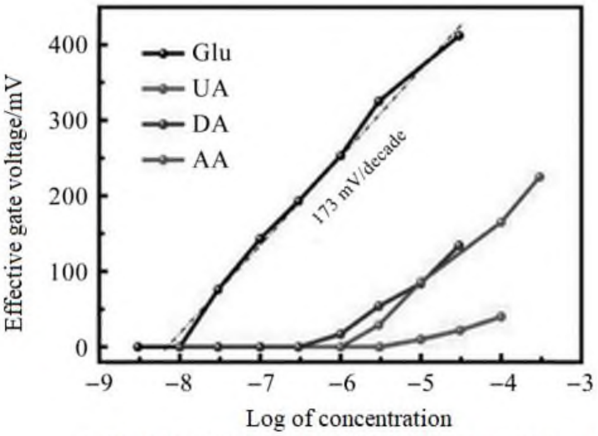
Yan Feng's research group[44] from the Hong Kong Polytechnic University used nylon monofilament dip-coat PEDOT:PSS as a channel material and deposited metal on the fibers as electrodes using magnetron sputtering. They also used the same method to deposit another nylon monofilament as a grid electrode and modified the electrode with enzymes and polyaniline. The two fibers were assembled in parallel into a transistor and its performance was tested (**Figure 13**).



(a) Schematic of fiber based OECT operating in electrolyte



(b) The OECT current response to different concentrations of glucose inset: measured OECT transfer curve



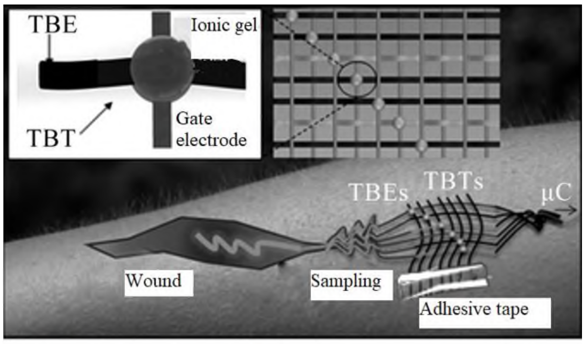
(c) Relationship between different concentrations of glucose, UA, DA and AA and effective grid voltage in fiber-based OECT

Figure 13. Schematic diagram of sensing mechanism and sensing performance of FECTs-based sensor.

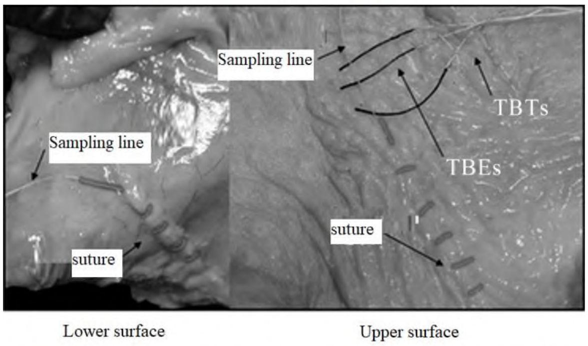
Finally, the device was stitched on a diaper and monitored remotely in real-time with a mobile phone application, The highlight of their work was that by coating conductive polymers and metals with fiber coating, they studied the effect of the coating material on the mechanical properties of the fiber while investigating the degree of change in the electrical properties caused by the bending of the fiber before weaving. The studied fiber was then further integrated with a fabric-based wearable biosensor for the detection of human secretions, which paved the way for wearable devices and flexible electronics.

4.3. Other application exploration of fiber-based organic electrochemical transistors

Owyeunget al.[45] fabricated two different fiber-based electrochemical transistors using a gel composed of silica nanoparticles and 1-ethyl 3-methylimidazolium bis (trifluoromethyl sulfonyl) imide (EMI TFSI) ionic liquid as an electrolyte with assembled carbon nanotubes (CNTs) and poly3-hexylthiophene (P3HT) on a linen line as semiconductor channel materials as shown in **Figure 14**.



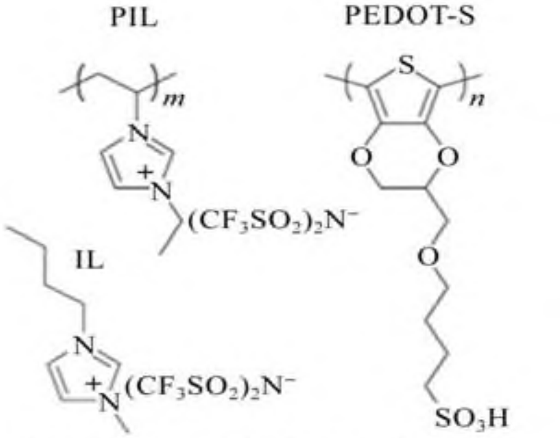
(a) Schematic diagram of fiber based integrated transistor system for advanced sensing of biological related ions



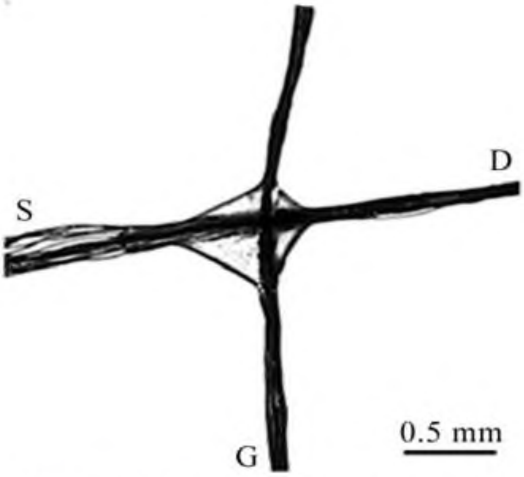
(b) Fiber based integrated transistor system stitched into chicken skin

Figure 14. Schematic of a fiber-based integrated transistor system.

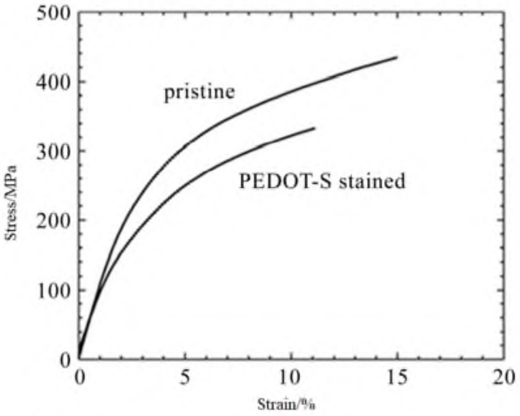
The thread-based electrochemical sensor (TBE) is interconnected, and a multi-channel diagnostic device based on a full thread was designed. Mlleret al.[46] reported a new method to demonstrate that a continuous film of conductive poly (3,4-ethylenedioxythiophene) can be coated on a textile monofilament with a diameter of 10–100 μm, and the monofilament can be coated with a continuous film of poly(3,4-ethylenedioxythiophene) for the preparation of microscale WECT on a single fiber. They also demonstrated inverters and multiplexers for digital logic. This paves the way for 3D polymer microelectronics to design large-scale circuits and integrate them directly into the 3D structure of woven fibers (**Figure 15**).



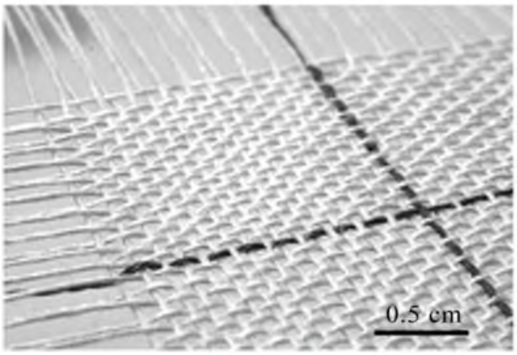
(a) Chemical structure of imidazole based ionic liquids



(b) Micrograph of FECT device of silk fiber with source (S), drain (D) and gate (G)



(c) Stress-strain curves of silk and silk fibers coated with PEDOT-S

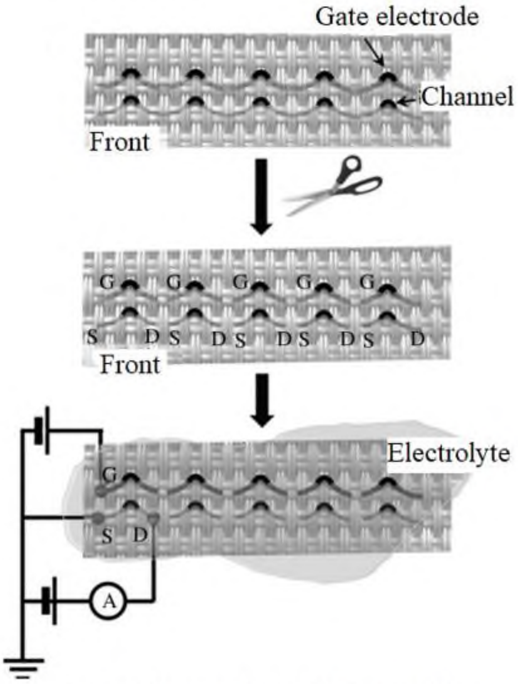


(d) Photo of silk woven fabric coated with PEDOT-S

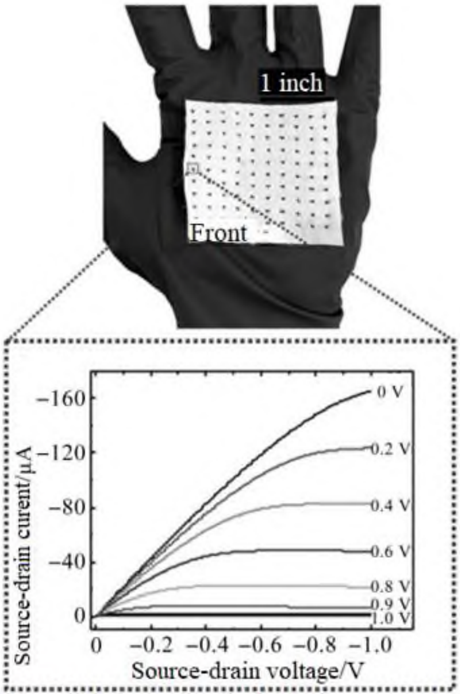
Figure 15. Stress-strain curves of silk conductive fibers and the actual weaving of the FECTs.

Zhang *et al.*[47] coated the conductive polymer PEDOT on nylon fiber monofilaments by gas-phase polymerization and demonstrated that fiber-based electrochemical transistors can be embroidered on fabrics for wearable and implantable bioelectronics devices.

Electrochemical transistors with fixed, micron-sized channel lengths were fabricated in parallel structures on hydrophobically treated silk fabrics with a high on/off ratio of 1,000, zero gate voltage and low applied drain bias (The transconductance value at 0.7 V) at 100 μS. Under these conditions, the device can then be incorporated into low-power integrated circuits. This demonstrates that large-area arrays of transistors can be rapidly generated by stitching monofilament fiber channels directly onto fabric substrates (**Figure 16**) and that a simple embroidery method can be used to fabricate spatially resolved electrodes for electrophysiology applications array.



(a) Process diagram of embroidering parallel electrochemical transistor array on silk backing



(b) Parallel electrochemical transistor array on a 2 × 2-inch fabric opticle picture of the array (top) and transistor output curves (bottom)

Figure 16. Construction of transistor arrays and performance testing on silk fabrics.

Tao et al.[48] used a new geometric pattern to fabricate OECTs by twisting PEDOT:PSS-coated monofilaments together, making it easier for transistors to be inserted into textile fabrics to enable mass production. Transistors can be up to several centimeters in length with an on/off ratio over 100 and a switching time that is close to 15 s. The inverter circuit and NOR gate control circuit were developed through a wire electrochemical transistor (WECT). An amplifier was also fabricated using a transistor to demonstrate the feasibility of an all-textile electronic circuit.

5. Conclusions

In short, fiber-based organic electrochemical transistors have been studied by a large number of researchers recently with accomplishments achieved by many research groups. The advantage of fiber-based organic electrochemical transistors is that they can combine high-sensitivity testing with wearable functions which is a very promising research topic. However, the research of fiber-based organic electrochemical transistors also faces some challenges. For example, most of the electrolytes used in FECTs are gel or water-based electrolytes and multiple difficulties are often encountered in practical tests, such as the uniformity of the sample preparation, the volatilization of the electrolyte, etc. In addition, the tests conducted using fiber-based electrochemical transistors are generally poorly repeatable and usually contain large data errors. Moreover, most of the fiber-based electrochemical transistors use p-type semiconductors and operate in the depletion mode and a few FECTs were found to operate in the accumulation mode. At the same time, in terms of applications based on FECTs, it can be seen that most of the research is mainly based on chemical or biological sensing and there is a lack of in-depth research on transistor mechanism as well as device structure-related exploration. The research direction is relatively narrow and it is not deep and detailed enough. Therefore, the future development direction of fiber-based electrochemical transistors may be the following: a) Study the operation mechanism of fiber-based transistors; b) solve the packaging problem of devices; c) study the relationship between structure and performance to improve the performance of flexible devices; d) research and explore the combination of n-type semiconductors and fibers as well as FECTs working in accumulation mode; e) explore more about the application of FECTs and conduct in-depth research.

Conflict of interest

The authors declare no conflict of interest.

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