Active Electronic Fibers and Woven Logic

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ABSTRACT

Giving textiles electronic functions while retaining the flexibility of weaves would open up new avenues for already mature textile technology. We review recent developments in this field, focusing on the combination of electronic polymers and textile fibers to make microstructured electronic systems on fiber platforms/weaves. The combinatorial possibilities inherent to crossing fibers in weaves may be exploited for large scale construction of many devices, with appropriate addressing and signaling, in processes derived from classical textile technology. The electronic elements realized on these substrates include electrochemical and field effect transistors, photovoltaic devices, and light emitting devices. We discuss the requirements for embedding electronic systems into textile due to the geometrical flexibility of textile fibers, conductivity of wires and geometries of active devices in the form of fiber crossings.

Keywords: Electronic Textiles, Fiber Transistors, Organic Electronics, Fiber Devices

1. Introduction

Electronics and textiles were integrated more than 80 years ago when resistive wires were stitched in textiles to produce heated fabrics for medical uses. Since then, numerous advances in material sciences and micro/nano technology have given rise to a number of new applications in the area of e-textiles. Here, the concept of mounting conventional devices onto textile substrates is prevailing, and already a number of commercial applications exist based in this approach (Service, 2003).

The approach of combining conventional off the shelf microelectronic components onto textiles will evolve as microelectronics continue to shrink in size and price (Buechley & Eisenberg, 2009), and smarter methods of mounting components in textile are invented. Some of the more complex e-textiles comprise, for example, the Lumalive™ textiles (http://www.lumalive.com/) based on hundreds of conventional light emitting diodes (LEDs) mounted onto textile substrates to form a display.

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However, this approach to e-textile manufacturing will be limited by the fact that the complexity and price of very large scale mounting of thousands or millions of components onto textile substrates scales with the number of components. The same limitation once existed for conventional electronics and was solved with the invention of integrated circuits.

Furthermore, the fact that today's silicon based microelectronic components are inherently planar and stiff, make them incompatible with the soft and bendable nature of fabrics.

Another still immature area of e-textiles comprises embedding fully functional advanced electronic components on the textile microfiber itself. Such fiber based components can completely open new possibilities to distribute components and design textile based integrated circuits using conventional textile manufacturing methods, and thereby eliminate the need for large scale mounting of components.

Such circuits can simultaneously retain the full flexibility of fabrics, if the fiber embedded components do not change the mechanical properties of textile fibers.

This review gives an introduction to active electronic textile fibers and fiber based components and systems.

The article presents advances in this field with a focus on organic electronic materials and especially those in the form of conjugated polymers (CPs). CPs represent a class of organic polymers with alternating single and double bonds which give rise to electronic functionality, and CPs have, since their discovery (Chiang et al., 1977) more than 30 years ago, undergone tremendous evolution and present many functions up to date, such as transistors/logic, solar cells, organic LEDs, high conduction, bio signaling, and more.

It is believed that organic materials and CPs are the most promising materials for e-textiles (Carpi & De Rossi, 2005), as they are cheap, lightweight, flexible and multifunctional.

In this review, first, a summary of electronically active organic electronic fibers is given, followed by a review of organic fiber embedded photovoltaic devices, and transistors. Finally, a short review of simple devices based on fiber transistors (referred to as "woven logic") is given.

2. Organic Electronic Textile Fibers

In order to achieve organic electronic components on textile fibers, it is necessary to start with the development of the building blocks, which are textile fibers functionalized with organic electronic materials to make the fibers electronically active.

These active fibers can then be used in manufacturing techniques, such as knitting and weaving, to realize components and functions (see Figure 1). Synthetic textile fibers are mainly manufactured using solution and melt spinning processes, followed by dyeing and other treatments.

As both dyes and the core material of synthetic textiles comprise organic polymers today, it is highly probable that organic electronic polymers that are considered the fourth generation of polymers (Heeger, 2001) will be as important to textiles as the introduction of the first generation of plastics was with the introduction of Nylon™ and other synthetic fibers.

In this section, therefore, a review of integration of CPs and textile fibers is given.

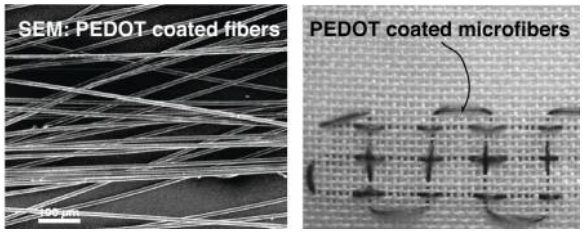

Fig. 1. (Left) SEM picture of polymerized PEDOT on polyester textile fibers.
(Right) Micrograph of PEDOT coated polyester microfiber bundles, sewn into conventional textile.

2.1 Homogeneous and Heterogeneous Microfibers

Homogeneous fibers are fibers that contain only one material. Non CP based conducting homogeneous microfibers are purely metallic fibers that have shortcomings in mechanical and other properties as compared to organic materials. CP based homogeneous fibers instead conduct through the CP, without any metal at all, where the CP chains act as both the mechanical and the electrical material.

The main process for producing these fibers to date is based on solution spinning. Here, the fibers are extruded through a highly concentrated solution (10-30 wt%) and coagulated in a bath. The main issues in solution spinning of the fibers is that high concentration of dissolved CPs is difficult due to their low solubility and rapid gelation (Skotheim T., 2007).

The most successful route for making high conducting homogeneous fibers is based on high molecular weight polyaniline (PANI).

Among the best results are reported by Pomfret et al., where one-step spinning of PANI fibers was reported with a conductivity of 600 Scm^{-1} and a high tensile strength of around 100 MPa (Pomfret et al., 2000), which make these fibers strong enough to be compatible with weaving.

Polypyrrole has also been melt-spun (Foroughi et

al., 2008), with conductivities of around 1 Scm^{-1} and low tensile strengths of 0.025 GPa.

No large-scale production is present yet. One reason could be that stiff CP chains cannot be melt-processed unless more complex blends or copolymers of CP are used to form heterogeneous microfibers.

Heterogeneous active materials can be regarded as blends of an insulating conventional microfiber polymer material and a conductive polymeric material or filler.

The most common organic filler to date is carbon black (CB), which is not a CP. If the amount of CB is above a percolation threshold, approximately above 4 wt%, conductivity is achieved throughout the fiber with values reaching up to 100 S/cm. The CB heterogeneous fibers, however, have lower mechanical properties due to the relatively high concentration of stiff CB microparticles which do not contribute or match the mechanical property of the pure melt spun polymer matrix.

CP materials can, however, be also used to make blends that can be melt-spun into heterogeneous fibers. However, the conductivity of these CP heterogeneous fibers is much lower to date. PANI has, for example, been blended with isotactic polypropylene, and nylon (Mirmohseni et al., 2006), and melt-spun. The conductivity of such fibers are, however, very low, about 10^{-8} Scm^{-1}.

In more recent developments of blended systems, di-block copolymers between CPs and plastics are used, and this will most probably be the best alternative for achieving high conductivity melt-spun microfibers from blends in the near future; recent examples of mechanically tough poly(3-hexylthiophene) (P3HT) di-block copolymer films by Muller et al. (Muller et al., 2007) represent a very good example.

There is still work to be done before CPs can entirely replace CBs in homogeneous microfibers. However, this route is very promising and can eventually be mass-produced.

If blended material have to work as purely conducting material, they compete with the already commercial CB fibers that have conductivities of 100 S/cm, and here, CP should surpass these materials in conductivity, strength and cost in order to be interesting.

However, blended CP materials could be melt spun into fibers to form semiconducting material, which is not possible with CBs, which can be used as channel material for field effect transistors or active materials in optoelectronic devices.

2.2 CP Coated Fibers

Another route to achieve CP active textile fibers is by coating the fiber with CP dyes. The thin coating does not affect the mechanical properties of the fiber at all, so the strength is retained. However, as the core is not conducting, the fiber will have higher resistance, and furthermore, become more sensitive to surface damage. Previously, a wide variety of processes have been used to coat fibers with metals, such as evaporation and electroless deposition.

One of the first CP coating of textile fibers was based on polypyrrole, as first reported by Kuhn et al., by using in situ polymerization methods (Kuhn et al., 1995), and surface resistances of 5 Ω/square were achieved.

In-situ polymerization of PANI (Kim et al. 2004) (20 Scm^{-1} for 150 nm film) and Poly(3,4-ethylenedioxythiophene (PEDOT) (Hong et al., 2005) (100 Scm^{-1} for 100 nm films) has been also reported, with film conductivities being the same as the conductivity of regular thin films of these polymers.

The process of in-situ polymerization can be done using fairly standard textile dyeing equipment, and therefore coated CP fibers are the only type of fibers that have been commercialized to date. Currently, Eeonyx™ is commercializing these materials (Eeonyx_Corporation).

Some different types of CP active fibers are summarized in Table 1. CP functionalized fibers is a very promising route for making woven e-textiles, where the combinations of different fibers and coatings can result in advanced woven electronic devices. This will be discussed in more detail.

Table 1. Summary of properties for different organic electronically functionalized fibers

Electronical-ly active material	Process route / Type	Tensile strength (MPa)	Scm^{-1}	Ωcm^{-1} 100µm Fiber
Reference: Nylon (ref)	Melt spin/ Homogeneous	>500	-	-
Reference: Metal (e.g. copper)	Homogeneous			<1
Carbon Black	Melt spin / Heterogeneous		100	100
PANI	Solution spin / Homogeneous	100	600	15
PANI	Melt spin / Heterogeneous	<500	10^{-6}	10^{9}
PANI	Polymerization / Coating	>500	20	10^{6}
PEDOT	Polymerization/ Coating	>500	1	$2\ 10^{6}$
PEDOT:PSS	Solution Coating / Coating	>500	100	$2\ 10^{2}$
Polypyrrole	Polymerization / Coating	>500		10^{5}

3. Organic Fiber Components

3.1 Introduction

The most powerful method for making highly integrated e-textiles is by embedding a large number of the components on the textile microfibers themselves. These textile microfibers must in turn be compatible with textile manufacturing to form fabrics wherein a large number of the components form an integrated device.

Two different approaches of achieving fiber embedded components are by:

1) placing the entire component on a single fiber, and

2) placing parts of the component on different fibers and achieving full component function by bringing parts of the fibers together at the junction of fibers, or around fibers.

In Case 1, the fiber has to have at least two connection points for components such as diodes or three connection points in the case of transistors or other multi terminal components.

These connection points must in turn, be designed so that they can be connected by other textile fibers in a textile manufacturing process.

In Case 2, the components are not formed until the textile manufacturing process has placed the different component parts in place.

As there are a large numbers of fiber junctions in a weave, the most natural way of embedding a large number of components would be to place these at junctions.

Just as in the construction of organic electronic components on planar substrates, each fiber embedded component should have a number of thin film layers (usually less than 100 nm thin) of organic materials and conducting electrodes, either as thin films or bulk substrate materials.

3.2 Optoelectronic Fiber Components Fiber OLEDs

Organic light emitting CP devices are constructed by sandwiching a thin film of electroluminescent organic polymer or molecule between an anode and cathode.

Upon application of voltage between the anode and cathode, holes and electrons are injected into the conduction, and the valence band of the active

polymer or molecule, respectively, and then recombined to generate light.

O'Connor et al. showed organic light emitting diode (OLED) fabrication on cylindrical shaped fibers (O'Connor et al., 2007; O'Connor et al., 2008) using a 480 um thick polyimide-coated silica fiber. The active light emitting material in this OLED is a small organic molecule (Forrest, 1997), and the anode and cathode materials are different metal compounds. All the materials have been grown using vacuum thermal evaporation. Figure 2 shows such a fiber OLED. The shortcomings of this technique are large number of layers, and active materials are added using evaporation, which is not really compatible with large scale fiber manufacturing. It is conceivable that conjugated light emitting polymers, metallic or conducting polymer anodes and cathodes can easier be produced. This has, for example, been described in patents by Duggal et al. (Duggal 2000).

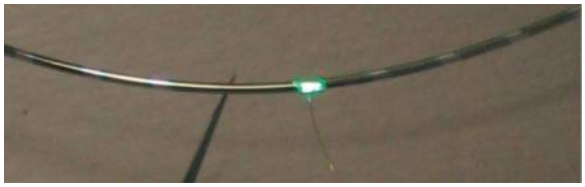

Fig. 2. Optical micrograph of a flexed fiber with a 1 mm long green emitting OLED (Copyright WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim).

3.3 Fiber Embedded Organic Photovoltaics

The most common organic solar cells up to date are based on bulk heterojunction blends that consist of a conducting polymer and a solubilized fullerene derivative, usually phenyl-C61-butyric acid methyl ester (PCBM), as first demonstrated by Sariciftci et al. (Sariciftci et al., 1992).

This blend is patterned from solution as a thin film between an anode and a cathode, where usually a conducting polymer acts as an intermediate hold collector between the active blend and the electrode.

Liu et al. (Liu et al., 2007a, b) demonstrated organic solar cells fabricated onto multimode optical fibers. These cells were fabricated by first creating an indium tin oxide (ITO) layer on the fibers and then applying the active organic material and the hole collecting material from solution by dip coating, followed by thermal evaporation of an aluminum electrode. Here, the entire device is realized on a single fiber, and the anode and cathode have to be contacted with secondary fibers. The thermal evaporation of metals again constitutes a problem, as it is not compatible with large-scale fiber manufacturing methods.

In later work by Lee et al. (Lee et al., 2009), the above problems were solved by using a clever method of placing the anode and cathode on two separate fibers. The fibers both constitute metallic conductors with highly smooth surfaces. The solar cell is created on one fiber by depositing three layers of material from the solution, comprising TiOx, solar cell composite material, and hole conductor PEDOT.

The second fiber is then wired around the first fiber so that physical and electrical contact between the two is accomplished (Figure 3).
These devices show almost similar performance as their planar counterparts.

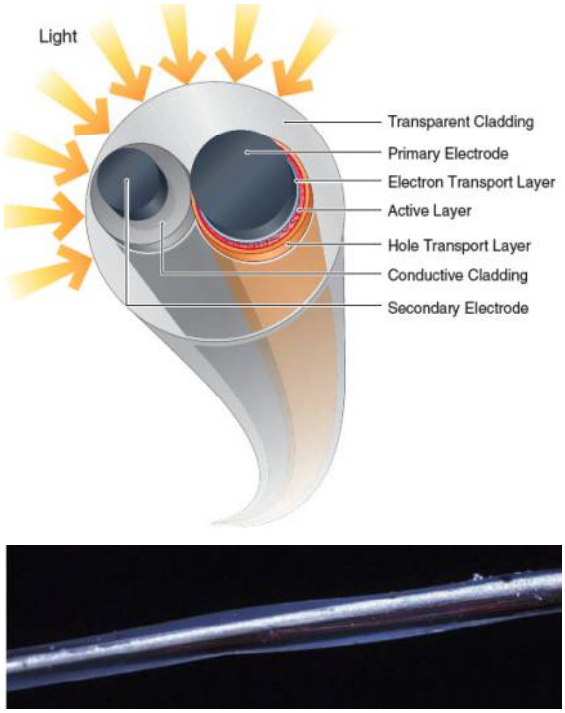

Fig. 3. (Top) Schematic picture of the double wire organic solar cell (Bottom) Optical micrograph of a polymer-clad double wire solar cell (Copyright by the American Association for the Advancement of Science).

3.4 Organic Fiber Transistors

The organic counterpart of the classical field-effect transistor, FET, is called organic FET (OFET). OFETs are devices with a thin film of an active CP layer that act as transistor channel material. The first OFET (Tsumura et al., 1986) was demonstrated in 1986 using polythiophene as the active CP layer. Like the classical FET, the OFET has basically a conducting source and drain connected to the semiconducting CP, and the gate is a conducting material placed above the channel and separated by a thin insulating film (creating a plate capacitor).

When a voltage is applied between the source and gate, majority carriers are generated at the insulator/semiconductor interface, which lead to the formation of a conducting channel between the source and drain.

Another class of organic transistors, which were actually reported before the OFET, is called electrochemical transistors or ECTs, as reported in 1985 by Thackeray et al. (Thackeray et al., 1985).

In ECTs, the gate comprises an electrolyte instead of an insulator, and the formation of conducting channels is instead a result of an electrochemical redox reaction in the CP layer controlled by the gate.

In recent years, the hybrid combinations of electrochemical and FETs have given rise to devices that are believed to work by the field-effect caused by the electric double layer that is formed at the interface of the electrolyte/semi conductor (Herlogsson et al., 2008; Panzer & Frisbie, 2005; Said et al., 2006).

3.5 Fiber OFET

Lee et al. (Lee & Subramanian, 2005) showed OFET transistors, directly formed on cylindrical fibers. Figure 4a shows the schematic structure of these fiber OFETs. Here, a metallic fiber is coated with a thin film of organic polyvinylpyrrolidone (PVP) insulating layer and subsequently, a second layer organic molecule pentacene is evaporated on top. Finally, source and drain contacts are evaporated through another fiber which acts as a shadow mask to form the source/drain (SD) contact points. The SD contacts are then contacted using other conducting fibers in a weave.

The authors showed that these transistors exhibit mobilities of 0.5 cm^2V^{-s} measured at 20V gate voltage, and stably operated under flexion stress similar to planar OFETs with on/off ratios that exceed 1000.

A similar cylindrical fiber pentacene OFET and polyimide gate dielectric have been demonstrated by Maccioni et al. (Maccioni et al., 2006a; Maccioni et al., 2006b).

A slightly different approach has been demonstrated by Bonfiglio (Bonfiglio et al., 2005) A planar free standing substrate was used, in this case, mylar film with 900 nm thickness. This film acts as the dielectric material in the transistor where a gate electrode is evaporated at the bottom of the film, and the channel is casted on top of the mylar film using a soluble semiconducting organic semiconductor, such as polythiophenes.

The idea is that such structures can be glued onto textile ribbons to form fiber building blocks that can be woven to form transistors, and devices. The SD contacts are created by crossing the ribbon with two parallel metal wires (Figure 5). The authors showed that these transistors operate at gate voltages of around 100 V, and furthermore, show very low current due to the poor contact of the SD contacts.

Locci et al. derived a theoretical model (Locci et al., 2007) that featured electrical characteristics of OFETs with cylindrical geometry. Here, not surprisingly, the model showed that for insulator and semiconductor thicknesses which are much smaller than the fiber cylinder radius, the model becomes very similar to its known planar analogous, as seen by the experimental results.

Some of the challenges with such microfiber OFETs are that most metal and plastic microfibers have a rough surface, which results in a rough semiconducting layer and a rough gate dielectric. The roughness can result in pin-holes, or uneven operation. Furthermore, the operating voltage of these devices scale with the insulator thickness, Since the thickness cannot be made too small, the operating gate voltage of the currently demonstrated transistors are in the range of 20 to >100 volts.

3.6 Fiber Electrolyte Gated Transistors

A number of the shortcomings of the fiber OFETs are overcome by using a solid electrolyte instead of an insulating gate dielectric to form organic electrochemical transistors (OECTs).

The biggest advantage of fiber OECTs is that the operation voltage does not depend on the thickness of the gate dielectric, but rather on the electrochemical potential of the system, which is around 1 volt. This means that the shape of the solid polymer electrolyte and the distances between the fibers can substantially vary without affecting the very low operation voltage, and thus the construction of these transistors is compatible with the rough precision of textile manufacturing. This enables easy construction of woven systems with many transistors, such as digital logic, see chapter 4.

We have demonstrated that OECTs can be created on cylindrical fiber geometries. The most simple form of such an ECT was demonstrated (Hamedi et al., 2007) by using fibers coated with the conducting polymer poly (3,4-ethylenedioxythiophene) / poly (styrenesulfonate) (PEDOT:PSS), through solution coating or chemical polymerization. A transistor was then formed at the junction of two such fibers. In this simple configuration, one of the fibers can act as the gate, and the other fiber acts instead, as the transistor channel (see Figure 4b). The transistor channel is defined by the area that is in contact with the electrolyte and the rest of the PEDOT:PSS material acts as the source and drain, and so no SD patterning is needed. This is because PEDOT:PSS is highly conducting in the pristine state, which also means that the transistor channel is open in its pristine state, and turned off as a gate voltage is applied (depletion mode).

We have also demonstrated fiber OECTs using organic semiconducting polymers (polythiophene) as channel material (Hamedi et al., 2009).

These transistors were made using a similar structure where the gate is a separate conducting fiber that connects to the channel via an electrolyte at the junctions. The difference is that the semiconducting layer needs to be connected, using conducting SD contacts. These contacts were made by first evaporating gold as SD contacts on a fiber through a textile fiber which acts as a shadow mask. The channel material was then patterned from the solution on the fiber.

The electrolyte used in these experiments comprised solid polymer ionic liquids (ILs). These classes of electrolyte material are very promising as they offer higher ionic density and mobility, and as CP electrochemical devices, are very stable in operation with ILs (Lu et al., 2002).

We demonstrated that enhancement mode fiber ECTs could be made with polythiophene channel and ILs. These OECTs operate at around 0.1-1 Hz. We believe that the real interesting mode of operation with these types of transistors, however, is based on electric double layer capacitance (EDLC) switching. EDLC OFETs can be more than 3 orders of magnitude faster. These types of devices remain to be demonstrated on fiber.

4. Woven Logic

Fiber embedded transistors and other components open new possibilities for distributing and designing systems, such as digital logic active matrices, and more through textile manufacturing methods. These digital logic based woven devices are referred to as "woven logic".

The On/Off ratios of the demonstrated fiber organic transistors all exceed 1000. These values are sufficient for making many types of digital devices.

Bonfiglio et al. proposed, for example, that OFETs on textile ribbons could be connected through piecewise conducting and non conducting threads to form simple logic devices, such as a ring oscillator (Bonfiglio et al., 2005) (Figure 5). No experimental demonstrations of fiber based OFET logic is, however, presented to date (to our knowledge).

The speed of digital circuits based on electrolyte gated transistors (Hamedi et al., 2007; Nilsson et al., 2005) are currently more than 1000 times lower than for OFETs, and the demonstrated PEDOT fiber OECTs and poly-thiophene OECTs operate in the 1 Hz regime. Due to the low and stable gate operation voltage, fiber OECTs simple woven logic devices can be designed with ease.

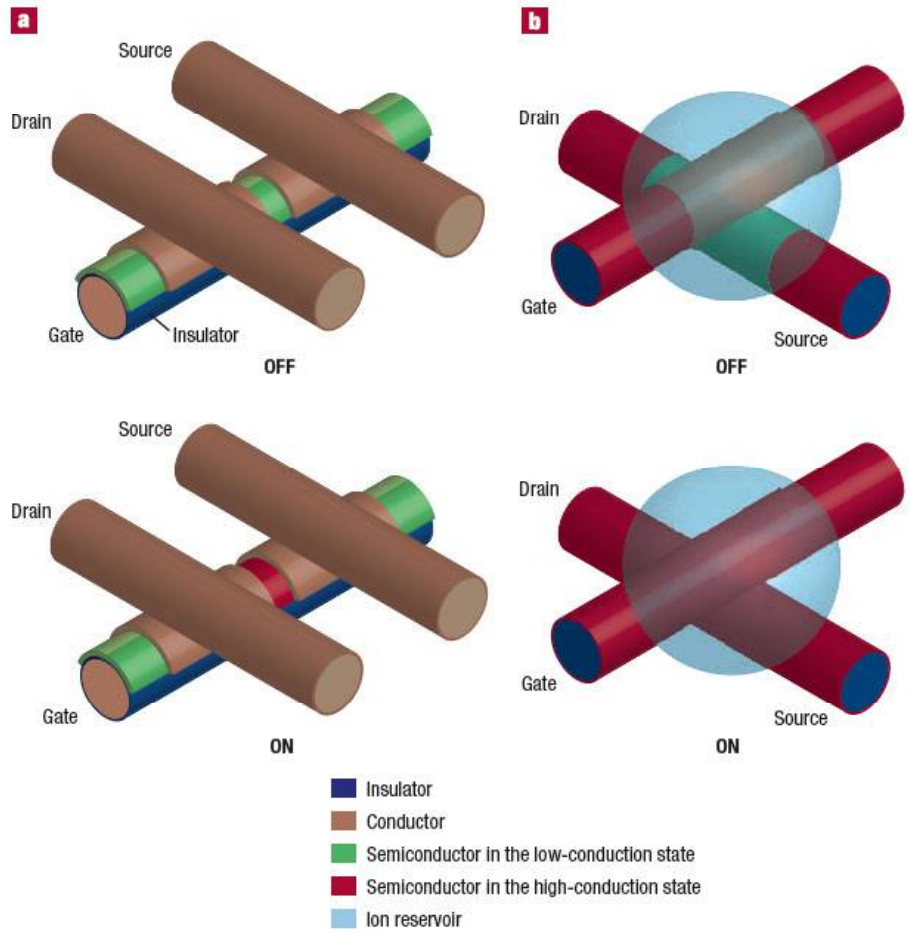

Fig. 4. Schematics of structure and operational principles of fiber OFET and OECTs.
(a) OFET switching from the OFF to the ON state under the action of the electric field from the gate electrode.
(b) Fiber ECT switching from the ON to the OFF state, when ions are depleted from the polymer semiconductor channel by electrodiffusion through the solid electrolyte under the action of the gate voltage (Copyright Nature Publishing Group).

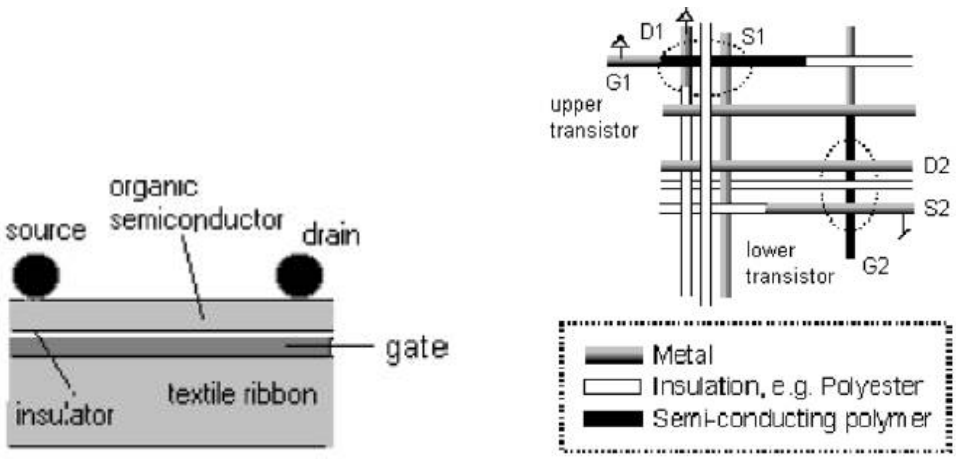

Fig 5. (Left) Schematics of ribbon based OFET. The gate is the metal layer deposited onto the insulating film and glued to the textile ribbon. Source and drain are metal wires that cross the ribbon
(Right) Example of a woven ring oscillator (Copyright IEEE).

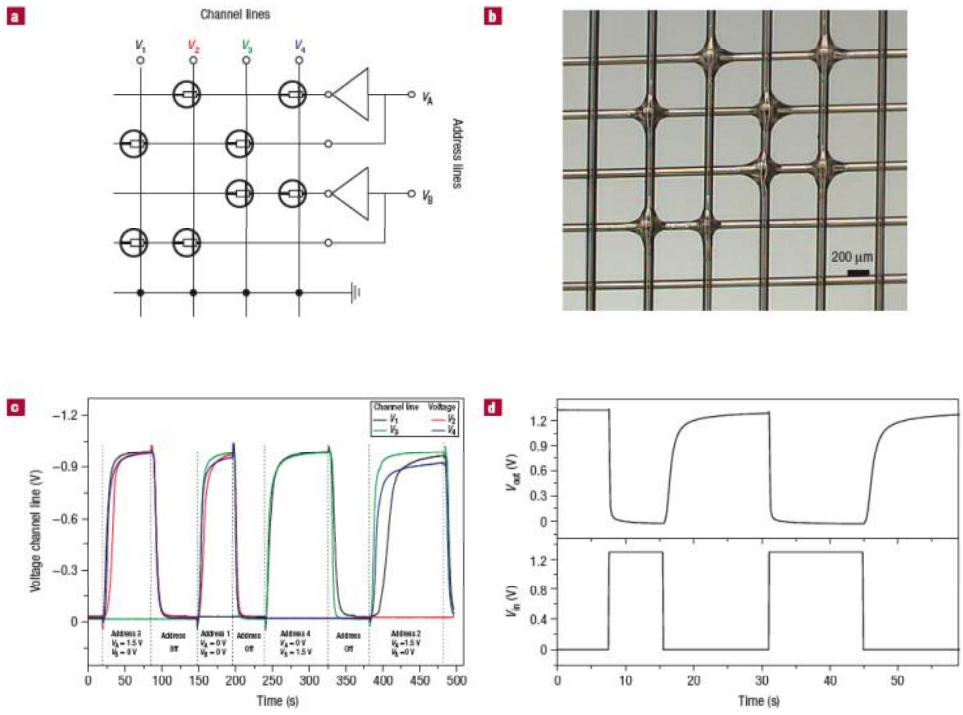

Fig. 6. Woven logic devices based on fiber ECTs
(a) Circuit diagram of a binary tree multiplexer with two address lines and four channel lines.
(b) Optical micrograph of a binary tree woven multiplexer
(c) Dynamic electrical characteristics of a woven multiplexer.
(d) Dynamic switch characteristics of a woven digital inverter (Copyright Nature Publishing Group).

As addressing of many wires and components is a challenge in textile, we have demonstrated a binary tree demultiplexer (demux) based on the PEDOT microfiber ECT. The binary tree demux needs 2log2N wires in order to address N wires.

Each addressing line of this demux comprises a single fiber which acts as a common gate for several transistors (Figure 6a, 6b).

We have also demonstrated inverters based on both the enhancement mode (Hamedi et al., 2009) and depletion mode fiber OECTs (Hamedi et al., 2007) (Figure 6d).

The speed of these inverters is around 1 Hz and indicates the maximum speed of logic systems that can be built using current EC mode of operation.

5. Outlook

The multi electronic functionality of organic electronic materials combined with mechanical flexibility, solution processability, and meltability, give rise to numerous options for embedding organic components devices on textiles.

This field is at its infancy and many challenges remain, such as:

i) large area manufacturing methods of constructing electronic fibers, with active cores and multilayers of active thin films. A great challenge here is to create films with minimal roughness, and minimal thickness deviation. Another challenge is to eliminate all conventional micro patterning steps,

ii) designing components that are inherently more suited for fiber/yarn geometries. Ideally, such components should be insensitive to the large flexion of textiles and large dimensional instabilities between fibers in textile manufacturing,

iii) designing tools and building devices where large-scale integration of components is achieved only through textile manufacturing

methods, rather than mounting, and

iv) making faster and more stable fiber transistors. Both the route of fiber OFETs and OECTs should eventually enable KHz – MHz speeds (Herlogsson et al., 2008), which are higher than demonstrated speeds for inorganic fiber transistors (Bonderover & Wagner, 2004).

E-textile transistors are of importance not only for making highly integrated logic, but also for sending, collecting and distributing data from sensors and components over large textile areas.

For example, piezo- (Huang et al., 2008) and thermo-resistive fibers are now available in textile compatible form (Skotheim T., 2007).

6. Conclusion

Organic electronics present huge opportunities for e-textiles (Carpi & De Rossi, 2005).

Eventually, the integration of fully organic electronic based e-textiles should be possible where all functions, including sensing, actuating (Mazzoldi et al., 1998; Spinks et al., 2006), and digital/analog electronic and power functions (Bhattacharya et al., 2009; McDermott and Brantner, 2002), are integrated into textile.

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