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Influence of structural properties on environmental stability of pentacene thin film transistors

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ABSTRACT

We studied environmental stability of top contact pentacene TFTs with active layer evaporated at different growth rates. We measured the transfer characteristics in vacuum and in air and after storing the devices in oxygen for several days. Different pentacene growth rates result in different grain size of active layer. This morphology difference influences the hysteresis of transfer characteristics induced by water absorption. On the contrary, aging effects on the transfer characteristics of pentacene O-TFTs, induced by oxygen diffusion into the active layer, are not related to structural characteristics of pentacene film.

1. Introduction

The environmental stability of electrical characteristics of devices is a fundamental requirement for organic thin film transistor (O-TFTs) applications. On the other hand, it has been shown that the exposure of these devices to air is in general detrimental for their performance [1–15]. Two main effects of environment have been identified in pentacene TFTs: hysteresis of transfer characteristics [1–7], when the devices are measured in air, and variation of transfer characteristics after exposure to air for a long time [8–15]. These phenomena are attributed to the diffusion of water molecules and/or oxygen into pentacene active layer.

The hysteresis of transfer characteristics is usually related to the effect of water and it has been explained in terms of different microscopic mechanisms. A possible explanation of the hysteresis effect is that the diffusion of water molecules into pentacene induces slow trapping of carriers in the device active layer [1,2] or at the semiconductor/insulator interface [7], with a consequent shift of threshold voltage during measurement. Charge injection into the gate insulator has been also considered as origin of hysteresis [6,16]. In particular, the mechanism proposed by Sharma et al. [16], that explains the bias-stress effect in terms of exchange of holes with protons in the presence of water at the semiconductor/insulator interface and the subsequent migration of protons into the oxide, could also explain the hysteresis phenomenon. Water diffusion has been also considered responsible of a variation of energy barrier at pentacene/metal interface [4] and a reduction of field-effect mobility [4,5]. It has been generally observed that the hysteresis is reversible and disappears almost completely when the devices are stored in vacuum or dry atmosphere. This seems related to a weak interaction between adsorbed H_2O and pentacene molecules [3,8], allowing an easy removal of the water molecules from the active layer.

A permanent variation of transfer characteristics has been observed when the device are exposed to air for a long time [8–15]. In this case all the main electrical parameters (field-effect mobility, threshold voltage and subthreshold swing) are degraded, while the hysteresis remains unaffected [9,12]. Although some studies [4,5] have shown that also moisture can play a role in the aging of pentacene O-TFTs, this effect has been mainly attributed

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to the diffusion of oxygen into pentacene layer that induces new gap states located at about 0.2–0.3 and 0.6 eV above the valence band [12–14]. Experimental results are in good agreement with theoretical calculations that consider defects in pentacene molecules induced by oxygen [15].

It has been shown that it is possible to reduce environmental sensitivity of pentacene TFTs by using opportune gate dielectrics [7] or by device passivation through barrier layers in order to reduce the molecule diffusion [11]. On the other hand, also the structure of the pentacene active layer seems to play a role on the environmental stability of pentacene O-TFTs [4,10]. Growth rate, substrate characteristics and deposition temperature have been shown to be key parameters in controlling the nucleation density [17–19] and, therefore, the pentacene film characteristics (grain size and grain boundary density). In this work we have investigated the influence of the morphology of pentacene film, deposited at different growth rates, on the stability of electrical characteristics of O-TFTs, measuring the transfer characteristics in vacuum and in air and after storing the devices in oxygen.

2. Material and methods

Top-contact (TC) bottom gate devices were fabricated using a highly doped-Si substrate as a large area gate with a 90 nm thermal oxide as gate dielectric. Before pentacene deposition a buffer layer of PMMA (5 nm thick) was spin coated and annealed at 70 °C for 15 min. It has been shown that a thin PMMA buffer layer improves the performance of pentacene O-TFTs both in bottom contact (BC) and TC configurations [20], improving the interface quality between pentacene and both Au contacts (in BC-TFTs) and SiO_2 gate dielectric (in BC and TC-TFTs). Pentacene active layers (30 nm thick) were evaporated, with the substrate at room temperature (RT), by using a Radak evaporation source, with growth rates $r = 0.01$, 0.03 and 0.07 nm/s.

Atomic force microscopy analysis, performed by a PSIA XE100 system in non-contact mode, of the pentacene layers deposited at different growth rates are shown in Fig. 1. As can be seen the film exhibits the typical morphology of highly ordered polycrystalline pentacene, with a characteristic "terrace" structure with 1.6 nm steps, corresponding to the height of one molecular layer. The analysis shows that, as already reported in literature [17,18,21], the deposition conditions influence the morphology of pentacene film. Indeed, whereas pentacene films grown at low rate show grain size up to 2 μm and a very compact structure, pentacene films grown at a faster rate have smaller grain size (less than 1 μm for sample deposited at a growth rate of 0.07 nm/s) and more pronounced grain boundaries. This results in a higher density of grain boundaries for samples deposited at higher growth rates.

Source and drain contacts were formed by evaporating gold (30 nm thick) after pentacene deposition and defined through a shadow mask. Device electrical characteristics were measured in a MMR cryostat using a Keythley 236 source/measure unit and a Keythley 2635 source-meter. In order to evaluate the hysteresis of transfer characteristics, measurements have been performed sweeping the gate voltage, sequentially, from off-to-on and from on-to-off (between 5 and −30 V). Field-effect mobility has been calculated considering the maximum of the transconductance relative to off-to-on curve.

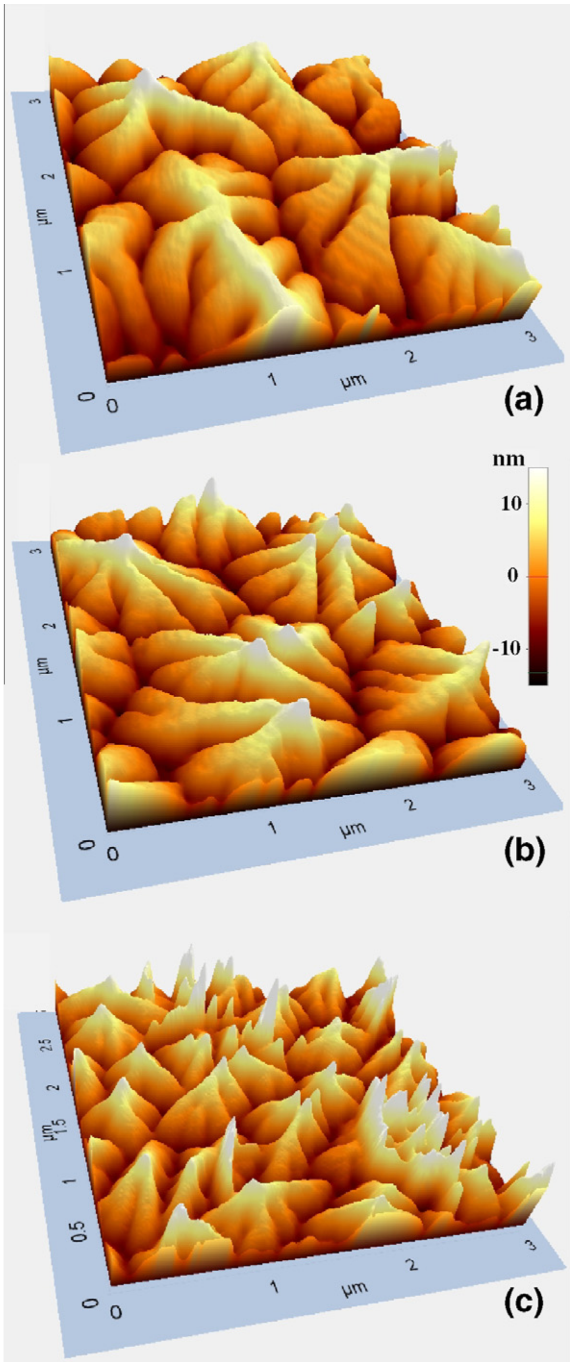

Fig. 1. AFM images of pentacene films deposited at different evaporation rates, (a) 0.01 nm/s (b) 0.03 nm/s and (c) 0.07 nm/s.

Aging effects have been investigated by storing in dark the pentacene O-TFTs in air and in pure oxygen