Organic Field Effect Transistors for Textile Applications

Annalisa Bonfiglio, Danilo De Rossi, Tünde Kirstein, Ivo R. Locher, Fulvia Mameli, Rita Paradiso, and Giovanni Vozzi

***Abstract*—In this paper, several issues concerning the development of textiles endowed with electronic functions will be discussed. In particular, issues concerning materials, structures, electronic models, and the mechanical constraints due to textile technologies will be detailed. The idea starts from an already developed organic field-effect transistor that is realized on a flexible film that can be applied, after the assembly, on whatever kind of substrate, in particular, on textiles. This could pave the way to a variety of applications aimed to conjugate the favorable mechanical properties of textiles with the electronic functions of transistors. Furthermore, a possible perspective for the developments of organic sensors based on this structure are described.**

***Index Terms*—E-textiles, organic semiconductors, organic thin film transistors.**

I. INTRODUCTION

IN THE LAST few years, "wearable electronics" has become one of the hottest themes in electronics and there are indications that this topic signals the first step of the next electronic revolution. But what does "wearable" mean? And which are the future directions that this field will take?

There are several ways to interpret this issue: "wearable" can refer to devices and systems that, due to their small size, can be embedded *on* a textile substrate; or "wearable" can be a device or a system that *is* a textile itself. For sure, this last concept is much more challenging and can only be developed on a longer timescale than the first, but it paves the way for a real revolution both in the technical and socioeconomic fields. As a consequence, E-textiles will have the revolutionary ability to sense, act, store, emit, and move while leveraging an existing low-cost textile manufacturing infrastructure. At the same time, systems based on flexible and smart technologies conformable to the human body will help to improve the autonomy and the quality of life of people. The use of "intelligent" materials, as such textiles, will allow the design and production of a new generation of garments with distributed sensors and electronic functions. The integration of electronic and electromechanical systems onto substrates which are not only flexible, but ideally conformable to the human body represents a breakthrough in various areas of application and opens new ways in man–machine interface technology.

The issues concerning the development of a textile endowed with electronic functions are indeed very complicate and need a deepening under several aspects, namely, materials to employ, technologies, structures, electronic models, and also compatibility of the proposed electronic structures with textile technologies. Clearly, the first functions to implement are switching and amplification, in one word, the transistor function. This is of particular importance, both because it is the basic block of more complicated electronic circuits and because many other functions (like field-effect based sensors) can be derived from this one.

Organic devices, in particular light-emitting diodes (LEDs) and field effect transistors have been the focus of an intense research work carried on during the last 15 years [1] that has given only recently the first examples of commercial products.[1] Organic semiconductors are very interesting materials, as they, on one hand, show good semiconductor properties, and, on the other hand, have the mechanical properties of polymers. Due to these reasons, the perspective of flexible electronics seems now very close, as also demonstrated by a recently proposed idea of "transistor in a fiber" [2]. Recently [3], a special structure has been proposed that fully exploits the mechanical properties of organic semiconductors. It is based on a completely flexible and transparent polyester film that, on one hand, is the insulator layer of the field-effect transitor (FET) structure, and, on the other hand, is the mechanical support of the whole structure.

Basing on this initial idea, we have developed a fiber realized by glueing this structure on a textile ribbon, in order to obtain a flexible yarn that could be employed in a textile process.

In this paper, we address several points which altogether will contribute to the final goal: materials and technologies which are best suitable to obtain such yarns; the electronic model of the yarn, seen as a "textile transistor;" the electronic model of the fabric, to evaluate its possible distributed digital or analog functions depending on the topology of the yarns; and the mechanical constraints that must be considered in order to obtain a textile component, suitable to be processed by means of textile technologies. In this work, we will address each issue, and show the main results.

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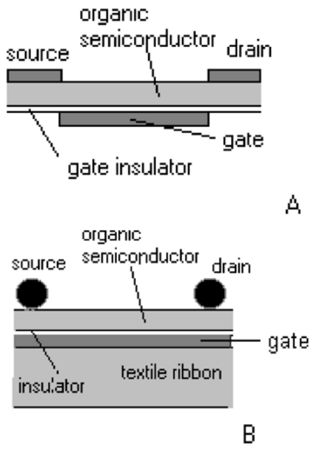

Fig. 1. (a) General scheme of a top contact thin film transistor. (b) Structure adopted for the device on a textile ribbon. The gate is the metal layer deposited on the insulating film and glued to the textile ribbon. Source and drain are metal (gold) wires that cross the ribbon in fixed positions.

II. PROBLEM DESCRIPTION AND METHODS

A textile structure has very strict mechanical constraints, therefore, the choice of materials is crucial for obtaining a suitable device. Traditional inorganic crystalline materials, as silicon, do not have the requested features. Organic semiconductors (polymers and oligomers), having the electrical properties of semiconductors and the mechanical properties of plastics, are good candidates for realizing flexible transistors, suitable to be transferred on unconventional substrates as textiles.

Transistors based on organic semiconductor are a special type of field effect transistors, named thin-film transistors (TFTs): source and drain are simply ohmic contacts formed by a metal (that could be substituted by a conductive polymer) on the organic semiconductor while the channel between source and drain is formed through a charge accumulation induced by the gate.

As stated in the introduction, a completely flexible structure assembled starting from a transparent insulating film has been realized that seems to be the ideal candidate for realizing a textile transistor [3]. In fact, the whole procedure for obtaining such structure [shown in Fig. 1(a)] is realized without inserting a substrate whose mechanical properties limit the flexibility of the whole structure. In this way, the substrate can be added to the structure only after its assembly, therefore allowing to employ unconventional substrates as paper, three-dimensional surfaces, and textiles.

A. Structure of Textile Transistors

For realizing the electronic ribbon, the insulating film was metal covered (by a thermal evaporation of gold) on one side, and a thin film (some tens of nanometers) of organic semiconductor was deposited on the opposite side. The film was then glued to the textile ribbon as shown in Fig. 1(b). To obtain the complete transistor structure, source and drain contacts were created by simply crossing the ribbon with two parallel gold wires kept at a fixed distance of about 100 μm (a distance compatible with most textile processes). In this way, we have simulated the electrical contacts existing between yarns of a mesh of a real textile. Of course, this arrangement is far from being optimal under the point of view of the metal–semiconductor contacts. In the section dedicated to results we will comment about the observed behavior and compare this case with the behavior of devices with thermally evaporated contacts.

B. Materials for Textile Transistors

As shown, a TFT independently of its geometry is made by three main layers: the insulator, the gate metal, and the organic semiconductor.

The insulating layer must have a proper dielectric constant (for comparison, the value for silicon oxide is 3.9) and should be as thin as possible (in order to ensure a suitable value of the dielectric capacitance per unit area). In addition, it must have mechanical properties similar to fabric, in order to allow the possibility of bending and stretching as it is necessary during a weaving process.

For these reasons we selected Mylar (commercial trademark for poly-ethylene therephtalate film, produced by Du Pont) as a material that perfectly fulfills the previous requirements. It has a dielectric constant of 3.0, a minimum thickness of 900 nm, and it is completely flexible, more than a fabric ribbon.

The gate metal layer must be a conductive layer, typically a metal or an organic conductor. There is no particular requirement for this layer, and then gold or aluminum layers can be thermally evaporated or alternatively, PEDOT:PSS [Poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate)] layers can be spin-coated on Mylar.

As semiconductor layer, many organic semiconductor materials with high charge mobility can be used to realize the device. Unfortunately, they are not always easily processable materials and sometimes need complex and expensive deposition techniques [4], [5]. Usually, conductive polymers are also poorly processable materials, but the synthesis of new monomers yields soluble materials in common organic solvents. Synthesis of regioregular poly-3-alkyl-thiophenes using the method developed by Collough *et al.* overcomes this problem enhancing conjugation between thiophene rings; a better ordering in the solid state occurs [6], [7].

In our experiments, we used three different semiconducting polymers, namely regioregular poly-3-exil-thiophene (supplied by Sigma-Aldrich, Milano), regioregular 3.3″-didocel-2,2′:5,′2″-terthiophene [8] (supplied by Prof. M. C. Gallazzi, Politecnico di Milano, Milan, Italy) and Pentacene (Sigma Aldrich, Milano, Milal, Italy).

The first two polymers were deposited by casting from concentrated solutions of polymers in pure chloroform and in chlorobenzene, at a concentration in the range 0.8%–0.5% weight, the last instead was deposited by thermal evaporation.

C. Electronic Model of Textile Transistors

As can be seen in Fig. 1, in the TFT structure the gate is electrically insulated from the organic semiconductor (as in all FET structures) and the source and drain contacts are simply ohmic (differently than most FET structures). Differently than in silicon MOSFETs, in such device, an inversion channel does not form. As source and drain are ohmic contacts, the channel is confined to the surface of the semiconductor where majority carriers (generally holes) accumulate due to the field effect induced by the gate. Therefore, the TFT is an accumulation device. This also means that a small current can flow even when an accumulation layer is not formed (OFF state) but this current is very low because of the intrinsic low conductivity of the organic materials. The equations that describe the behavior of an organic TFT can be directly derived from those of inorganic FETs providing to consider that the off TFT (OTFT) is an accumulation device. For a TFT, the relations that link the current I_d to the applied voltages are

$$I_d = (Z/L)^* \mu^* C_i^* [(V_g - V_t)^* V_d - V_d^2/2]$$

in the linear region and

$$I_{\text{dsat}} = (Z/2L)^* \mu^* C_i^* (V_g - V_t)^2$$

in the saturation region. Z and L are, respectively, width and length of the channel, μ is the carrier mobility, C_i the insulating layer capacitance (per area unit), V_g and V_t are, respectively, the gate and the threshold voltages, and V_d is the drain voltage. The threshold voltage is the value of gate voltage necessary to increase the conductivity of the surface channel with respect to the rest of the semiconductor (for low values of the drain voltage).

D. *Yarn Topology of the Electronic Fabric Model*

Building reliable transistors with well-defined electrical properties using conductive and semiconductive yarns implies small and stable geometrical structures of the fabric and within the fabric. Therefore, a woven structure emerges as a possible manufacturing technology since the smallest mesh lies in the range of 100 μm by weaving single fiber and since it is more rigid compared to a knitted structure.

For simplicity, a polymer transistor can be regarded as a P-MOS FET at a first stage. Therefore, when inserted in a fabric, this can be seen as a elementary network where "drain" (D) and "source" (S) are purely metallic wires that cross the yarn-like transistor indicated with "gate" (G) (Fig. 2). Since reliable connections of electrical contacts among threads seem difficult to achieve due to the drapability of textiles and mechanical stresses, redundancy by parallel connection of transistors improves functionality.

A structure as that shown in Fig. 2 cannot provide diverse electrical functions since the transistors are arranged in columns. Connecting transistors between different columns would lead to shorts of the drains and sources because they are metallic. To our knowledge, applications of such an array mainly lie in the sensing field where external interferences partially change the electrical characteristics of the textile since polymer transistor are rather sensitive to geometrical, temperature or even light variations.

In order to establish a self-contained device within the textile, piecewise conductivity and nonconductivity of threads are necessary avoiding shorts, multiple excitations of transistor gates and unwanted parallel connection of transistors. Fig. 3 shows a section of such a circuit in the case of a ring oscillator structure. Since distances between transistors can be large, manufacturing methods for section-wise plating need not to be precise.

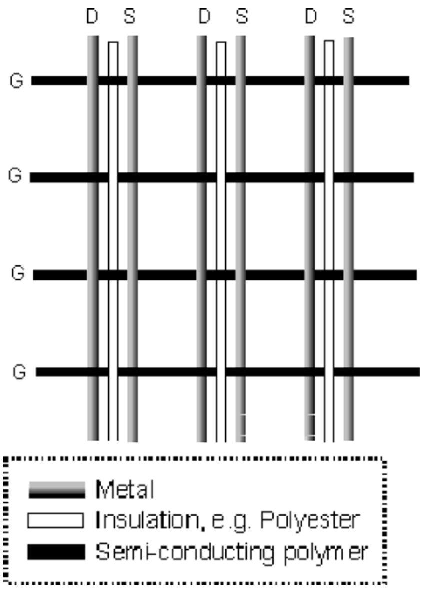

Fig. 2. Transistor array structure. GS represents textile ribbons with the gate contact and the organic semiconductor.

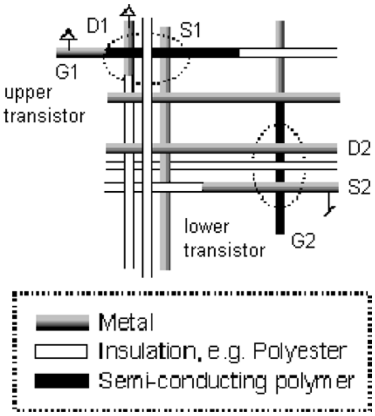

Fig. 3. Example of a ring oscillator structure. This structure implies the implementation of different conductivity properties (insulating, metal, semiconductor) on the same yarn.

E. *Mechanical Constraints for Textile Structures*

Textile industries have used metal yarns for years. Usually a single metal fiber is avoided, because of problems due to flexibility, resistance to stretching and friction, lower than other natural or artificial yarns, preventing its use with standard weaving machines. Possible solutions are: 1) production of a yarn with a core made of common textile yarn and with spiralled metal filament; 2) use of pure metal yarns made of several metal fibers, prepared as long filaments or from staples; 3) a yarn made by twisting metal fibers around a filament or a previous spun yarn, thus concealing the core.

With these techniques, metal yarns can be used with commercial weaving machines and have technical properties comparable with traditional yarns. It must be underlined that a new trend is observable in textile domain, as indicated by the production of several new circular knitting machineries able to process

TABLE I
MECHANICAL SPECIFICATION OF RIBBON

Composition: *Cotton 100% CO*					
Structure: *Tubular, subject to squashing*					
Ave. Nm	***Variance coeff.***	***Breaking force***	***Variance coeff.***	***Elongation at break***	***Toughness***
2.21	*4.0%*	*5.1 gr*	*>7.2%*	*>7.0%*	*11.0 gr/tex*
		UNI EN ISO 2062		*UNI EN ISO 2062*	

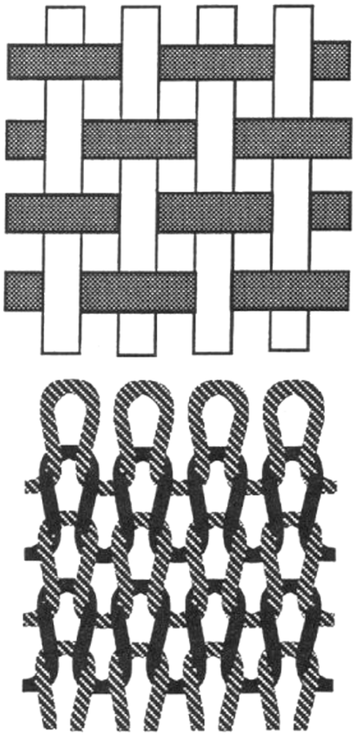

Fig. 4. Scheme of woven fabric on top and knitted fabric on bottom. Knitting is another possible textile assembly technique that could give rise to furhter topological configurations of yarns.

pure metallic and technical yarns. A valuable alternative is to employ a textile ribbon that can be knitted or woven like a yarn. As an example, a ribbon can be used as substrate of a transistor made on an insulating film with a width (average) of 3.5 mm: technical details are described in Table I.

Ribbons can be processed by means of two fabric weaving processes in order to realize woven fabric and knitted fabric. Woven fabrics are generally composed with two sets of yarns, made by interlacing them at right angles. The knitted fabric is made by interlocking series of loops of one or more yarns, a scheme of both the fabric is shown in Fig. 4.

The fundamental difference in topology between these two processes is that for the woven fabric the yarns are organized in a network scheme, while for the knitted fabric there is only a continuous yarn that is running up and down on weft direction.

Of course, such differences in topology reflect on the global properties of the fabric in terms of elastic properties but, in case of a ribbon with electronic properties, also on the global "transfer function" of the fabric.

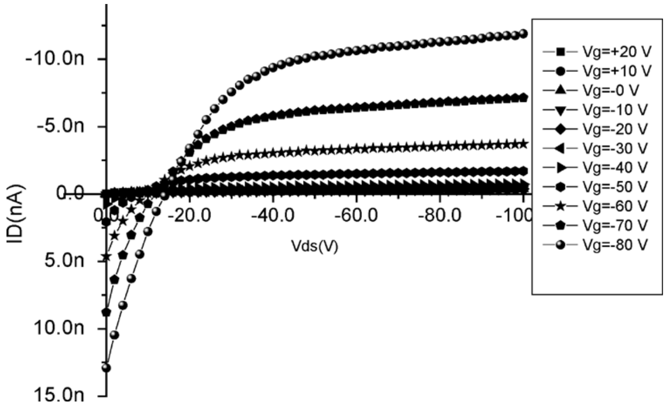

Fig. 5. I_d–V_d curve of the ribbon structure obtained with an organic layed made with pentacene.

III. RESULTS

We have characterized the "electronic ribbon" as a single transistor. In Fig. 5, the I_d–V_d (drain current versus drain voltage) curve of the device is shown. A clear field effect can be observed even if the recorded current values are very low. Several reason can be invoked to justify this behavior. First, as shown in (1)-(2), the current intensity depends on the aspect ratio Z/L. In the case of the ribbon structure, this ratio was very low (with L in the order of 100 μm, and Z of about 4 mm, the nominal ratio did not exceed 40. In most devices reported in literature, this ratio generally varies from some hundreds to thousands). Furthermore, the source and drain contacts were made by simply crossing the ribbon with two parallel gold wires, as shown in Fig. 1. Therefore, the contact between metal and the organic semiconductor was not so intimate as it is normally obtained with evaporated contacts, so the real value of the aspect ratio was probably even smaller. But the geometry is not the only reason of the low value of currents. It must be said that corresponding structures obtained with the same organic semiconductor, same geometry of the contacts, but thermally evaporated source and drain contacts, currently gives currents of the order of several tens of microamps. Therefore, it seems that a key factor for obtaining a good transistor behavior is the quality of metal–semiconductor contacts. This affects not only the real geometry of contacts, but also the height of the energy barrier for hole injection that exists at the junction. A high injection barrier reflects in a resistive component in series with the channel R_S that decreases the effective voltage across the channel, by an amount of $R_S I_D$. This contribution is present also in devices with thermally evaporated contacts, and this issue has been largely discussed, even if not definitely clarified, in many papers [9]–[15]. Usual values of R_S can also exceed values of mega-ohms. In this case, it is likely that the imperfect contact between metal and organic semiconductor, gives rise to R_S values some orders of magnitude higher and this can give a reasonable explanation of the observed low values of current.

So, it seems that the optimization of the metal-semiconductor interface is the crucial problem to solve in order to obtain reliable results with this structure. To improve the contacts, without renouncing to the idea of a yarn mesh, it is necessary to ensure an intimate contact among the yarns and also to impede yarns shifts during the device working; this could be obtained by applying a constant and homogeneous pressure between the metal wires that constitute the source and drain contacts and the textile ribbon. A possible idea for doing this is the lamination of the mesh between two external layers, as it is normally done in sail technology. This could allow to fix the reciprocal positions of yarns in the mesh, giving rise to acceptable textile characteristics without increasing the rigidity of the obtained fabric. Therefore, again in the frame of textile technology, it is possible to envisage a possible technical solution of the problem that does not compromise too much the textile quality of the final object.

IV. CONCLUSION

A transistor with a form factor suitable to be employed in a textile process has been studied. This study has demonstrated that several complicated points must be taken into account when designing and realizing a textile system with an electronic function. Not only questions concerning the electronic properties of materials are important as in conventional circuits but also issues concerning the mechanical properties and the topology of the yarns in the fabric; furthermore, these issues are often cross-correlated.

In addition, once obtained the single yarn, other questions arise concerning the possibility of producing textile circuits. As a matter of fact, the final "transfer function" of a textile depends not only on the properties of the component yarns but also on their topology. Clearly, electrical contacts between yarns as well as resistive and capacitive effects associated with yarns depend much on the yarn topology. In this sense, textile technology offers many different possibilities of "circuit architectures." Weaving and knitting, but also embroidering and multilayer lamination, can be in fact employed, alone or in combination, to obtain an electronic textile.

Concerning the basic yarn, the employment of such devices for the realization of "smart" fabrics seems to be affordable for a class of recently developed devices based on organic semiconductors. The electronic properties of such materials, together with their mechanical features (many of them are polymers and can be organized in form of flexible thin films) make them the ideal candidates for the final goal of obtaining an electronic yarn. The study has demonstrated the feasibility of such idea, but, at the same time, has pointed out also the main problems that must be solved in order to obtain a reliable and reproducible transistor behavior. Charge mobility (at present still much lower than in inorganic materials) represents the main limit in order to reach practical applications, but, at the same time, the continuous advance in chemical synthesis obtained in the last years make realistic the objective of reaching, in a reasonable timescale, at least the performance of amorphous silicon.

Furthermore, it must be recalled that for a future application perspective, several interesting properties of organic semiconductors could be further exploited. One possibility consists in their chemical properties [16]: some of them are strongly sensitive to some chemical species as oxygen and other atmosphere gaseous species and what is normally considered as detrimental for the behavior of transistor devices can be considered in a favorable way when exploring a possible application as sensor devices. Furthermore, the versatility of chemical synthesis could allow to develop specific functionalization of organic semiconductors for specific chemical detection.

Also the possibility of pressure and/or elongation sensing can be considered as the current in the transistor channel is sensitive to the pressure applied to the structure. This property could allow interesting applications of textile devices for biomedical signal detection.

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