Pressure sensing by flexible, organic, field effect transistors

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A mechanical sensor based on a pentacene field effect transistor has been fabricated. The pressure dependence of the output current has been investigated by applying a mechanical stimulus by means of a pressurized air flow. Experimental results show a reversible current dependence on pressure. Data analysis suggests that variations of threshold voltage, mobility and contact resistance are responsible for current variations. Thanks to the flexibility of the substrate and the low cost of the technology, this device opens the way for flexible mechanical sensors that can be used in a variety of innovative applications such as e-textiles and robotic interfaces. *© 2006 American Institute of Physics*. [DOI: 10.1063/1.2357924]

Organic thin-film transistors (OTFTs) have excellent potential for application in low-cost, large area, and flexible electronics. Impressive progresses have been made in the last years, leading to the development of innovative and interesting devices for optoelectronics and sensing.[1–6]

In particular, for sensing applications, OTFTs have many advantages over other types of sensors. First, organic transistors can be manufactured on plastic films at room temperature; therefore, they are mechanically flexible and potentially inexpensive to manufacture. Second, transistor-based sensors are active devices: many different electronic parameters (not only one as for instance in piezoresistive sensors) can be extracted from their electrical characterization. Therefore, they are multiparametric sensors and offer the possibility of using a combination of variables in order to characterize their response to the parameter to be sensed. Finally, active sensors combine in the same device both switching and sensing functions, and this allows to easily obtain a sensing matrix of limited size and improved reliability.

Many promising applications, including chemical and biological sensors[7–9] and humidity sensors,[10,11] have been reported in literature. On the other hand only a few examples of mechanical sensors have been presented so far.[12–14]

Someya and co-workers reported[3,12,13] about a flexible pressure sensor matrix in which organic transistors are used to derive pressure data from piezoresistive sensors. In this pressure sensor network, pentacene-based organic transistors are employed to address a single sensor in a matrix and selectively extract data from a pressure-sensitive rubber element.

Darlinski *et al.*[14] described the sensitivity of an organic TFT on a rigid substrate that can act as sensor element; in this case, the mechanical force is applied directly to the entire device (channel+source and drain contacts) using a microneedle.

In this letter, we propose an alternative structure where the organic semiconductor device combines in itself both switching and sensing functions. Our approach takes advantage of the favorable properties of a structure that allows to obtain a completely flexible film that can be applied, after its assembly, to any kind of substrate, paving the way for flexible sensors that can be employed in a variety of innovative applications.

The device consists of a pentacene-based, substrate-free, structure, with gold bottom contact source and drain electrodes as shown in Fig. 1(a).

A 1.6 μm thick Mylar™ sheet (Du Pont) acts as gate insulator (dielectric constant of 3.3, dielectric rigidity of 10^5 V/cm) and also as mechanical support of the whole structure.

Bottom contact Au electrodes with $W/L=100$ ($W=5$ mm and $L=50$ μm are the channel width and length, respectively) have been patterned on one side of the flexible dielectric previously adapted on a plastic frame, using a standard photolithographic technique, while the Au gate electrode is patterned on the opposite side of the Mylar film, obtaining an autoalignment of source/drain and gate contacts that allow to drastically reduce parasitic capacitance effects. Experimental details on the fabrication of source and drain contacts have been reported elsewhere.[15] To study the role of the contact/semiconductor interface in the pressure sensitivity, also top contact devices were obtained by means of soft lithography. In this case, the material used for making contacts is the conductive polymer PEDT:PSS. Couples of top contact and bottom contact devices have been made on the

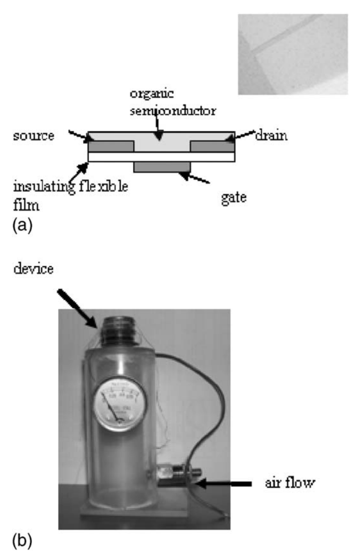

FIG. 1. (a) Basic structure of the device. Inset: detail of the channel area of the device. (b) Experimental setup for testing the pressure sensitivity of the device.

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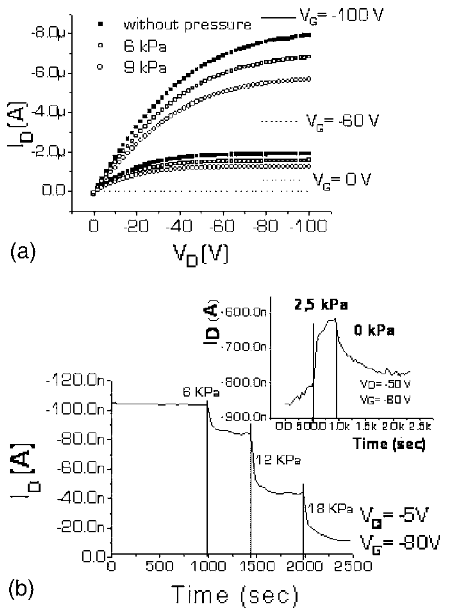

FIG. 2. (a) Comparison between I_D vs V_{DS} curves with different pressure states. (b) I_D vs time curves with different applied pressures. Inset: effect of the pressure application and removal.

same substrate, with the same active layer. For details about the fabrication technique of these devices, see Ref. 16.

Prior to semiconductor deposition, the substrate has been cleaned with acetone, washed with de-ionized water, and dried with a nitrogen flux. Pentacene (Sigma Aldrich) has been used as received. Pentacene films with a nominal thickness of 50 nm have been grown by vacuum sublimation at a nominal deposition flux of about 1 Å/s.

To study the correlation between the electrical performance of the device and pressure, we employed the experimental setup shown in Fig. 1(b). The device is employed as a freestanding film glued on the circular edge (2.5 cm in diameter) of a cylindrical sample holder; the sample holder is hermetically clamped to an air reservoir provided with a pressure meter for measuring the pressure difference between the external and the internal of the reservoir. The pressure difference is applied by means of an air flow coming from an external air compressor. In this way, the deformation applied on the film has a spherical symmetry.

Measurements of drain-source current (I_{DS}) versus drain-source and gate-source voltages have been carried out at room temperature in air, using a HP 4155 semiconductor parameter analyzer. For measurements of drain-source current (I_{DS}) versus time, a fixed bias was initially applied until the output current was stable. Then the mechanical stimulus was applied. Several minutes are normally necessary to reach a stable base line value of the current.

Measurements recorded on the uncompressed device show that the device has the typical behavior of organic *p*-type field effect transistors, working in accumulation mode, with increasing negative values of I_{DS} with increasing negative V_{DS} values and with a clear field effect induced by the V_{GS} voltage. Typical recorded values of hole mobilities are in the range of 10^{-3}–10^{-2} cm^2/V s, while threshold voltages are of the order of tens of volts.

Figure 2(a) shows the drain-source current I_{DS} versus the drain source voltage V_{DS} with and without pressure. The characteristics show a decrease in the drain-source current when pressure is applied. The observed sensitivity concerns the whole curve, i.e., both the triode and the saturation regions. Figure 2(b) shows the time variation of I_{DS} (in the linear region) while pressure is applied to the device. The drain current variation is reproducible, linear, and reversible even though hysteresis is present [see inset in Fig. 2(b)]. This phenomenon can have many concurring reasons; among them is the possible electrical degradation due to the long time of continuous bias that is necessary to reach a stable output current and that can concurrently contribute to the possible degradation of the semiconductor due to environmental parameters (e.g., humidity[17]). The sensor responds very fast to the mechanical stimulus (i.e., within hundreds of milliseconds) but the time necessary to reach the steady state is much higher. This is mainly to be attributed to the behavior of organic semiconductors (the device has been measured in air and is not encapsulated) as the structure parasitic capacitance effects have been minimized through the autoalignment of contacts. Nevertheless, this problem could negatively affect the performance of such devices in practical applications, and a higher mobility and stability of organic semiconductors is obviously desirable.

The drain-source current in the triode regime is satisfactorily described by

$$I_{DS} = -\frac{W}{L}\mu C_i\left((V_{GS}-V_{\text{th}})V_{DS}-\frac{1}{2}V_{DS}^2\right). \quad (1)$$

Variation of W/L ratio, mobility μ, insulating layer capacitance C_i, and threshold voltage V_{th} can be related to the pressure-induced variation of the drain-source current. In a more complex model, also the contact resistance R_S can be included among the parameters that can be affected by the applied pressure:

$$I_{DS} = -\frac{W}{L}\mu C_i\left[(V_{GS}-V_{\text{th}})(V_{DS}-R_S I_{DS}) - \frac{(V_{DS}-R_S I_{DS})^2}{2}\right]. \quad (2)$$

To understand which of these parameters are responsible for pressure sensitivity, it must be reminded that the mechanical stimulus has been applied by means of the air flow which is isotropic; therefore the plastic layer (which is mechanically isotropic as well) is isotropically deformed and the W/L ratio does not vary when a pressure is applied. Furthermore, the possible thinning of the plastic layer induced by the stimulus would cause an increase in the insulating layer capacitance C_i which should result in an increase of the drain-source current; this is obviously not the case here. Therefore, mobility, threshold voltage, and contact resistance are the only parameters possibly affected in these measurements. Mobility, threshold voltage, and contact resistance have been extracted by fitting our data with Eq. (2). Data plotted against pressure are shown in Fig. 3.

The data show that the observed decrease in drain-source current is due to mobility variations but we observe that the pressure-induced changes are also reflected in the threshold voltage V_{th} and in the contact resistance R_S. We therefore can assume that the pressure-induced changes in drain current can be related not only to the strain dependence of the semiconductor conductivity but also to the distribution and activity of trap states near the metal/semiconductor interface, that typically affect contact resistances and threshold voltages.[18]

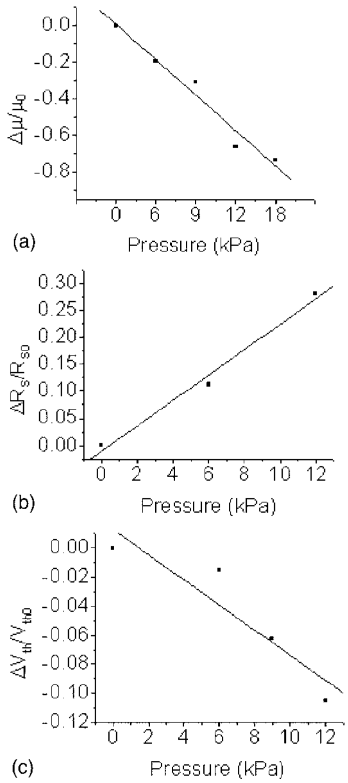

FIG. 3. (a) Mobility, (b) contact resistance, and (c) threshold voltage vs pressure.

To check this point, we performed a pressure measurement on couples of devices obtained on the same semiconductor layer with two different structures: a bottom contact device (with source and drain deposited on the insulating layer and the semiconductor thermally evaporated on top of them) and a top contact structure (with source and drain deposited on top of the semiconductor layer previously evaporated directly on the insulating layer). In this way, the geometry of contact is exactly the same and the only difference between the two devices is the interface between source/drain contacts and the semiconductor layer; this is known to affect the device performances through threshold voltage[19,20] and contact resistance.[18] The results of these measurements are shown in Fig. 4. No correlation has been found between threshold voltage and pressure for the top contact device (series resistance effects cannot be evaluated with the same model in top and bottom contact devices therefore the comparison is not possible). This confirms the role of the metal/semiconductor interface in determining the pressure sensitivity of the device. On the other hand, mobility has a very similar trend in the two devices, indicating also a direct contribution of the semiconductor in the channel to the observed sensitivity.

In summary, we have realized a fully flexible mechanical sensor. The device is based on pentacene thin film grown on gold contact patterned on a 1.6 μm thick Mylar™ gate dielectric. We have observed a marked sensitivity of the drain current to the elastic deformation induced by a mechanical stimulus applied on the device channel. The electrical characteristics indicate that the output current varies reversibly in response to the mechanical stimulus applied to the film. Taking advantage of the full mechanical flexibility of the insulating sheet, attractive developments can be envisaged: thanks to this feature, it is possible to apply this structure on any kind of substrate, allowing a perfect adhesion between the substrate and the film. The underlying mechanism of the observed pressure sensitivity is not completely clear yet. In fact, besides a decrease of pentacene mobility in the channel, we suppose that interface effects in the source/drain surrounding areas, due to the morphological modification of pentacene layer under stress, may be among the main responsible for drain-source current variations in bottom contact devices. Work is in progress to further clarify this point.

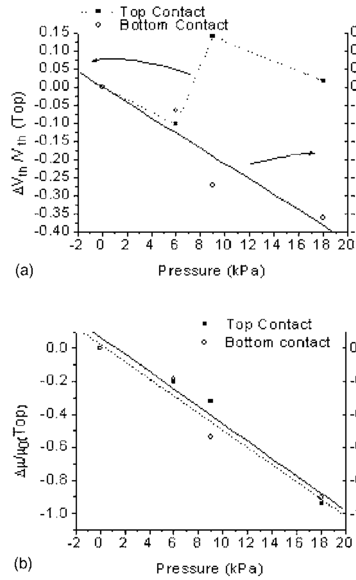

FIG. 4. Comparison between threshold voltage vs pressure and mobility vs pressure in top contact and bottom contact devices.

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