Electrical and environmental stability of organic transistors

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1. Introduction

Electronics based on organic materials has experienced unprecedented progress in recent years. The prospect of flexible, unbreakable, extremely lowweight electronics at relatively low cost has stimulated a lot of research and development on flexible display media,^[1] organic memories,^[2] and organic radio frequency identification (RFID) tags.^[3] Progress in this field has been sustained by the synthesis of new materials,^[4] the improvement of electronic devices,^[5,6] and the development of novel and improved processing techniques such as inkjet printing, and micro contact printing. Even though significant advances have been achieved in recent years, fundamental issues surrounding the origin of gap states in small molecule materials are not resolved, and relatively little is known about the influence of these states on the electronic properties and the electrical stability of organic devices. It is important to address these questions because stable device operation is a major requirement in realizing organic displays and radio frequency identification tags. Furthermore, gap states affect the lifetime and the reliability of organic transistors and integrated circuits. Therefore, it is essential to gain a fundamental understanding of such effects and the underlying microscopic processes.

2. Experimental

The cross section of a staggered pentacene thin film transistor with bottom drain and source contacts



Fig. 1: a.) Molecular structure of pentacene $(C_{22}H_{14})$. b.) Schematic cross section of a polycrystalline pentacene thin film transistor.

is shown in Fig 1b. A highly doped silicon wafer was used as a substrate. The gate dielectric of the transistor was formed by a 100 nm thick silicon oxide layer. The bottom drain and source contacts were defined by optical lithography. In order to improve the adhesion of the gold drain and source contacts on the substrate, a 2-3 nm thick titanium film was evaporated prior to the gold film. Before depositing the pentacene molecules (Fig 1a) the thermal oxide was treated by hexamethyldisilazane (HMDS). The pentacene molecules were deposited by Organic Molecular Beam Deposition (OMBD) using a deposition rate of 0.5 Å/s. The source material was two times sublimation purified before depositing the molecules at a base pressure of $5 \cdot 10^{-6}$ Pa. The films were prepared by keeping the substrate temperature constant at 70 °C. The source temperature was kept constant at 275 °C while depositing the pentacene films. The final pentacene layer has a thickness of 10 nm. Device structures were fabricated ranging from 2 µm to 50 µm channel length.



Fig. 2: Measured transfer characteristic of a pentacene thin film transistor for drain voltages of $V_D = -1$ V and -10 V. The transfer characteristic was measured under vacuum conditions. The device was measured before and after exposing the device to dry oxygen.

3. Results and Discussion

The formation of gap states and the influence of oxygen on the formation process were studied by electrical in-situ measurements. The transfer characteristic of a polycrystalline TFT is shown in Fig. 2. The transistor has a channel length of 20 μ m and a width-to-length ratio (W/L ratio) of 4000. The transistor was measured under vacuum at room temperature. The transistor exhibits a mobility of 0.6 cm²/Vs, an on/off ratio larger than 7 orders of magnitude, and a threshold voltage of -1 V. Furthermore, the transistor exhibits a subthreshold slope of < 100 mV/decade. The onset voltage of the drain current, defined as the gate voltage for which the drain current starts to increase, is 0 V.



Fig. 3: Measured and simulated transfer characteristic of a polycrystalline pentacene thin film transistor for a drain voltage of -1 V. The marks represent the experimental data, whereas the solid lines represent the simulation of the transfer characteristic by using a density-of-state model.

In the following the sample was exposed to dry oxygen. The concentration of oxygen was controlled by the pressure in the high vacuum chamber (10^{-1} Pa). During the oxygen exposure no electrical bias was applied to the electrodes of the transistor. After exposing the device to oxygen the transistor was pumped back to high vacuum ($< 10^{-6}$ Pa) and the devices were characterized. In this case the transfer characteristic of the transistor was not affected by the oxygen exposure. The transfer characteristic of the transistor before and after oxygen exposure is shown in Fig. 2. The oxygen exposure was repeated for different biasing conditions. If the transistor is turned-on (negative gate voltage) during the oxygen exposure no change of the device

characteristic is measured. However, if the transistor is turned-off (positive gate voltage) a distinct change of the device characteristic is observed while exposing the device to oxygen. The transfer curves obtained after biasing the transistor in the off-state are shown in Fig. 3. Now a significant shift of the onset voltage towards positive gate voltages is observed. All transfer curves in Fig. 3 were measured under vacuum conditions. The transfer curves differ in the gate voltage which was applied while exposing the devices to dry oxygen.

The experimental results were complemented by first principles pseudopotential density functional calculations for different types of oxygen-related defects in pentacene. The results of the density functional calculations were used as input parameters to simulate the current/voltage characteristic of pentacene TFTs. The transistor characteristics were modeled by a density-of-states transport model. Simulations of the device characteristic will be presented and compared to experimental results. Gap states are formed by an electrochemical process. The formation energy depends required on the electrochemical potential which can be controlled by the applied bias voltage. Shifting the electrochemical potential towards the conduction band, in the presence of oxygen or air, leads to the formation of gap states with energies close to the valence band maximum. The gap states act as p-type dopants. Such gap states are responsible for electrical instabilities and complicate the realization of organic integrated circuits. It can be expected that other organic semiconductors exhibit similar electric field induced doping effects.

4. Summary

Gap states in pentacene are formed by an electrochemical process. The required formation energy depends on the electrochemical potential which can be controlled by the applied bias voltage. Such gap states are responsible for electrical instabilities and complicate the realization of organic integrated circuits.

References

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