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Arrays of pressure sensors based on organic field effect: a new perspective for non invasive monitoring

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Abstract— In this paper we propose totally flexible organic field effect transistors (OFETs) assembled on plastic films as sensors for mechanical variables. In the first part, mechanical sensors for pressure and bending detection are presented. A sharp and reversible sensitivity of the output current of the device to an elastic deformation induced by means of a mechanical stimulus on the device channel has been observed and suggested the idea of employing arrays of such sensors for detecting the deformation applied onto a planar surface. In the second part, the possibility of using similar devices for bio- and chemo-detection is described. By exploiting the properties of the basic structure, the device can be combined with any kind of substrate to detect for instance the pressure applied by people walking or standing on a functionalized carpet. This emerging technology seems to be promising for applications in the field of remote and non invasive monitoring of elderly and disabled people.

I. INTRODUCTION

Research in biomedicine and engineering during the last years has led to a remarkable interest in sensor technologies for biomedical applications. Silicon technology is not suitable for manufacturing low-cost large-area sensor devices that are preferably light, flexible, and even disposable (for some biomedical applications). Its inherent high temperature fabrication processes make it very difficult to use inexpensive flexible substrate materials, resulting in high fabrication costs. On the other hand, organic semiconductor-based devices offer very interesting opportunities for sensor applications due to the low-cost and easy fabrication techniques, and the possibility of realizing devices on large and flexible areas on unusual substrates as paper, plastic or fabrics. Sensors seem therefore to be the optimal candidate for fully profiting from the properties of organic materials. Organic materials, based on conjugated organic small molecules and polymers, have paved the way, in the last decade, for the production of devices on large-area, low-cost, plastic substrates.

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So far, great progress has been made in the field of optoelectronic devices, like Organic Light-Emitting Diodes (OLEDs) [1] and for switching functions by means of Organic Field Effect Transistors (OFETs) [2].

Organic semiconductors offer several advantages due to easy processing, good compatibility with a wide variety of substrates including flexible plastics, and great opportunities in terms of structural modifications. Furthermore, thin films of organic semiconductors are mechanically robust and flexible, and this characteristic offers interesting possibilities for future electronic/sensor applications based on flexible substrates.

In this paper, we report on arrays of organic field-effect transistors that have been employed for pressure detection on relatively large surfaces. Despite the low mobility of organic materials (compared to crystalline semiconductors, it is about three orders of magnitude lower [3]) there are applications, as the recently suggested electronic skin [4], in which the lower speed is tolerable and the use of organic materials seems to be more beneficial than detrimental. In fact, being able to obtain large sensing areas is certainly a benefit for a wide set of applications and using printing techniques for creating sensing devices on unusual substrates could certainly widen the set of possible applications where sensing is required.

Relatively little progress has been made in the field of pressure or bending recognition [5]-[7] compared to the areas of gas [8] and chemical sensing [9], mainly because mechanical sensing requires attributes of conformability and flexibility and three-dimensional large area shaping that in many cases are difficult to achieve even for organic devices.

The effect of strain on the mechanical and electronic properties of organic semiconductors is an emerging research topic in fundamental physics and applications. Although mechanical flexibility is one of the main advantages of organic materials, organic semiconductors strain properties have not yet been fully exploited in order to realize devices for detecting physical parameters as for instance pressure or bending.

II. EXPERIMENTAL

We recently proposed an innovative, substrate-free, organic field-effect transistor structure based on pentacene for pressure and strain detection [10]. A cross section of the structure is shown in Fig. 1.

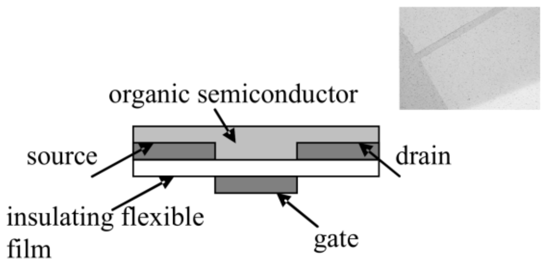

Fig. 1. Cross section of substrate-free OFET for sensing applications. Inset: detail of the device channel.

The main peculiarity of this structure is that it is assembled starting from a flexible insulating film, but without any substrate. Thanks to this feature, both sides of the insulating layer are accessible so it is possible to apply to both of them an external stimulus (i.e. a pressure) or to glue the final flexible device onto whatever kind of substrate (for instance a 3-D surface). This is usually impossible for structures assembled on a rigid substrate as, typically, OFETs realized on Silicon/Silicon dioxide, in which the presence of the substrate drastically limits the flexibility of the device. The flexible insulating layer is a thin polyethylene terephthalate sheet Mylar™, Dupont, with thickness 1.6 µm, dielectric constant 3.3, dielectric rigidity of 10^5 V/cm that allows applying a gate bias sufficiently high to induce a field-effect in the organic semiconductor.

Thanks to its electrical and chemical characteristics, Mylar can be used as received without any further surface treatment while thanks to its mechanical properties it acts not only as gate insulator but also as mechanical support for the whole structure. This is usually impossible with conventional organic dielectrics that are solution-processed; in this case, as a matter of fact, a flattening support is essential. To form a transistor structure, gold bottom-contact source and drain electrodes were patterned on the upper side of the flexible dielectric foil, using a standard photolithographic technique, while the gold gate electrode lied on the opposite side. The channel width (W) and length (L) used were 5 mm and 150 µm respectively, in an interdigitated configuration. Since the Mylar is transparent to UV light, in the photolithographic process for the device assembly, source and drain may be used as mask for the gate patterning. This point is a distinctive feature of our structures and it is a consequence of the absence of the substrate. As a consequence of the auto-alignment between source-drain and gate electrodes, all the parasitic capacitance effects due to metal overlapping are drastically limited [10]. A 50 nm thick vacuum-sublimed Pentacene (Sigma-Aldrich) is used as active layer. Arrays of such devices have been produced on Mylar films, realizing 3x3 matrix structures as shown in Fig.2.

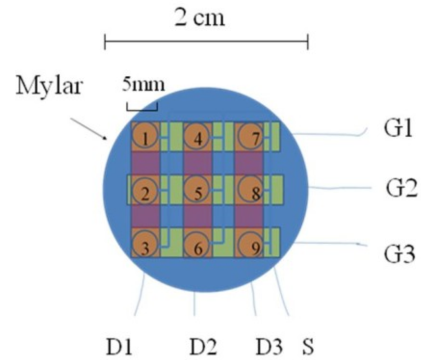

Fig. 2. Schematic representation of the employed matrix configuration

As can be noticed, a common source configuration was used, where, all the devices in the same row have a common gate and all the devices in the same column have a common drain. In this way every single transistor in the matrix can be switched on independently. In this way, a spatial resolution of c.a. 9 devices over $4cm^2$ area was achieved, with $25mm^2$ area per each device and a lateral spacing of 2mm between two adjacent devices.

III. RESULTS

All the assembled devices within the active matrix showed typical p-type field effect behaviour with reproducible electrical performances. In particular, p-type OFETs with hole mobilities up to 10^{-1} cm^2/Vs and I_{on}/I_{off} up to 10^5 were obtained.

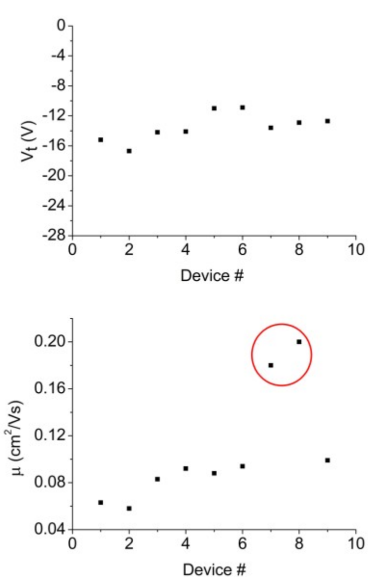

Fig. 3. An example of the electrical performances of all devices within the matrix.

Moreover, as can be seen from the graphs reported in Fig. 3, the devices are characterized by a very similar electrical behaviour with a very uniform threshold voltage, close to -15V. Also, a rather similar mobility was found; only 2 within 9 devices gave rise to a mobility value which is not comparable to the other samples. This is very important, because it shows that even a non conventional substrate, not optimized for organic electronics applications, can be employed for the realization of high performances OFETs. These matrixes of distributed sensors were employed for pressure detection. In order to avoid the active layer degradation during the experiments, a thin (1 mm thick) polydimethylsiloxane (PDMS) film was deposited on the entire surface of the matrix. The electrical response of a certain device within the matrix was then monitored when an external pressure is applied to every single transistor area separately.

In this example, reported in Fig. 4 where the electrical behaviour of device #1 is shown, the device has been biased using V_{DS}=-10V and V_{GS}=-10V. As can be clearly seen, despite very small applied pressures, approximately 1kPa (around 3g/0.25cm^2), the device showed a marked decrease of the measured current when the external stimulus is applied; moreover, a significant response has been observed only when pressure was applied on its own surface area.

It is noteworthy, that even if the lateral spacing between two adjacent transistors is rather small (around 2 mm), no significant current variation has been measured when pressure was applied to the adjacent cells within the same row. When pressure was applied on adjacent transistors in the same column, meaning that the two devices (the mechanical stressed and the measured one) have the same source and drain electrodes, as can be noticed in Fig. 4, a very slight change in the monitored device current can be measured, which can be possibly be attributed by electrical interference introduced by the mechanical deformation of source and drain electrodes which, in this case, have the same potential of the monitored device one. However, it can be also observed that such a change in the current is much smaller (ranging around 2%) than the one measured when the pressure was applied directly on the same device.

In synthesis, we developed a fully flexible matrix of distributed transistors which can be used for monitoring mechanical deformation (in this case induced by an external pressure applied to the single devices). The described system showed very good reproducibility of the results and very good spatial resolution, with 0.25cm^2 sensors with vertical and horizontal spacing of 2mm. As a result, this system can be used for monitoring pressure distribution over large areas with very good spatial resolution. Moreover, thanks to the very high flexibility

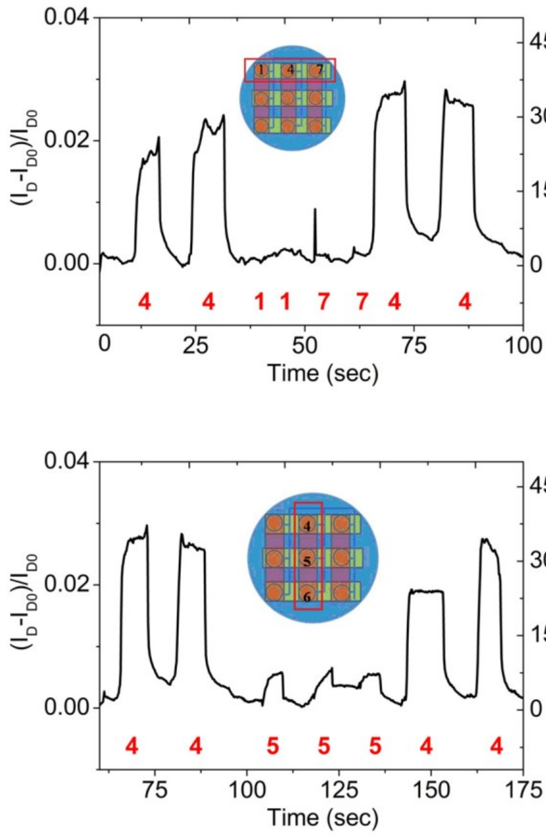

Fig. 4. Drain current variation recorded in device #1 when pressure was applied to adjacent devices in the same row (a), in the same column (b). The red numbers reported in the bottom of the plot indicate on which device the pressure is applied.

of the employed structure, such a system can be very easily transferred onto whatever kind of substrates, as paper, fabric or 3D structures allowing a very wide range of possible applications.

IV. Applications: A Smart Carpet for Remote Monitoring

An important bio-engineering application uses these area detectors to monitor the elderly and even to provide security. Detecting the walking pressure or the individual prone on the floor can provide a rapid means to alert care givers to respond to falls. Falls are a leading cause of death of the elderly. In security the area sensor detects footfalls on a location where there should be none or where there is corroborating indication of unauthorized entry.

The signal requires connecting the sensor to an amplifier then a microprocessor and to a computer. This provides ample capability to determine which sensors send the data and to display it in some meaningful way- e.g. a map of the floor. The variables that allow for choice of sensor include the power supply, the geometric arrangement of the arrays and the signal detection matrix. For example one configuration is to set the power supply lines fixed and to obtain row and column data from FET source. Such an arrangement avoids the mxn detection and allows for m+n data lines. An important issue is the low level of current that must be amplified; furthermore the high impedances allow for low currents.

Finally future work will be to test these in a patient's room. In the immediate future we will test mock up carpets to determine the best placement of sensor and carpet so that there is no slippage or cushioning. Individuals with dementia expend significantly more effort in walking than those with out cognitive challenges.

V. Conclusions

In conclusion, we have presented a system for pressure detection on relatively large areas based on the use of organic thin film transistors for realizing arrays of pressure sensing units on planar plastic surfaces.

These results are very promising in view of innovative applications in the field of remote and non invasive monitoring of elderly and disabled people. In particular, the realization of distributed transistors and sensors by printing techniques is the most promising perspective for this kind of applications as it would allow producing large areas with a very fast method.

Acknowledgment

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