

Study of New Organic Field Transistors for RFID, Optoelectronic and Mobile Applications

Marius Prelipceanu and Adrian Graur

Abstract. We present our results in developing processes and new materials for realization of new organic transistor which are promising for optoelectronics and radio frequency identification (RFID) applications. In this report we discuss the films morphology, profilometry and the field-effect transistor (FET) performances of pyrrolo phenanthroline derivatives (RA). We consider that because of π -conjugation which is extended and good alignment of molecules, the pyrrolo phenanthroline devices exhibited hole mobilities of up $0.031 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. The performance of these devices can be adequate for construction of 135-kHz RFID or high resolution display.

1 Introduction

In the last years, studies in organic semiconductors have grown because of their multiple applications in optoelectronic devices and radio frequency identification (RFID) tags [1-9]. These materials have a few advantages compared to conventional inorganic electronics. We can mention here a good and easy processability, a good chemical control concerning the injections of the charge, a good fit in with plastic substrates, and reduced production price [10-13]. It is important to have particular molecular ordered architectures in this material, in order to obtain high carrier mobility. Good alignments of molecules in established orientation is fit in for intermolecular charge migration and also for a productive charge transport, necessary for a new generation of device [14-16]. During the research of organics, a lot of studies were made to obtain highly crystalline films [17-18]. The FETs, RFID and organic emitting diodes characteristics likewise, depend on the film morphology [19]. Here we report on the OFET particularities of pyrrolo compounds [7,8] including correlation between morphology structure and performance of electrical measurement.

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2 Materials and Methods

Fig.1 shows the structure of pyrrole derivatives. Their synthesis is presented in literature [9-13].

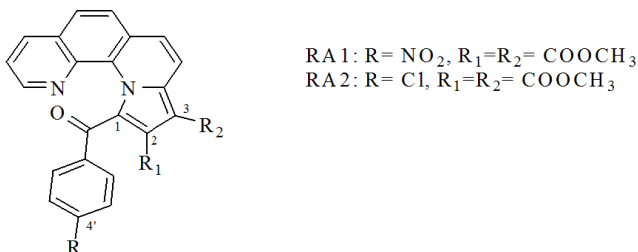


Fig. 1 Chemical structures of examined compounds

The structures of RA1 and RA2 compounds were studied first by NMR spectroscopy. The signals of the protons have been assigned in accord with the current data presented in literature [9-14]. Therefore, ¹³C nmr spectra for RA1-RA2 compounds were improved and results certified the chemical structures [15-17].

The electrical properties of the FETs were measured in vacuum. We used a measurement system formed from two Keithley source meters. For surface structure characterizations, the semiconducting materials were spin coated onto quartz-glass substrates simultaneously with the FET devices. The surfaces morphology of the films have been obtained utilizing an AFM, working in non-contact method. The AFM measurements were made in air at ambient temperature.

The thickness and index of refraction of films have been obtained used an Ellipsometer who works at 632,8 nm wavelength. The thickness of the thin films has been compared with data obtained with a Dektak Profilometer, which has the ability to measure the structure down to a few nm. UPS measuring have been effected at BESSY (Berlin) [7]. A toroidal grating monochromator was used (range of photon energy - 5 to 190 eV) [7]. The photoelectrons were added together with a special spectrometer system at room condition. Pending the experiment the pressure had a constant value, 2×10^{-10} mbar [7].

3 Results and Discussions

We have previously reported UPS measurement of compounds RA1(a) and RA2 (b) and their mathematical simulations for two incident photon energies [7]. We found a good arrangement amongst experimental and theoretical results [7, 15-18]. In the case of our two compounds, the emission is producing especially by π -orbitals [7, 8].

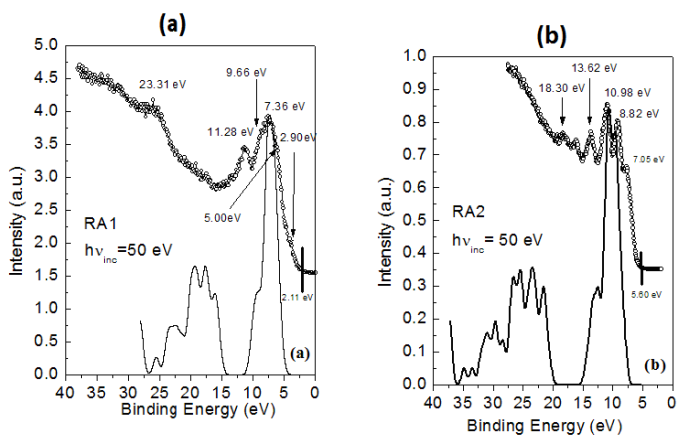


Fig. 2 UPS valence band spectra of compounds RA1 (a) and RA 2 (b) at 50 eV incident photon energy. Experimental-symbol line; simulated spectra-full line and energetic diagram for RA derivatives.

The HOMO levels were established utilizing the onset potential of the oxidation process of RA1 and RA2 compounds [7-8] and this are comparing with the UPS results. The onset of oxidation appears at 0.9 V and 0.8 V, who fulfill to E_{HOMO} values of -5.25 eV and -5.40 eV determined and shown by UPS measurement. Thus the HOMO levels of the active layer fit well with work functions of gold used as electrode. These correspond to a good hole injection in device. FETs were manufactured utilizing the bottom contact geometry (Figure 3c).

The channel's length is $L = 100 \mu\text{m}$ and the width is $W = 500 \mu\text{m}$. The top electrodes (source and drain) were fabricated from gold coated by thermal evaporation by means of precise shadow mask. Silicon oxide was used as a dielectric (150 nm).

The thin films were spin coated the organic semiconductor onto a cleaned SiO_2 , glass and quartz-glass surfaces and device from a solution 5% dimethylformamide (DMF) in the meantime, in order to study the morphology of layers.

Thus, the pyrrolo phenanthroline derivatives are organic semiconductors, which are enabling for the solution processing. They can dissolve well in organic solvents (DMF, chloroform or chlorobenzene).

We found that such compounds can be used for spin-coating, stamping and printing. In Table 1 are shown the solubilities of phenanthroline derivatives in different organic solvents solutions.

Table 1 Stability and solubility of phenanthroline derivatives in organic solvents

Solvent solution	phenanthroline derivatives
Acetone	Partial soluble/instable in solution/weak films
Chloroform	Soluble/instable in solution/fair films
Ethanol	Partial soluble/ instable in solution/fair films
Chlorobenzene	Soluble/stable in solution/fair films
Dimethylformamide	Soluble/stable in solution/ good films

We fabricated test chips made by doped silicon with an aluminum metallized back serves like the gate electrode, in order to obtain a good electrical characterization of the organic semiconductors (see Fig. 3b). The FET device is completed by spin-coating the organic material. After deposition the test chip was investigated by microscopy methods in order to observe the quality of electrodes and to measure channel length and width. The thickness determined by AFM and Ellipsometry was in range of 10 - 100 nm. (Figure 3a).

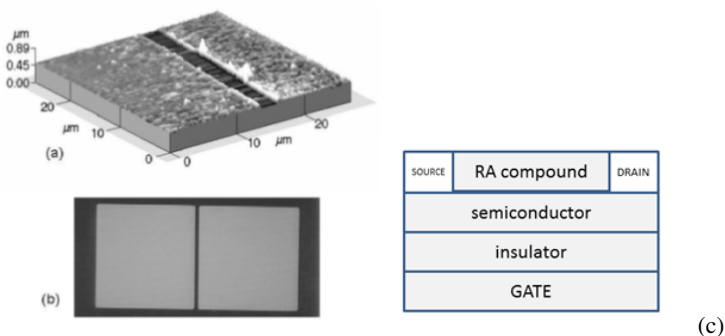


Fig. 3 AFM Electrodes investigation (a) AFM investigations of transport channel, (b) top view of chip. FET bottom contact geometry (c).

The electrical particularities of OFETs depend strongly on the molecular alignment in the film and on the injection of charge from the gold contacts [17-18]. The AFM micrographs of the phenanthroline films described morphologies which vary with spin speed (see Figure 4).

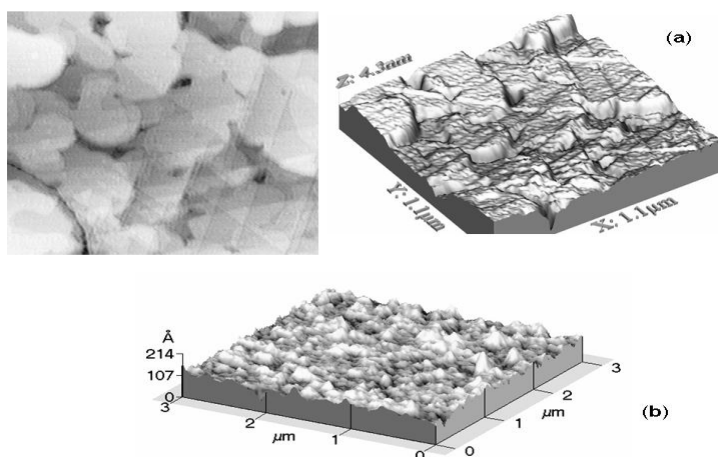


Fig. 4 Surface morphology of phenanthroline derivatives films (a) 3000 rot/min speed spin, (b) 1500 rot/min speed spin

By AFM investigation, was found the preferred crystal orientation in all phenanthroline films. This is due, probably, because of spin-coating direction. The grains are big in dimension, in range of 20 – 160 nm. They are isolated by little grain boundaries.

We observe smooth surface in all investigated films. Root mean square (RMS) roughness determined by ellipsometry and profilometry measurements is in range of 1 nm and 3 nm. At higher speed in spin-coating process, the RMS values which we achieved denote a smoother surface. The typical relief of a phenanthroline derivatives film on a SiO_2 layer is shown in Fig. 4. The layers thick films were investigated by X-ray diffraction. The spectra does not show Bragg peaks because, probably, an insufficient crystallinity of the layers. Also this observation can confirm that domains with different inclination angles are present in the film.

The thin-film transistors of RA1 – RA2 presented typical p-channel characteristics. At a negative bias applique, the drain–source current scaled with the negative gate voltage because of the grown number of charge carriers, holes in our situation. The produced curves at various gate biases and the transfer curves at steady V_D for the phenanthroline derivatives films are shown in Figure 5. The output characteristics show a good saturation region.

We calculate the field-effect mobilities in the saturation regime at a drain voltage of $V_D = -50$ V, the capacitance of the SiO_2 insulator C_i is considered 12.3×10^{-9} F cm^{-2} and the value of V_G is the gate voltage and V_T threshold voltage are from experiment.

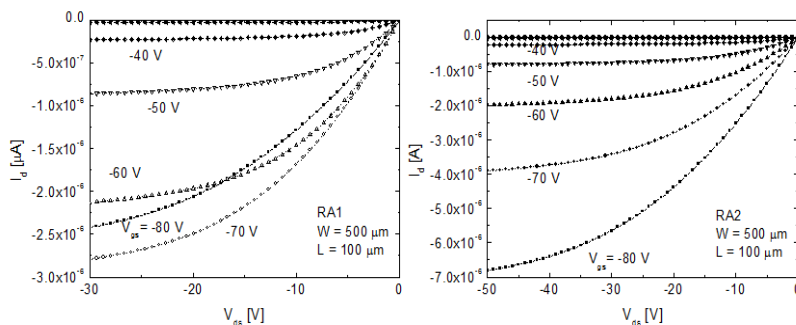


Fig. 5 Output characteristics of the RA1-2 devices at various gate biases

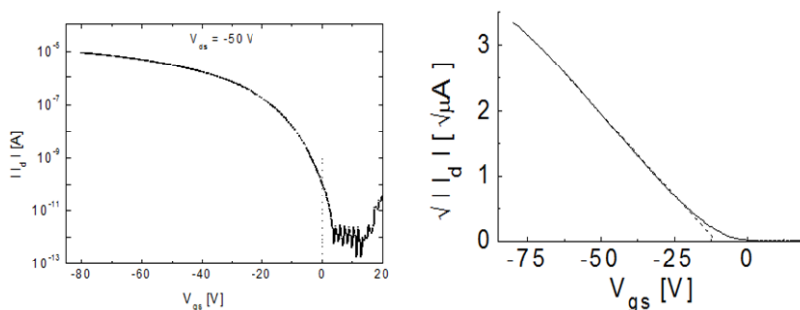


Fig. 6 Plots of the transfer at steady $V_D = -50$ V and semilogarithmic and plot of $(-I_D)^{1/2}$ versus V_G

The FET devices were determined in air and the results are presented in Table 2.

Table 2 Field-effect mobility (μ_{FET}) and threshold voltage (V_{th}) for RA devices at 25°C substrates temperature

Material	T_{sub} [°C]	μ_{FET} [cm ² V ⁻¹ s ⁻¹]	I_{on}/I_{off}	V_{th} [V]
RA1	25	0.008-0.006	10^7	-18 to -14
RA2	25	0.031-0.020	10^7	-14 to -11

The phenanthroline derivatives devices showed hole mobilities of in range of 0.0006 – 0.031 cm² V⁻¹ s⁻¹ and threshold voltages of –18 V and –11 V. The performances of the RA derivatives devices may be due to the right fit amongst the ionization potential of each phenanthroline derivatives and the work function of the gold electrodes. To obtain the smaller channel length of device in order to increase the speed function, the gold contacts (source and drain) must cover the gate contact, but in this way we get large capacitance. To understand the impact of

this capacitance on performance, measurements were performed on devices with 300 μm overlap (fig. 7). As expected, the overlap capacitance causes substantial roll-off at 10 kHz, which is reasonable for 135-kHz RFID.

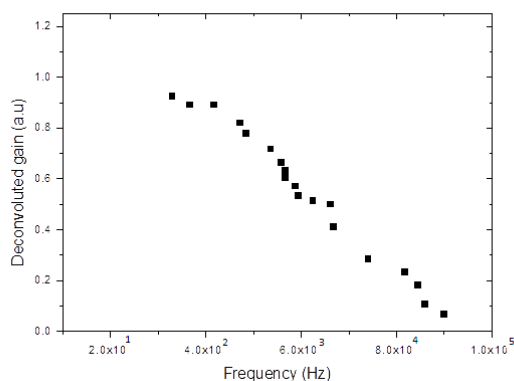


Fig. 7 AC performance of devices with 300 μm overlap

The FET particularities of OFETs depend, in the first case, on the molecular alignment in the film and on the injection of holes from the electrodes. We assume that the molecules are aligned perpendicular to the substrate and the π - π superposition amongst close molecules is increased at maximum and carrier transport can exist. The rigidity and planarity of RA compounds can give a high crystallinity and vertical alignment into the reasonable and efficient molecular orientation. In principle, for such organic compounds that present great mobilities at the highest substrate temperatures because the grain dimension tends to grown and the number of grain boundaries tends to decline with increased temperature [19]. Unfortunately, the OFET devices made from phenanthroline derivatives showed a weak stability after 15 days in air.

4 Conclusions

We have studied new semiconducting organic materials containing different radicals group and manufactured OFETs utilizing those materials as active layer. Because of the expanded π -conjugation, productive charge injection, and right alignment of the molecules, the phenanthroline devices showed hole mobilities in range of 0.0006 - 0.031 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$. In phenanthroline films, the carriers, holes in our case, move effectively, and thus the FET particularities are efficient, when the molecular orientation favors π - π superposition and the grains are big in dimensions and isolated by little grain boundaries. The molecules aspired to align approximately perpendicular to the substrate, which favors π - π overlap between close molecules. Furthermore betterment in FET performance may be possible by improving the manufacturing conditions – using various substrates temperatures and the surface treatment in order to improve the orientation of molecules.

Our new organic transistors are promising for construction of integrated circuits on thick flexible polyester substrate, using methods compatible with printing processes for mass production. These circuits can be used in optoelectronics, mobile and radio frequency identification (RFID) applications.

We can mention here few advantages as a good and easy processability, a good chemical control concerning the injections of the charge, a good fit in with plastic substrates, and reduced production price

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