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Towards the textile transistor: Assembly and characterization of an organic field effect transistor with a cylindrical geometry

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Cylindrical organic field effect transistors have been obtained starting from a metallic fiber used in textile processes. The metal core of the yarn, covered with a thin polyimide layer, is the gate of the structure. A top-contact device can be obtained by depositing a layer of organic semiconductor followed by the deposition of source and drain top contacts, made by metals or conductive polymers, deposited by evaporation or soft lithography. Thanks to the flexibility of the structure and the low cost of technologies, this device is a meaningful step towards innovative applications of textile electronics. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2357030]

Organic materials, based on conjugated organic small molecules and polymers, offer the opportunity to produce devices on large-area, low-cost, plastic planar substrates.[1] These materials are becoming of great appeal also in the field of e-textiles,[2] as they show an interesting combination of electronic and mechanical properties that can be favorably exploited in smart textiles. Nowadays, only a few steps towards new architectural possibilities have been made: one an example of nonplanar devices[3] and one of textile based devices,[4] both giving a chance to the realization of circuit topologies that can be implemented with textile techniques. A number of applications, as for instance smart textile systems for biomedical monitoring functions[2] or new man-machine interfaces,[5] could greatly benefit from this possibility.

In this letter, we present an example of organic field effect transistor (OFET) characterized by textile process fully compatible size and geometry. The device has been obtained starting from a cylindrical metal fiber with a diameter of 45 μm, covered by a uniform layer of polyimide of about 1 μm (Elektrisola). As a result, this yarn is very flexible and can be employed, twisted to a cotton fiber, in textile processes.

We have obtained a cylindrical top-contact OFET [general structure shown in Fig. 1(a)] by evaporating pentacene (Sigma Aldrich) on the structure. This was done without rotating the wire with respect to the crucible; therefore a nonuniform coverage of the wire has been obtained (basically, about half of the lateral surface is covered; the nominal thickness on a flat surface beside the wire is 50 nm). This could be avoided by rotating the wire during the semiconductor evaporation. After this step, source and drain contacts have been realized in two different ways: either by evaporating gold electrodes directly on pentacene by interposing a thin crossing wire as a shadow mask during the evaporation procedure [Fig. 1(b) an optical microscope image of the channel; in this way, a channel length with almost the same size as the wire diameter is obtained, but a good control on dimensions is not possible] or by employing a soft lithographic process for transferring a thin layer of the conductive polymer poly(ethylene-dioxythiophene)/polyStyrene sulfonate (PEDOT:PSS) on the pentacene surface. This method has several advantages: it allows to exploit the favorable mechanical properties of conductive polymers as contacts; it allows to have an optimal control of geometries because the relieves of the stamp used for soft lithography are obtained with a high resolution technique as already demonstrated for planar devices[6] (from photolithography to a number of high resolution techniques[7]); it allows (by rotating the yarn on the stamp surface) to deposit contacts on the whole surface of the yarn (while with evaporation only the side exposed toward the crucible is uniformly covered); it allows to easily make a whole set of contacts along the wire length at the same time.

A complete electrical characterization has been made, in air, by means of a HP 4155 semiconductor parameter ana-

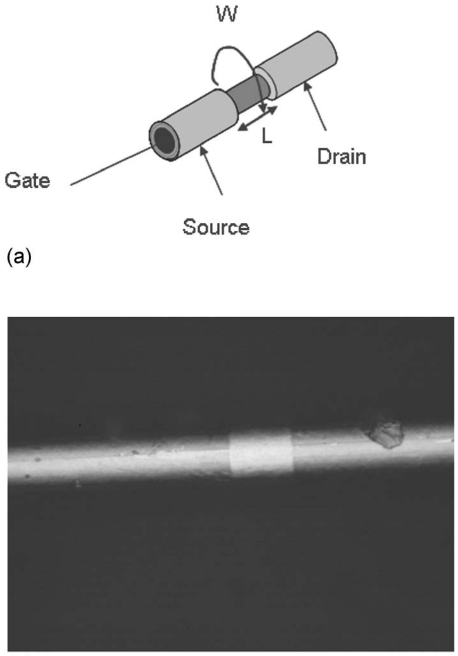

FIG. 1. (a) Structure of the cylindrical OFET. (b) Optical microscope image of the channel area.

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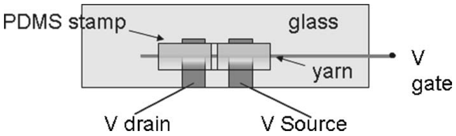

FIG. 2. Measurement setup for the device made by soft lithographic stamping PEDOT:PSS contacts.

lyzer (for drain current versus drain voltage, I_D-V_D, and drain current versus gate voltage, I_D-V_G, curves) and by means of Agilent 4284A precision *LCR* meter, 20 Hz–1 MHz (for capacitance versus voltage, *C*-*V*, curves), provided with gold tips. In devices with gold contacts, the gold tips have been simply pressed against the source and drain of the transistor wire. In devices with PEDOT:PSS contacts (Fig. 2), the measurements have been made by sandwiching the wire between a cover slide where two gold electrodes had been previously deposited and a poly(dimethyl siloxane) stamp reproducing source and drain covered with a thin layer of PEDOT:PSS (Baytron P CPP 105D).

Atomic force microscopy (AFM) investigations were performed by means of a scanning probe microscopy Solver Pro by NT-MDT in semicontact mode.

In Fig. 3 the I_D-V_D curves of a device with gold source and drain 3(a) and PEDOT:PSS contacts 3(b) are shown. It is worth to note that establishing a reliable electrical contact with source and drain was particularly difficult due to the very low dimensions and also to the nonplanar surface of the wire. Interestingly enough, despite the above mentioned problems and the very low value of the W/L ratio (estimated as 1.2), the on current and, most of all, the $I_{\mathrm{on}}/I_{\mathrm{off}}$ ratio are reasonably high (around 10^4), fully comparable with those of planar devices. In order to derive a reliable estimation of the electronic parameters, we fitted the *I*-*V* curves with an electronic model that takes account of the cylindrical geometry of the devices.[8] In addition, we estimated the series resistance effect according to the concept proposed by Horowitz[9] but fitting the whole *I*-*V* curves in order to have a reliable value of all free parameters of the model (threshold voltage, mobility, series resistance). We found a difference in devices made with gold contacts with respect to those obtained by soft lithography assembling of PEDOT:PSS contacts. In Table I, the main parameters are shown for a couple of representative devices. As can be observed, the device with gold contacts shows a lower value of mobility, together with a higher value of series resistance. In addition, also the threshold voltage is more negative. Therefore, it seems that, despite the better value of the $I_{\mathrm{on}}/I_{\mathrm{off}}$ ratio [estimated on curves with the same V_G-V_T value], the trend for the main electronic parameters is more favorable in devices with PEDOT:PSS contacts. Obviously this issue is of great importance, especially in view of future applications in "textile circuits." It is worth noting that the derived mobility values in cylindrical devices are comparable if not better than those recorded for polycrystalline pentacene on planar devices. In order to better understand the reason for this behavior, we performed AFM investigations on the channel area of the wire (Fig. 4). The morphology of the pentacene layer is pretty regular, with the typical granular aspect that is observed also on a planar insulating layer. In comparison with pentacene depositions made with the same evaporation parameters (rate, distance between crucible and sample) on polyethylene terephthalate thin film substrates that we typically use as insulating films of planar OFETs,[6] the mean dimension of the domains is significantly higher. Typical grain dimensions around 150 nm have been found for pentacene grown on polyethylene terephthalate films, while, in this case, we obtained grain dimensions in the range of 200–250 nm. Considering a model where the mobility is limited by traps localized at grain boundaries, this should coherently result in a higher

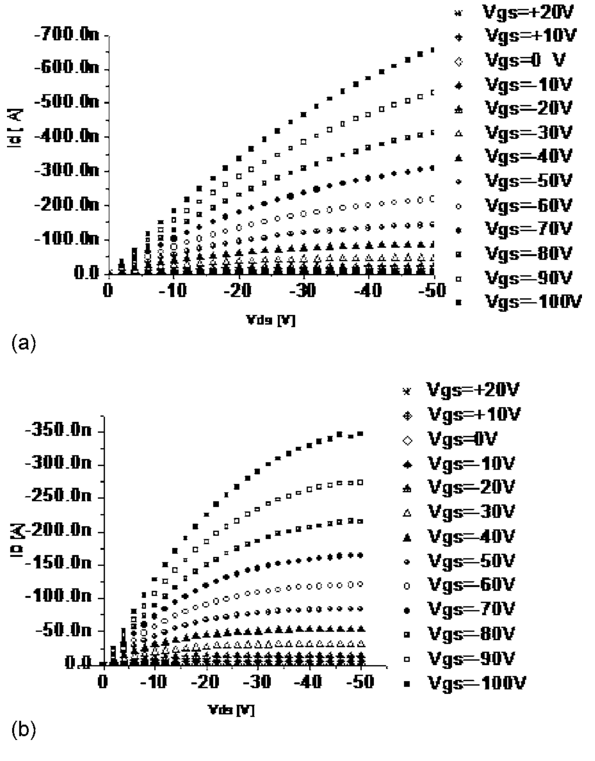

FIG. 3. I_d-V_d curves of cylindrical OFET structures having source and drain contacts made by gold (a) and by PEDOT:PSS contacts (b).

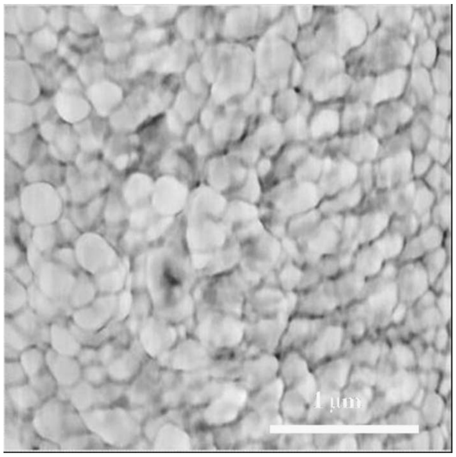

FIG. 4. AFM phase image of pentacene grown in the channel area of the device.

TABLE I. Tabulation of the most meaningful paramters for gold electrodes and PEDOT:PSS electrodes devices.

Device	$I_{\mathrm{on}}/I_{\mathrm{off}}$ $(\times 10^3)$	V_t (V)	μ (cm^2/V s)	R_s (MΩ)
Gold contact device	7	−17.3	0.04	32
PEDOT:PSS contact device	3	−9.6	0.06	14

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value of mobility. This is confirmed by the electrical measurements, where a typical value in the range of 10^{-2} V cm/s^2 has been recorded for the cylindrical transistor (while in planar devices the typical value is lower than 10^{-2}) showing that polyimide, as previously reported in literature for planar devices,[10] forms a good insulator/organic semiconductor interface.

Therefore, the good performance obtained with these cylindrical devices paves the way towards the realization of simple circuits obtained by crossing the transistor yarn with conductive yarns that contact source and drain contacts distributed along the yarn. In this way, it is possible to obtain a textile matrix that is particularly useful for future developments in distributed sensor systems made on a textile platform.

In conclusion, we have obtained a cylindrical organic thin film transistor that, due to its form factor and the employed materials, is fully compatible with a textile process (weaving and knitting equipment). This transistor has shown very interesting performances, with typical values of the electronic parameters (mobility, threshold, $I_{\mathrm{on}}/I_{\mathrm{off}}$ ratio) very similar to those of planar devices. This result is very promising in view of innovative applications in the field of smart textiles. In particular, the realization of distributed transistors and sensors in a textile network is the natural, most promising perspective for a variety of applications.

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[1] Proc. IEEE **93**(7) (2005), special issue on flexible electronics technology.
[2] F. Carpi and D. De Rossi, IEEE Trans. Inf. Technol. Biomed. **9**, 295 (2005).
[3] J. B. Lee and V. Subramanian, IEEE Trans. Electron Devices **52**, 269 (2005).
[4] A. Bonfiglio, D. De Rossi, T. Kirstein, I. Locher, F. Mameli, R. Paradiso, and G. Vozzi, IEEE Trans. Inf. Technol. Biomed. **9**, 319 (2005).
[5] T. Someya, T. Sekitani, S. Iba, Y. Kato, H. Kawaguchi, and T. Sakurai, Proc. Natl. Acad. Sci. U.S.A. **101**, 9966 (2004).
[6] P. Cosseddu and A. Bonfiglio, Appl. Phys. Lett. **88**, 23506 (2006).
[7] Y. Xia and G. M. Whitesides, Angew. Chem., Int. Ed. **37**, 550 (1998).
[8] S. Locci, M. Maccioni, E. Orgiu, and A. Bonfiglio (unpublished).
[9] G. Horowitz, P. Lang, M. Mottaghi, and H. Aubin, Adv. Funct. Mater. **14**, 1069 (2004).
[10] K. N. Narayanan Unni, S. Dabos-Seignom, and J.-M. Nunzi, Appl. Phys. Lett. **38**, 1148 (2005).

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