Quantitative physical analysis of gate-insulator/organic-semiconductor interaction and its impact on the OTFT performance

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Organic electronics is a viable candidate for low cost, disposable, large-area and flexible electronics. The transistor is the main building block for any electronic circuit. In the last years, impressive improvements of the transistor performance have been achieved. The transistor parameters (i.e. drain current, stability, on/off current ratio, subthreshold slope) are not only defined by the organic semiconductor (OSC) itself but they strongly depend on the interface between the OSC and the gate insulator (GI), the interface between the metal electrodes (source and drain) and the OSC as well as on the transistor structure (i.e. coplanar or staggered). Since in Organic Thin-Film Transistors (OTFTs) the charge transport takes place very close to the GI/OSC interface [1], the interaction between the insulator and the semiconductor plays an important role in determining the transistor performance [2-4].

In this work, we provide a quantitative analysis of the interaction between the gate insulator and the organic semiconductor. OTFTs made with different structures, gate insulators, organic semiconductors, and fabrication processes are considered. In particular, we have fabricated bottom gate bottom contact pentacene-based transistors with Al₂O₃ and PVP gate insulators. These are compared with other coplanar devices (data taken from [2]) which use evaporated pentacene semiconductor and several insulators: PVP, PVP copolymer, SiO₂, and SiO₂ treated with OTS. We also consider in our analysis top gate bottom contact TFTs (data taken from [3]) which use PTAA as active layer and PMMA or a fluoropolymer (FP) as gate insulators. The electrical characteristics of the transistors are modelled assuming a variable range hopping transport [5-7] and the density of states (DOS) is calculated in order to achieve a good fit between the model and the measurements. The integral method proposed in [8] yields the model parameters and eventually the physical parameters of the DOS. The procedure to calculate the DOS parameters with the model [6] and the method [8] is described in [7]. The derived DOS takes into account the trap distribution in the first ~15nm from the insulator interface of the OSC, which correspond to about four/five monolayers. The comparisons between the extracted DOS of pentacene- and PTAA-based TFTs are drawn in Figs. 1 and 2, respectively. The DOS obtained for the different transistors can be approximated by a single exponential $g_E = (N_t/E_t) \times \exp(\Delta E/E_t)$ or by a double exponential function $g_{2E} = (N_t/E_t) \times \exp(\Delta E/E_t) + (N_d/E_d) \times \exp(\Delta E/E_d)$. This is also in agreement with many works reported in literature [9-11]. In the case of pentacene TFTs (Fig. 1), the total number of deep states obtained with the PVP insulator are one order of magnitude lower than the ones of Al₂O₃ transistor ($N_d(PVP) = 3.6 \times 10^{19}$ cm⁻³, $N_d(Al₂O₃) = 4.5 \times 10^{20}$ cm⁻³, $E_d(PVP) = E_d(Al₂O₃) = 73.5$ meV); while the tail states are not affected by the gate insulator ($N_t(PVP) = N_t(Al₂O₃) = 1 \times 10^{21}$ cm⁻³, $E_t(PVP) = E_t(Al₂O₃) = 31$ meV). Other transistors made with PVP copolymer/pentacene and PVP/precursor pentacene give similar results. The derived DOSs suggest that the tail states are an intrinsic
property of the organic semiconductor whereas the deep states are strongly dependent on the insulator material used and hence they are a direct measure of the interaction between the GI and the OSC. It is worth noting that the deep states have a direct impact on the TFT field-effect mobility $\mu$; in fact $\mu_{\text{PVP}}$ is three times the $\mu_{\text{Al}_2\text{O}_3}$ ($\mu_{\text{PVP}}=0.154$ cm$^2$/Vs and $\mu_{\text{Al}_2\text{O}_3}=0.045$ cm$^2$/Vs). When the SiO$_2$ or SiO$_2$ treated with OTS are used as gate insulators, the DOS can be approximated by a single exponential function, with physical parameters: $N_{t(\text{SiO}_2)}=1 \times 10^{21}$ cm$^{-3}$, $E_{t(\text{SiO}_2)}=42.6$ meV, $E_{t(\text{SiO}_2+OTS)}=36.8$ meV, respectively. In this case, the variation of the tail states disorder indicates that the morphology of the pentacene is changed, and this is reasonable because the device is coplanar. In order to further check this point, staggered PTAA-TFTs with different insulators are analyzed and the derived DOS are drawn in Fig. 2. Increasing the insulator permittivity ($k_{\text{PTAA}}=3$, $k_{\text{FB}}=2.1$) the local polarization effect induces more trap states at the GI/OSC interface. These traps are located at deep energies and according to the PVP/ and Al$_2$O$_3$/ pentacene-TFTs the tail states are insensitive to the insulator material used. These results show that the interaction between GI and OSC can be directly measured from the DOS because additional trap states located at deep energies are present when a high-k insulator is used. Furthermore, our analysis gives a quantitative indication that the insulator is not only capable of affecting the morphology of the semiconductor layer, but can also change the density of states by local polarization effects. This quantitatively supports the experimental works reported in [3, 4].

Fig. 1: Density of states of pentacene-based TFTs with different gate insulators.
Fig. 2: Density of states of PTAA-based TFTs with different gate insulators.

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References