

Determination of the field-effect mobility and the density of states of a Thin-Film Transistor*

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In this project we determined some basic parameters for characterizing an organic thin-film transistor (OTFT) one week after fabrication and compared them with the parameters right after fabrication, in particular the transfer characteristics, the charge carrier mobility (also known as the field-effect mobility), the activation energy, and the density of states (DOS). The material which our OTFT was made of is pentacene, a widely used organic compound in OTFT fabrication.

I. INTRODUCTION

A Thin-Film Transistor (TFT) is an electronic device that uses an electric field to control the conductivity of a channel in a semiconductor material. A TFT is a three-terminal device, consisting of three electrodes (Drain, Source and Gate) and a thin-film of semiconductor in contact with a dielectric layer. The electrical current flowing between the Drain and Source electrodes is controlled by the electric field applied at the Gate [1]. Organic Thin-Film Transistors (OTFTs) are TFTs that use organic semiconductor in its channel. They offer many technological advantages such as mechanical flexibility, lightweight, low-temperature and low-cost fabrication, allowing this way the emergence of a new research field known as plastics electronics [2].

Nowadays a lot of research is being carried out in order to understand the so-called trap-limited charge transport in organic thin-films. That makes the determination of the density-of-states in the gap of the semiconductor a crucial step. In this sense TFTs are especially useful devices to study the DOS of semiconducting layers [3].

The semiconductor used in this project was p-type, meaning that the charge in the conductive channel is dominated by holes. In this work, we fabricated pentacene OTFTs on crystalline silicon dielectric substrate and gold electrodes. The electrical characteristics were measured using an Agilent 4156C parameter analyzer. The device temperature was varied from 30°C to 90°C by means of a MMR Technologies controller (model K-20).

II. DETERMINATION OF THE FIELD-EFFECT MOBILITY AND THRESHOLD VOLTAGE

When the TFT is in saturation regime, the Drain current depends on the Gate-Source voltage in the following manner:

$$I_D = \frac{W}{L} \mu C_i \frac{1}{2} (V_{GS} - V_{th})^2 \quad (1)$$

In our case $C_i = 1.5 \cdot 10^{-8} \text{F/cm}^2$ is the capacitance of the oxide per unit surface; $L = 20 \cdot 10^{-4} \text{cm}$ and $W = 0.2 \text{cm}$ are the length and the width of the transistor.

The capacitance can be obtained from:

$$C_i = \frac{C_{ox}}{S} = \frac{\epsilon}{t_{ox}} = \frac{8.85 \cdot 10^{-12} \text{F/m} \cdot 3.9}{230 \cdot 10^{-9} \text{m}} = 1.5 \cdot 10^{-8} \text{F/cm}^2$$

being $t_{ox} = 230 \cdot 10^{-7} \text{cm}$ the width of the oxide and $\epsilon_r = 3.9$ the relative permittivity of the oxide.

Taking the square root of Eq.1 a linear dependence between $\sqrt{I_D}$ and V_{GS} is obtained:

$$\sqrt{I_D} = \sqrt{\frac{W}{L} \mu C_i \frac{1}{2}} \cdot V_{GS} - \sqrt{\frac{W}{L} \mu C_i \frac{1}{2}} \cdot V_{th} \quad (2)$$

In other words, the slope of the $\sqrt{I_D}$ vs. V_{GS} plot can be used to obtain the value of μ while the intersection with the origin gives V_{th} . By linearly fitting experimental data of our TFT one week after fabrication to Eq.2, we get a value of $0.004 \text{ cm}^2/\text{Vs}$ for the field-effect mobility and -22.813 V for the threshold voltage. The R^2 value for the fitting is 0.999.

The value is one order of magnitude smaller than the one obtained right after fabrication, $0.029 \text{ cm}^2/\text{Vs}$ with a threshold voltage of -17 V . (Fig.1, inset).

One week later the measurements were performed on the same TFT under a temperature ramp from 30°C to 90°C, in 10°C steps. The same procedure was carried out to obtain the different values for μ and V_{th} at the different temperatures. The result was that the threshold voltage had increased, from -22.813 V to -29.385 V at $T = 30^\circ\text{C}$. The increase of the threshold voltage could be explained as the fact that positively charged trap states related to aromatic impurities might be partly neutralized by ionized oxygen molecules [4]. Therefore, these trap states became less effective to either trap or scatter holes in the channel region, thus needing a higher threshold voltage.

* This project was based on [2] and [3], and pretended to be a continuation of the lab session *Fabrication and Characterization of an Organic Thin-Film Transistor (OTFT)*

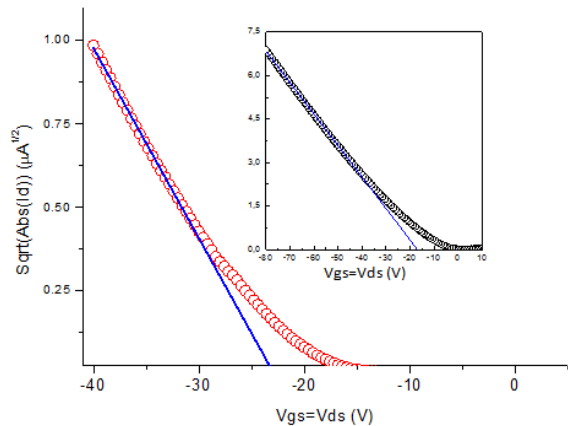


FIG. 1. Saturation curve of the OTFT ($V_{DS} = V_{GS}$) measured in vacuum, at 30°C, a week after fabrication. The inset corresponds to the same measures right after fabrication.

III. DETERMINATION OF THE ACTIVATION ENERGY

By plotting $\ln \mu$ versus $1/KT$, being T the temperature and K the Boltzmann constant, we can calculate the activation energy, a parameter that measures the distance from the Fermi level (E_F) position to the transport band edge, in this case the HOMO level of pentacene (E_H). In other words, the activation energy can be interpreted as the energy barrier for thermal release of trapped carriers. According to the formula:

$$\mu = \mu_0 \exp\left(\frac{-E_{act}}{KT}\right) \quad (3)$$

and the logarithm of it:

$$\ln \mu = -E_{act} \cdot \frac{1}{KT} + \ln \mu_0 \quad (4)$$

the activation energy is given by the slope of the linear fitting of the data obtained at different temperatures.

The degenerate TFT data fitting indicates an activation energy of 0.18 eV, which is similar to 0.15 eV, measured right after fabrication by J. Puigdollers et al. [5]

IV. DETERMINATION OF THE DENSITY OF STATES

In order to calculate the DOS the following formula is applied ([6]).

$$DOS(E) = \frac{C_i}{q} \frac{1}{t(dE_a/dV_{GS})} \quad (5)$$

with $C_i = 1.5 \cdot 10^{-8} \text{F/cm}^2$ the capacitance of the oxide per unit surface (calculated in section II); $t = 10^{-7} \text{cm}$ the

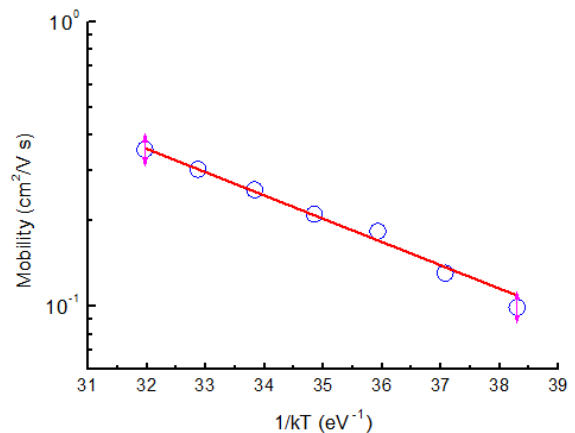


FIG. 2. Plot of the field-effect mobility as a function of $1/KT$, at high V_{GS} (-39 V). The fit indicates an activation energy of 0.18 eV.

thickness of the channel, typically a few nanometers; and $q = 1.602 \cdot 10^{-19} \text{C}$ the carriers' charge.

This formula can be explained intuitively: A fast variation of E_{act} with V_{GS} indicates that the Fermi level easily shifts towards the band edge. This behavior would indicate a low density of localized states that have to be filled by trapped carriers. On the contrary, a high DOS in the gap would result in slower variations of E_{act} with V_{GS} .

To obtain the DOS, first it is necessary to determine the activation energy as a function of the Gate-Source voltage. To do so, let us consider the dependence of the Drain-Source current I_{DS} on the conductivity σ , at fixed V_{DS} :

$$I_{DS} = V_{DS} t \frac{W}{L} \sigma \quad (6)$$

On the other hand, σ presents a thermally activated behavior, according to:

$$\sigma = \sigma_0 \exp\left(\frac{-E_{act}}{KT}\right) \quad (7)$$

Thus yielding a linear dependence between $\ln I_{DS}$ and $1/KT$ with a slope $-E_{act}$.

The Drain-Source current of the degenerated TFT was obtained for different values of V_{GS} and different temperatures. A first temperature rise from 30°C to 90°C in 10°C steps was performed. These measurements were repeated while the samples slowly cooled down to room temperature. Finally, a second temperature rise was done to observe the effect that thermal treatments would produce in the DOS of the pentacene active layer. The result, therefore, consisted of three I_{DS} vs. $1/KT$ plots (Arrhenius plots, usually with a $1000/T$ scale for the X-axis), as shown in Fig.4. The Drain-Source voltage was fixed at -10 V.

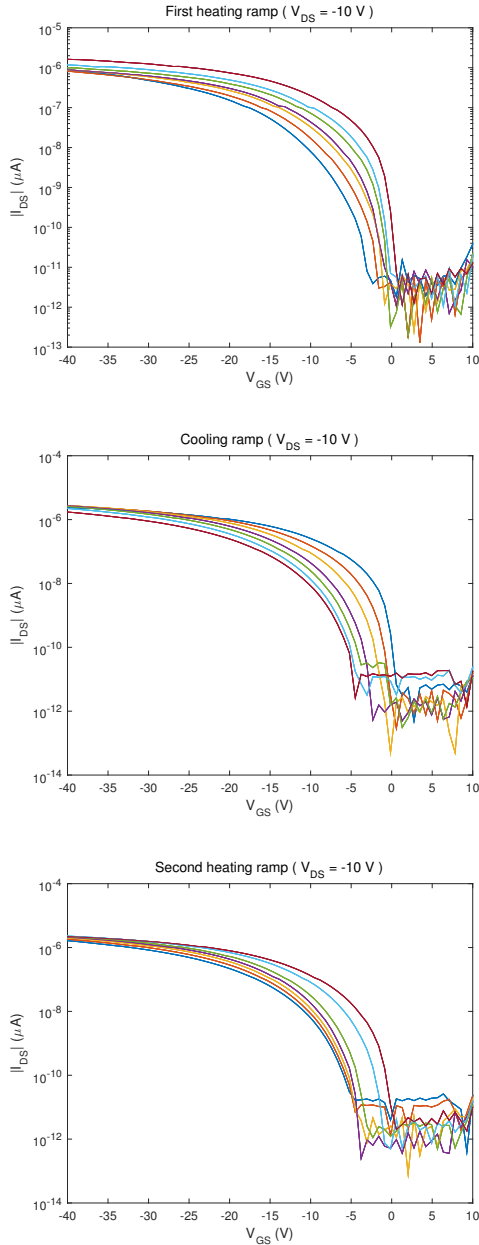


FIG. 3. From top to bottom, the transfer characteristics of the pentacene OTFTs at vacuum for the three temperature ramps, at different V_{GS} , and with V_{DS} fixed at -10 V.

The transfer characteristics were also measured for the three ramps and depicted in Fig.3.

Although not so clearly as it can be observed in [3], we can notice that the transfer curves spread more during the first temperature rise than in the second one. These differences would indicate that thermal treatments had induced a variation in the DOS of the pentacene active layer.

The plot of the activation energy as a function of V_{GS} (Fig.5), clearly shows the exponential dependence of the activation energy on V_{GS} .

Then, applying Eq.5, we can calculate the DOS in the

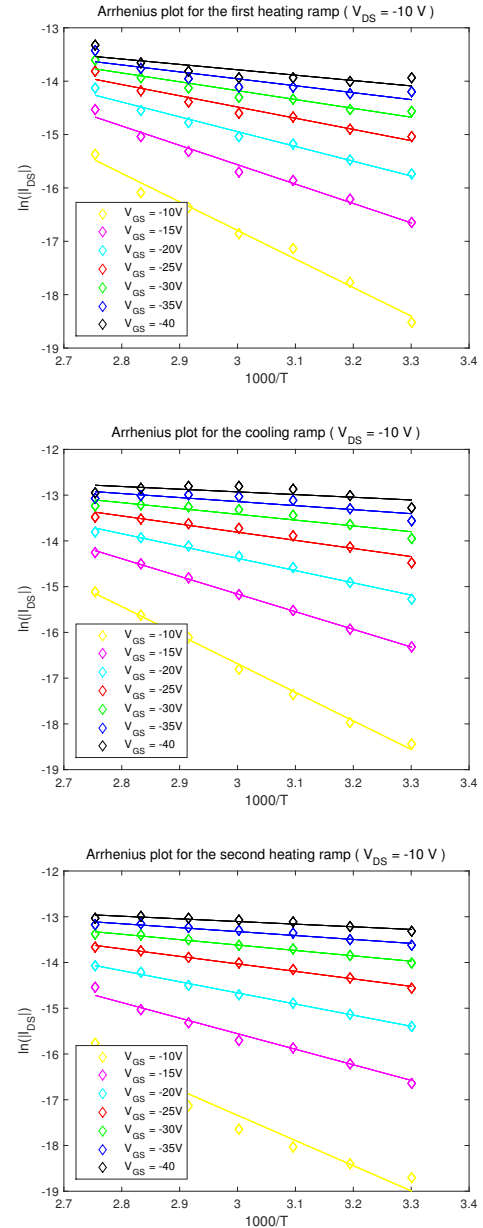


FIG. 4. From top to bottom, the Arrhenius plot at vacuum for the three temperature ramps, at different V_{GS} , and with V_{DS} fixed at -10 V.

region of the gap close to the HOMO level of pentacene ($E - E_H < 1.29\text{eV}$ [7]). In order to approximate the value of the derivatives both the forward difference and the backward difference methods were used. The results are depicted in Fig.6 and 7.

The highly linear form of the plot suggests an exponential dependence of the DOS on the energy, which agrees with what is assumed in [3]:

$$DOS(E) = DOS_0 \exp\left(-\frac{E - E_H}{KT_0}\right) \quad (8)$$

It can also be observed that a deep level around 0.7

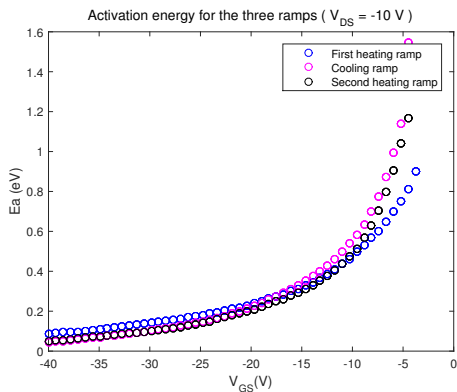


FIG. 5. Activation energy for the three ramps ($V_{DS} = -10$ V)

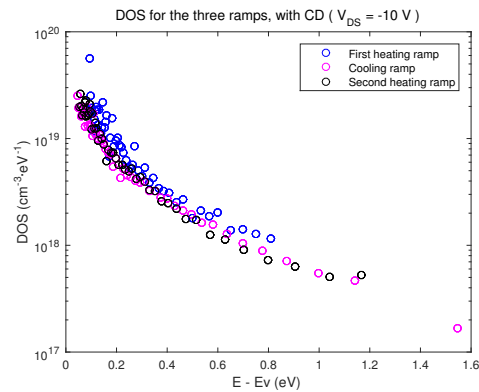


FIG. 7. DOS for the three ramps, with CD ($V_{DS} = -10$ V)

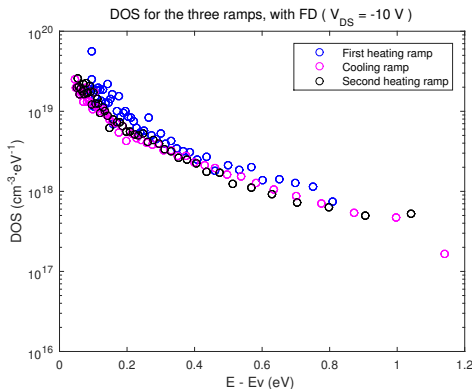


FIG. 6. DOS for the three ramps, with FD ($V_{DS} = -10$ V)

eV observed in the first temperature rise was completely healed by the thermal annealing. Desorption of water molecules is a plausible explanation of this metastability.

V. CONCLUSIONS

In this study the DOS of a pentacene OTFT has been obtained. As it has been shown, the activation energy of the channel conductance as a function of the gate voltage collects valuable information about the DOS in the active layer. The method followed can be applied to thin-film transistors based on any other organic semiconductor, offering valuable information about the density of localized states in the gap, either due to structural disorder or related to extrinsic contaminants. The healing effect of thermal annealing has also been shown. The observed enhancement in the threshold voltage and the variation in the mobility values support the expected ideas regarding the degenerative process of an organic TFT, affecting its performance as an electronic device.

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- [1] Fabrication and Characterization of an Organic Thin-Film Transistor (OTFT), Practical guide for the lab session J. Puigdollers
 - [2] Comparison between the density-of-states of picene transistors measured in air and under vacuum, *Synthetic Metals* 161 (2012) 2554–2557
C. Voz, A. Marsala, C. Moreno, J. Puigdollers, R. Alcubilla
 - [3] Density-of-states in pentacene from the electrical characteristics of thin-film transistors, *Organic Electronics* 11 (2010) 1333–1337
J. Puigdollers, A. Marsal, S. Cheylan, C. Voz, R. Alcubilla
 - [4] N. Kawasaki, Y. Kubozono, H. Okamoto, A. Fujiwara, M. Yamaji, *Appl. Phys. Lett.* 94 (2009) 043310
 - [5] Electrical characterization of pentacene thin-film transistors with polymeric gate dielectric. *Synthetic Metals* 146 (2004) 355–358
J. Puigdollers, C. Voz, I. Martin, M. Vetter, A. Orpella, R. Alcubilla
 - [6] Density of Deep Bandgap States in Amorphous Silicon From the Temperature Dependence of Thin Film Transistor Current. *MRS Proceedings*, 336, 823
T. Globus, H. C. Slade, M. Shur and M. Hack (1994). doi:10.1557/PROC-336-823.
 - [7] Energy level diagrams of C_{60} /pentacene/Au and pentacene/ C_{60} /Au, *Synthetic Metals* 156 (2006) 32–37
S.J. Kang, Y.Yi, C.Y. Kim, S.W. Cho, M.Noh, K. Jeong, C.N. Whang