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Charge Carriers Photogeneration in Pentacene Field Effect Transistors

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Abstract. Organic FET transistors (OFETs) were fabricated on silicon substrates using pentacene as active organic layer and gold source and drain contacts. OFETs were used as test structures in order to study carriers photogeneration effect in organic layers. Photogeneration process was induced by exposing organic layers to a laser beam with 625 nm wavelength and an applied power varying in the range 10–40 μW. As an effect of light exposure, OFET drain current is increased by three-to-six orders of magnitude, depending on devices operation conditions and their geometry. It is suggested that both electrons and holes generated in pentacene layer contribute to current increase. We put in evidence that electrons trapped at the pentacene-dielectric interface can act as a negative biased gate, demonstrating new operating capabilities of OFETs as well as light sensing functionality.

1. Introduction

In the last years organic semiconductors have shown a great potential in devices applications. The main achievements were demonstrated in flexible displays and flexible nanodevices due to low fabrication costs [1–3]. Optoelectronic devices such as light emitting diodes, thin film transistors and recently light emitting field effect transistors have been fabricated [4, 5]. Improvement in functionality and reliability of organic devices are subjects of an intense investigation. Two major drawbacks remain low carriers mobility in organic films and low level injection of carriers at metal-organic interface [6]. The mobility attends actually 15–20 cm^2/Vs in organic single crystals and few cm^2/Vs in organic layers of conjugated molecules [7]. Among the components of small conjugated molecules group pentacene and tetracene are mostly involved in devices fabrication, with mobilities of 2×10^{-2} cm^2/Vs and 5×10^{-2} cm^2/Vs demonstrated in thin films [8]. The mechanism of carriers transport in organic layers remains a matter of debate. It is presently considered that the conduction take place through a hopping mechanisms between organic molecules and that the process involves first monolayer at the interface of organic layers with the dielectric substrate [9]. This specific behavior actually request improvement of deposition processes of organic layers in order to obtain optimization of structural arrangement of organic molecules on various dielectric substrates. Carrier injection in organic layers is an unfavorable process due to potential mismatch at the metal-organic interfaces [10]. Organic light-emitting field effect transistors allow a better control of carrier injection and by gate electrode bias one can also control the location of excitons recombination region [11, 12]. In the present paper we used OFETs structures in investigation of carriers photoexcitation in organic layers of pentacene. If the potential in light emission from organic layers have been demonstrated, very few papers treating carriers photogeneration effects were reported by present. OFETs structures were fabricated with various channel dimensions using pentacene as active region. The process of carriers photogeneration by red light exposure ($\lambda = 625$ nm) of pentacene films was investigated by analysing the influence on the output and transfer characteristics.

2. Experimental test structures

OFETs test structure with pentacene active layer were fabricated in bottom gate geometry where the substrate is used as the transistor pseudo-gate as can be seen in Fig. 1.

The substrate is (100) Si p-type wafer. A SiO_2 layer with a thickness of 73 nm, was thermally grown on wafer to form a high quality gate insulator. The source and drain contacts were obtained by thermal evaporation of gold, at room temperature, in high vacuum (10^{-6} Torr). The semiconductor organic layer, pentacene ($C_{22}H_{14}$) with the thickness of 50 nm, was deposited on the top of the structure by thermal evaporation in high vacuum (10^{-7} Torr) with a deposition rate of 3 Å/min.

OFETs were designed with channel widths (W) in the range of 5–500 μm and channel lengths (L) between 3 and 50 μm. One should note that such large dimensions correspond to a low cost lithography (1 μm) and are needed to obtain reasonable levels of current because to the reduced values of effective mobility in organic FETs (around 0.51 cm^2/Vs in our fabricated devices).

The electrical output, the transfer characteristics and the current photogenerated due to red light incidence on the organic layer were measured using an Agilent 4156C parameter analyzer, in air, at room temperature. In our experimental setup the light source was a semiconductor laser, operating at wavelength $\lambda = 625$ nm. The excitation beam was focused using a 10× objective lens of an optical microscope, which controls the spot size and position. We used an optical fiber as a light guide between the laser output and the focal system.

The pumping power was varied between 10 μW and 40 μW, with a 10 μW increment. The modification of the drain current, Ids, by light exposure was analyzed as a function of drain and gate biases for several channel dimensions.

3. Results and discussion

The schematic representation of a OFET test structure, with *backgate* and *bottom-contact source* and *drain* architecture is shown in Fig. 1.

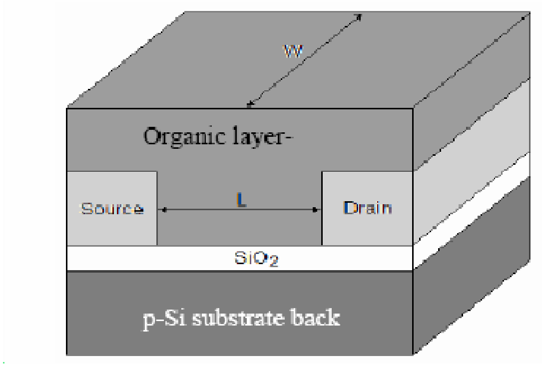


Fig. 1. OFET test structure fabricated on a p-type silicon substrate with gold source and drain electrodes and pentacene active layer.

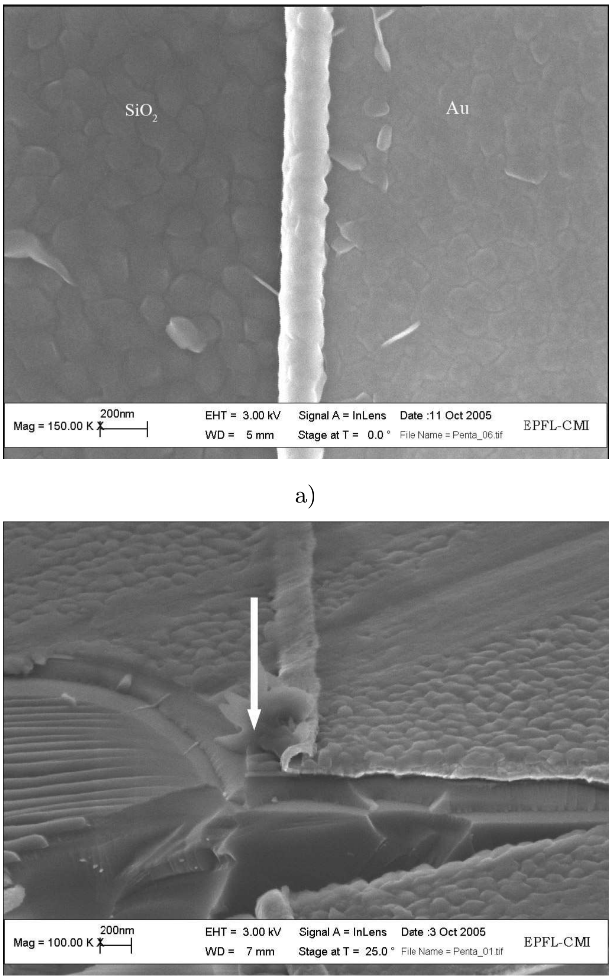
Scanning Electron Microscopy (SEM) images of pentacene film surface are presented in Fig. 2. The pentacene film reveals a polycrystalline structure, with an average grain size of 150 nm, and a good uniformity on both the SiO_2 and gold surfaces. A closer examination of Fig. 2a shows that the grain boundary region is more extended at the SiO_2 surface. The cross section image in Fig. 2b suggests that the polycrystalline structure of pentacene follows the structure of gold substrate. The arrow points the gold surface under removed pentacene film.

Ids-Vds output characteristics, for various channel configurations, are presented in Fig. 3 and Fig. 4. The devices were operated with voltages not exceeding 20 V. Ids-Vds curves of a set of devices with W = 5 µm and L = 3–50 µm are plotted in Figs. 3a and 3b. Similarly, Ids-Vds characteristics for a set of devices with W = 500 µm and L = 3–50 µm are shown in Figs. 4a and 4b. All devices show typical p-FET characteristics.

It can be observed that for small W devices, Ids current attains a saturation regime for lover Vds if L is large, as can be seen comparatively in Fig. 3a and Fig. 3b. In case of devices with W large saturation regime of Ids appears at almost same Vds, for various values of L (Fig. 4a and Fig. 4b). Ids at saturation increases cuadratically with Vgs, according to the following the equation [13]:

$$|I_{ds,sat}| = \frac{W}{2L}\mu C_{ox}(V_{gs} - V_T)^2,$$

where W, L, C_{ox} and μ are channel width, channel length, oxide capacitance and holes mobility and V_T is gate voltage threshold.



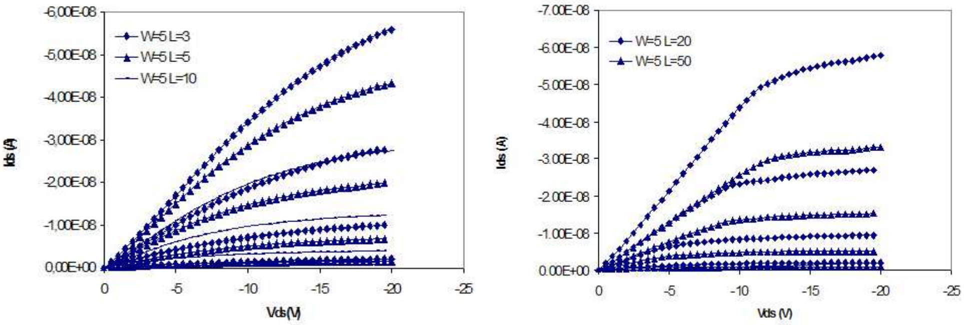
a)

b)

Fig. 2. SEM micrographs of pentacene layer deposited on SiO_2 and the Au contacts. Grains with average size of 150 nm were formed at a deposition rate of 3 Å/min, top view (a) and cross-section (b) images.

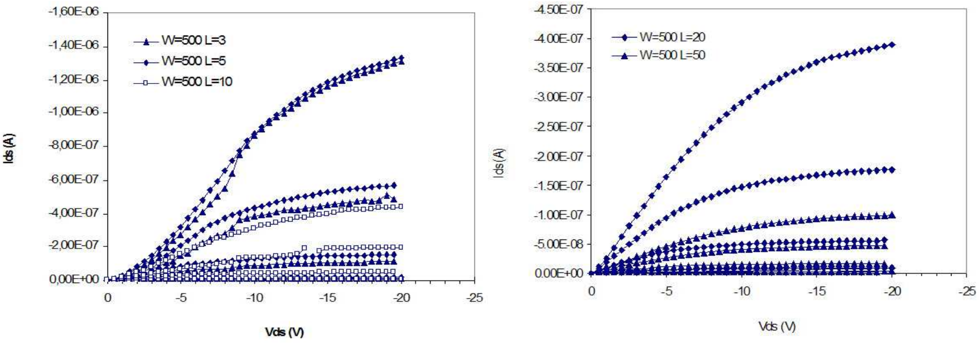
If the trap level is not assumed to be discrete but to be an exponential, Gaussian, or uniform distribution the current will be not proportional to V^2. Thus, we have to take into consideration a discrete trap filling effect and possible implications in devices functionality. Before starting to analyze experimental result of light interaction with pentacene thin films, two ideas have to be mentioned. First, hysteresis loops were observed by scanning Vgs from +20 V to –20 V and backward, at Vds = –10 V.

Previously, this effect was attributed to increase of threshold gate voltage induced by charge trapping [10]. Hysteresis effect appears both for devices with small and large W, as is presented in Fig. 5a and Fig. 5b respectively.



a) b)

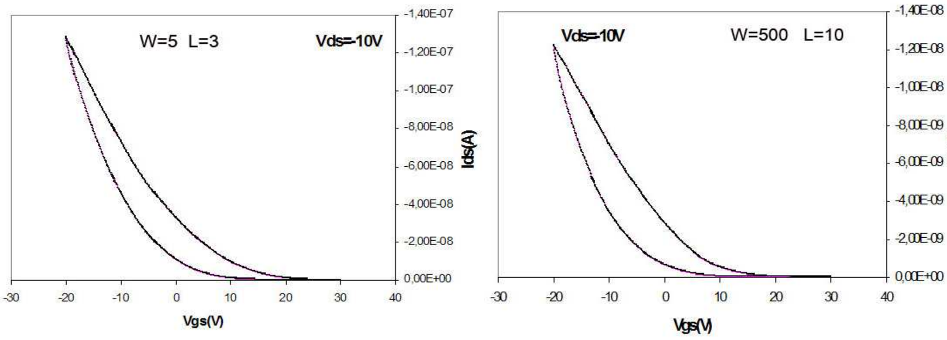
Fig. 3. *Dark output* characteristics, Ids-Vds, of fabricated OFETs. The channel parameters are: W = 5, L = 3, 5 and 10 μm in (a), and W = 5, L = 20 and 50 μm in (b). Vg = +15 V, –15 V.



a) b)

Fig. 4. *Dark output* characteristics, Ids-Vds, of fabricated OFETs. The channel parameters are: W = 500, L = 3, 5 and 10 μm in (a), and W = 500, L = 20 and 50 μm in (b). Vg = +15 V, –15 V.

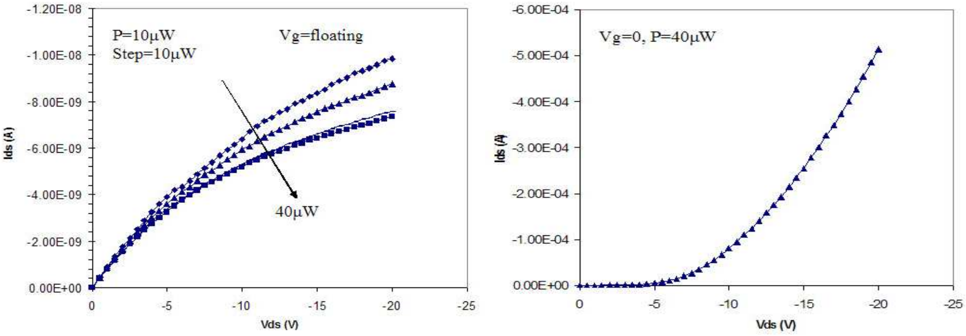
Second, the trap filling process could be driven by the application of initial depletion voltage on the gate if the polarizable gate insulator is used in OFET structure. Charge storage at the interface between the gate and the semiconductor channel results in modification of effective channel voltage relative to the voltage nominally applied at the gate contact [11]. It is then expected that the presence of traps as those put in evidence in transfer characteristics of present OFETs (Fig. 5) can induce modification of output characteristics under light exposure. Carriers photogenerated in pentacene by irradiation with light at a wavelength of 625 nm, will contribute to the conduction and also can be trapped, affecting in this way the electric field distribution in the channel. These aspects were evidenced in our experiments.



a) b)

Fig. 5. Transfer characteristics Ids-Vgs corresponding to OFETs with the channel parameters: W = 5, L = 3 μm in (a), and W = 500, L = 10 μm in (b).

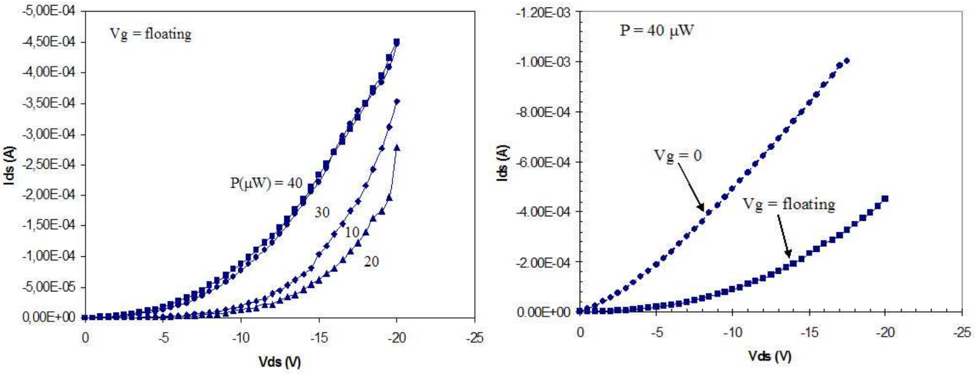
The effect of light exposure was tested on devices with channel width W = 5 and 500 μm and having small values of the channel length, L = 3 and 10 μm, respectively. The variation in Ids, for Vds in the range 0–25 V, was measured by exposing the pentacene to incident red light of various power levels, P, varying from 10 μW to 40 μW, with and without the gate electrode connected. Figure 6a shows the Ids-Vds characteristic of the OFET with W = 5 μm and L = 3 μm, measured with *floating* Vg. Output characteristics measured with Vg = 0 V are presented in Fig. 6b.



a) b)

Fig. 6. Ids-Vds characteristics *under light exposure* of a OFET device with the small channel dimensions: W = 5 μm, L = 3 μm. (a) 2-terminal configuration with Vg = *floating* and laser power, P, as a parameter varying from 10 μW to 40 μW and (b) Vg = 0 and applied laser power, P = 40 μW.

A first important observation is that the level of Ids current is significantly increased by the light excitation, like in other semiconductors, but the dependence of this increase of the bias conditions is very particular. Surprisingly, for small geometry devices, after a certain intensity threshold the intensity of the photoexcited current decreases when the power of incident light increases (at least for the light intensities applied in our case), as may be noted in Fig. 6a. This is inconsistent with what one could expect on a simple intuitive basis, i.e. that light exposure increases the charge carrier concentration and thus an increased current should be observed. Previously, photoinduced excess charge carriers were reported in organic layers as a result of exposure to light. Although the physical process involved is still under debate, it has been proven that the generation of electrons and holes may result by direct photoexcitation [14]. Photogeneration of electron hole (e-h) pairs was reported upon white light exposure of pentacene and of semiconductor polymer (P3OT) [14, 15]. A sharp increase in the drain current by exposure to light with energy of ~2.3 eV ($\lambda = 539$ nm) and flux ~1 mW/cm^2 was observed in a device biased at Vds = −40 V [15].



a) b)

Fig. 7. Ids-Vds characteristics *under light exposure* of a OFET with the channel geometry: W = 500 μm, L = 10 μm: (a) Vg = *floating* (2-terminal configuration) and laser power as parameter and (b) Vg = 0 compared to Vg = floating at power of 40 μW.

On the other hand, our experiments on large dimensions OFETs (W = 500 μm and L = 10 μm), measured with both floating Vg (2-terminal configuration) and with Vg = 0 (3-terminal configuration), show very large increase of the Ids current under light exposure (Fig. 7). Moreover, in this late experimental case, the Ids-Vds characteristics, obtained when the light intensity increases from 10 to 40 μW (Fig. 7a), show that the current increases with the applied light power. Concretely, the current increases by three orders of magnitude (~10^{-4} A compared to ~10^{-7} A) in the *Vg = floating* configuration and upon exposure to light with P = 40 μW in comparison with the dark state value observed in Fig. 4a. A further increase in Ids is observed in the Vg = 0 V configuration, see Fig. 7b, Ids value at Vg = 0 is by six orders of magnitude higher than that measured in dark, Fig. 4.

A possible interpretation of our experimental results is based on *electron trapping* phenomena at the interface between pentacene and gate insulator. Electron-hole pairs are generated in the pentacene layer upon red light excitation and their concentration increases when the light flux increases. The *electron trapping* seems to be a very effective process in pentacene films. Previously, electron traps were reported in pentacene based thin film transistors and observed through *hysteresis effect* in the transfer characteristics [16]. The traps are not uniformly distributed in the pentacene layer; they are located mainly at the pentacene - SiO_2 interface. Therefore, a *localized negative charge accumulation* results in this region, due to the trapped photogenerated electrons [17].

The negative charge build-up (following photogeneration) may *play the role of a gate effective negative bias* and influences the current levels in various regimes, depending on the applied gate voltage (transversal field). The effect of negative charge trapping at the organic dielectric interface was proposed by Dutta *et al.* [15] and Gu *et al.* [16]. This interpretation could offer a basis to account for the present experimental results. One should also consider that in successive experiments the device is not completely relaxed (being charged by the previous measurement) and this can influence the history of the measurements. However, the difference between the different behavior of small and large devices is not completely understood and a possible role of the size of the Schottky contacts should be considered.

Nevertheless, we evidence that the conduction mechanism is rather *bipolar* than *unipolar* in OFET structures with small and large channel widths, see Figs. 5b and 6b, upon red light excitation that generates electron-hole pairs. The *vertical electric field* and *carrier (electron) trapping* in the field can significantly influence the level of the current and the conduction in thin pentacene films. It appears that larger channel widths (> 100 µm) are likely to favor the optical sensing process.

4. Conclusions

In summary, we have experimentally studied the electrical response to laser excitation ($\lambda = 625$ nm) of pentacene field effect transistors with various dimensions. As a result of efficient photogeneration in thin pentacene films, the drain current is increased by several orders of magnitude compared to the dark current, depending on the applied biases. The negative charges trapped in the film could explain the various observed characteristics. In general, device illumination induces a bipolar conduction in the devices. The reported experimental data show a high sensitivity to light and bias conditions of OFETs, which may open applications in light sensing and light controlled switches made of organic field effect devices.

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