Pentacene-based thin film phototransistors

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***Abstract*—Organic thin film phototransistors (OPTs) are fabricated using pentacene as semiconductor and the photo-curable polymer ActivInk D150 as gate insulator. The photoresponse was studied through a simple model developed to describe the direct photocurrent (photoconductive effect) and the current enhancement due to the threshold voltage shift (photovoltaic effect). The results show a nearly linear correlation between photocurrent and incident optical power, with a high responsivity. Furthermore, the direction of threshold shift can be modulated by a persistent gate bias during illumination.**

I. Introduction

THIN film phototransistors based on conjugated organic materials have gone through significant developments enabling their use in cost-effective, large area and flexible applications [1]. The advantages of organic phototransistors (OPTs) are the large variety of organic semiconductors and their particular sensitivity to light, the good response time and the high responsivity. The control of channel conductance can be enabled by both the gate voltage magnitude and the light absorption. However, the electrical and optical properties, as well as the performance, of devices are strongly affected by the material morphology [2][3] and by the quality of semiconductor-insulator interface [4][5], where traps altering the charge transport in the channel are concentrated.

In this contribution, the photocurrent of pentacene-based OPTs is investigated through a simple model, which allows to distinguish the effect of photogenerated electrons and holes. A particular attention is devoted to the effect of charge trapping at the semiconductor-insulator interface which influences the threshold voltage [4][6] and its shift induced by light.

II. Methods and results

OPTs were fabricated on glass substrates in bottom-gate top-contact configuration, starting from a transparent gate electrode of indium-tin-oxide (ITO). As gate insulator a photocurable polymer by Polyera Corporation (ActivInk D0150) was spin-coated with a thickness of 600 nm and cured at 300 nm to activate the bulk crosslinking (the measured dielectric constant is 3.3). Then, a pentacene film (50 nm) and the gold source and drain electrodes (50 nm) were thermally evaporated through shadow masks.

The devices were characterized in dark and under light at different wavelengths (285÷630 nm) over the pentacene bandgap energy and various irradiances. The experiments were performed in ambient air and oxygen appears not to react irreversibly with pentacene in dark or under visible light, whereas permanent modifications were induced under an ultraviolet light [4][7].

The transcharacteristics collected in dark and under illumination were shown in Fig. 1a for the linear regime. The current under light is higher than in dark, thanks to the photo-generation of mobile charge carriers. The photoresponse is greater for low gate voltages, where the channel conductance is dominated by the light-induced charges and less controlled by the gate field. The curves under illumination exhibit also a shift toward more positive gate voltages, similarly to the bias stress effect [8].

III. Discussion

The devices were analyzed in the linear regime, in order to consider a nearly uniform charge concentration along the channel. Due to the dispersive conduction mechanism in pentacene [2][4], where the transport occurs in the delocalized band but is limited by the intra-gap traps, the field effect mobility μ_{FE} results to depend on the bias according the relation $\mu_{FE} = \mu_0(V_{SG}-V_T)^\gamma$, where μ_0 is the low-field mobility, V_T is the threshold voltage and $\gamma = 2(T_0/T-1)$ is a parameter proportional to T_0, that is the equivalent temperature describing the band tail sharpness.

Starting from the dark current having a superlinear dependence on the gate field:

$$I_d = K\left(V_{SG} - V_T\right)^{\gamma+1} V_{SD}\,, \tag{1}$$

with $K = \mu_0 C_i W/L$ (C_i is the insulator capacitance, W and L the channel width and length), the expression proposed by the model for the drain current under illumination is:

$$I_{illum} = K_L\left(V_{SG} - V_{TL}\right)^{\gamma+1} V_{SD} + G_L\left(V_{SG} - V_{TL}\right)^{\gamma} V_{SD}\,. \tag{2}$$

Here, K_L and V_{TL} are the parameters equivalent to K and V_T under light conditions, while G_L is related to the semiconductor conductance due to the photogenerated carrier density n_{ph}: $G_L = q\mu_0 n_{ph}/L^2$. In (2), the first term corresponds to the sum of the dark current and the current contribution due to the threshold shift (photovoltaic effect), whereas the second term represents the primary photocurrent (photoconductive effect). In detail, while the photoconductive contribution is due to the photogenerated holes, the photovoltaic effect is given by the photogenerated electrons trapped in the localized states that, mostly present at the semiconductor-insulator

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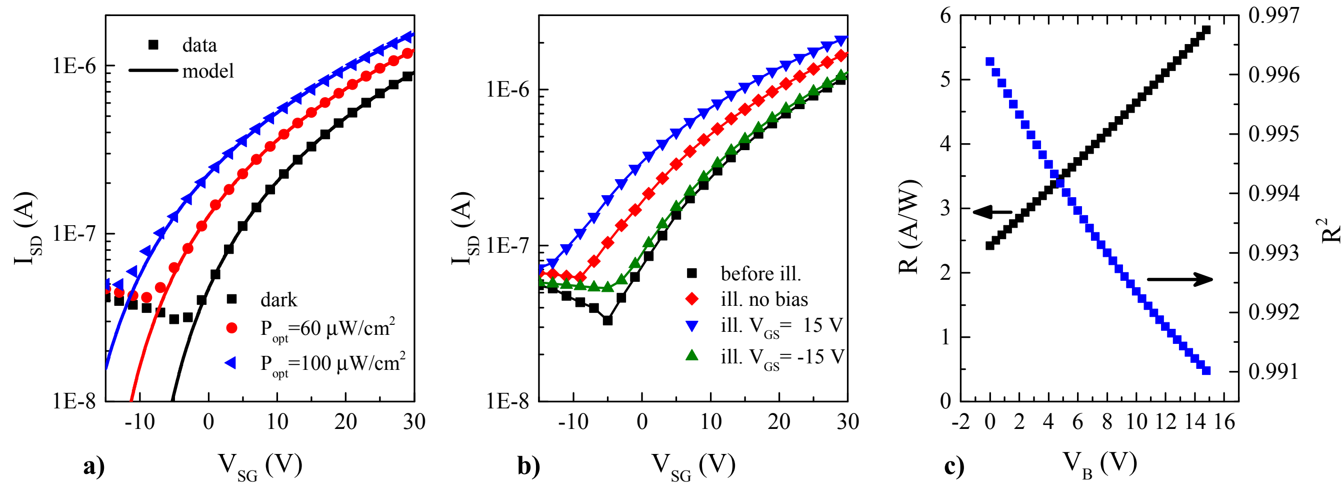

Fig. 1. a) Transcharacteristics of pentacene-based OPTs (V_{SD}=15 V) in dark and under light at 550 nm with different optical power densities; experimental data are fitted with (1) and (2); b) transfer curves collected in dark before and after illumination; the devices were irradiated for 5 min without bias or under stress conditions with positive or negative gate bias; c) extracted responsivity and the coefficient of determination correlating photocurrent and optical power.

interface, screen the gate field leading to a threshold shift $\Delta V_T = V_{TL} - V_T = qn_{it}/C_i$, where n_{it} is the trapped electron surface density.

The experimental data reported in Fig. 1a are collected at a wavelength of about 550 nm, where pentacene exhibits a photoresponse peak. The exponent γ, obtained from the comparison with the proposed equations, is 1.2, equivalent to a band tail width of about 40 meV, while μ_0 is about $2\cdot10^{-4}$ cm²/V$^{2.2}$s. The results collected under visible light also show that the low-field mobility remains almost constant, indicating that the semiconductor structure is not affected by the green light.

Due to the trapping mechanism, the coexistence of light and bias can be critical [7]. Fig. 1b shows the OPT transfer curves collected in dark after an illumination period, during which, with grounded source and drain, the gate electrode is bias-stressed. If a positive gate bias is applied, the light-induced leftward shift of V_T is enhanced. On the contrary, a negative gate bias reduces the light-induced threshold voltage shift, since the photo-generated holes are confined in the channel and can easily recombine with the light-induced electrons.

In order to polarize the pentacene-based OPT in linear regime, drain and gate electrodes can be short-circuited ($V_B = V_{SG} = V_{SD}$). In this case, the photocurrent I_{ph} can be written as:

$$I_{ph} = K\left(V_B - V_{TL}\right)^{\gamma+1} V_B - K\left(V_B - V_T\right)^{\gamma+1} V_B + G_L\left(V_B - V_{TL}\right)^{\gamma} V_B, \tag{3}$$

where both V_{TL} and G_L depend on the incident optical power P_{opt}. In Fig. 1c, the responsivity $R=I_{ph}/P_{opt}$ is reported for the illumination at 550 nm, showing an increase with the bias. However, at high voltages the coefficient of determination, which indicates the linear correlation between the photocurrent and the optical power, reduces.

IV. Conclusion

The current-voltage photoresponse of pentacene-based phototransistors has been analyzed and has been described through a model, allowing to distinguish a photovoltaic and a photoconductive effect. The results demonstrate a competition phenomenon between these two effects and the critical coexistence of light and bias stress. Moreover, the fabricated devices show a high responsivity, with a good linearity between the photocurrent and the incident optical power.

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