Comparisons Among p-Channel, n-Channel and Mixed n/p -Channel OTFTs

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Abstract - **Some theoretical approaches of an alternative organic semiconductor device are presented in this work. The Organic transistors are based either on n-type or p-type or mixed p/n overlapped layers. The carrier modulation insides different films is carried out by two gates electrodes, as is usual in the thin film transistor field. This paper introduces some novel aspects for these kinds of organic transistors, selecting a suitable biasing regime. The simulations emphasize a stronger influence on the static characteristics when the superior gate is acted. One of the novelties of this paper concerns the electrical conduction occurrence by two simultaneous channels, in comparison with one volume channel conduction, for different gate voltage regimes. A similar work regime is also encountered in the SOI devices with ultra-thin films that develop a volume channel. The volume channel regime is advantageously when the technology of fabrication of the organic semiconductors on different insulators provides an extremely charged interface, which can degrade the surface currents. Comparisons and applications for both situations - with one volume channel or two accumulation channels - are finally discussed. The vertical n/p junction arose between the upper n-channel and the bottom p-channel, offers novel physical properties and prevented any interaction among channels. The device simulations revealed multiple behaviors, depending on the Top and Bottom Gate voltages, if a positive drain-source voltage is applied.**

Keywords: *organics transistors, thin films, simulations, alternative materials in electronics.*

I. Introduction

The organic technology provides facile methods of the thin film transistors manufacturing, at room temperature processes as inkjet printing, sol–gel process, roll-to-roll printing, which provides low cost technologies, against the classical lithography from the silicon technology, [1-3].

Even with the last years rapid progress in the organic materials manufacturing [4], an Organic Thin Film Transistor (OTFT) with better characteristics than a Metal Oxide Semiconductor Field Effect Transistor (MOSFET), rests a major issue, [5].

For example, the Organic MEtal Semiconductor Field Effect Transistor (OMESFET) developed by another researcher group [6], operates at lower voltages than usual OTFT, with better ON/OFF current ratio, but only use the conduction thru a channel with p-type conduction, [6]. The well-known technologies of the Pentacene OTFT transistors frequently demand conduction thru a p-type organic layer, except for a few low band-gap organic polymers. Recently, other authors claim that n-type conduction can be used in conjunction with convenient organic gate dielectrics [7], even in special low band-gap organic semiconductors, where the electrons mobility increases to $0.05cm^2/Vs$, [8].

Till nowadays, the more performant Organic-TFTs are fabricated by the p-type organic polymers, offering conduction regime with accumulation channel. An additional reason for the n-type organic-TFT avoiding is the electrons entrapping at the semiconductor–oxide interface by hydroxyl groups, present as silanols in the usual SiO_2 insulator, [8]. OTFTs with pentacene onto a dielectric polymer layer enriched the drain current excursion from 8nA to 80nA at the same gate voltage biasing, [9].

Therefore, in this paper, a mixed solution - with a p-organic layer on an n-organic layer - is considered to enrich the current way. The source to drain conduction is possible by accumulation channels [10] or by volume channels, [5]. In this paper we take into account the possibility to ensure a superior conduction by the superposition of both these two mechanisms. The polyimide material is considered as buried organic insulator and the oxide material is considered as the upper insulator, for the proposed Organic-TFT. The compatibility between the circuit integration technology and the surface oxide is wellknown, while the matching with polyimide material was proved elsewhere, [11]. The expected results envisage a larger current capability by a suitable work regime and alternative functions for these transistors.

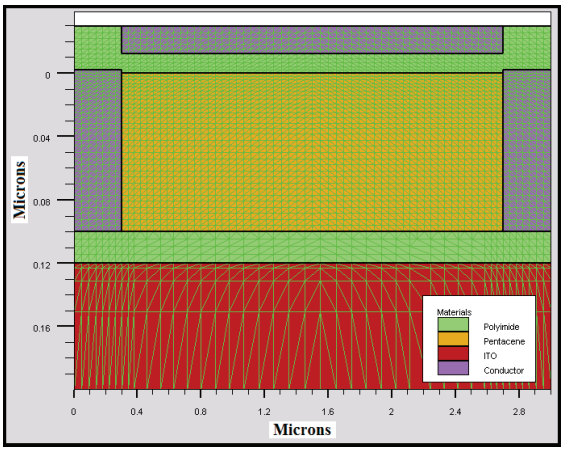
II. The Devices Structure And physical Parameters

This organic thin film transistor also belongs to the Semiconductor on insulator SOI transistor class [12], due to similar configuration with sub-100nm organic films placed onto an insulator support from polyimide. Therefore, the back and front gates from SOI architectures [13] are labeled here as bottom and top gates, to be in agreement with the TFT terminology, [6, 7].

The investigation software tools from this paper involve the Atlas 2D from Silvaco, adapted for our OTFT device. In fig. 1.a is presented the proposed structure besides to the mesh for a sole p-channel transistor or similar

for n-channel and in fig. 1.b is presented the adopted structure with mixed n/p channels with modified geometry. In this last case, the structure gathers an accumulation current localized at the upper interface with oxide and with the inferior interface with polyimide. In this way, multiple conduction routes occur: by upper n-channel and bottom p-channel. However, the metallic shortcut on the vertical direction, achieved by the deep source and drain contacts, ensure a zero current within the pn junction on the Oy axis.

From the material point of view, the organic semiconductor can be depicted either as the default pentacene from the Atlas library [14], or as optimized organic semiconductors from literature [15] simply labeled as Organic.



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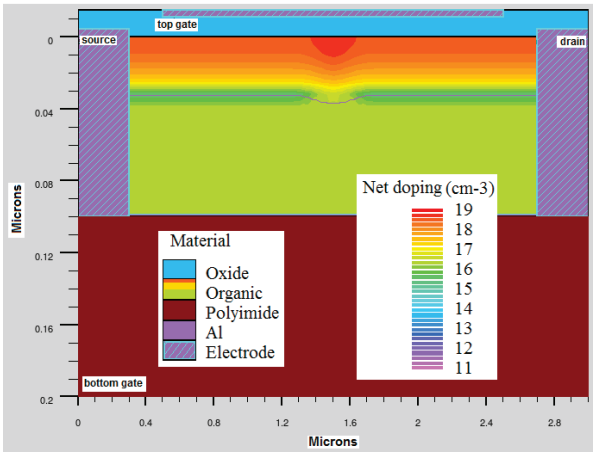
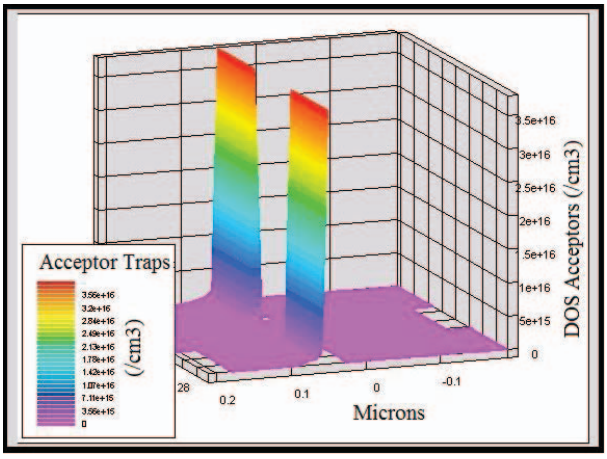


(b)

Fig 1. Materials and doping profile within the O-TFT with (a) sole p-channel; (b) mixed p/n-channels.

In the literature, the carrier motilities inside the organic semiconductors are typically of 0.1...1cm^2/Vs, or more, [16]. We considered an average value of 0.8cm^2/Vs in these simulations. In order to make possible both electrons and holes charge transport, the Lowest Unoccupied Molecular Orbital (LUMO), besides to the Highest Occupied Molecular Orbitals (HOMO) - energy levels must be localized as close as possible and the gate dielectrics must suppress the electron capture at the organic-dielectric interface.

In order to be closer to a real behavior, in this paper, the the Density Of States (DOS) are distinctly defined at the organic semiconductor / polyimide interface by for ionized acceptor states - g_A=3.75x10^{16}cm^{-2}, fig 2.a, and ionized donor states g_D=9.5x10^{16}cm^{-2}, fig. 2.b, [17].



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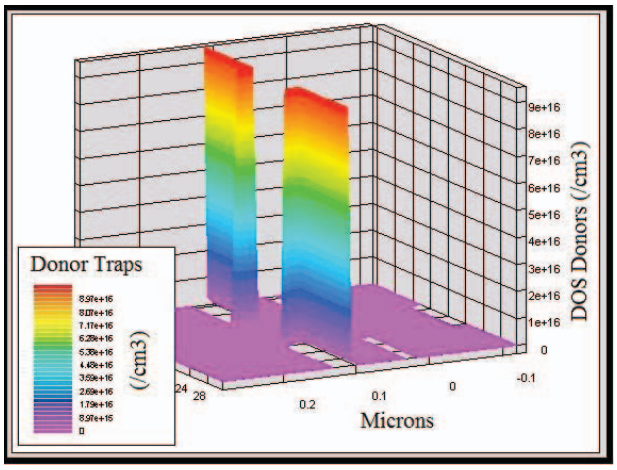


(b)

Fig. 2. The ionized states density taken into account in simulations: (a) for acceptors; (b) for donors.

For the presented OTFT structure, the aluminum contacts provide a Schottky barrier, while the gold contacts offers better ohmic contacts and they are finally included in simulations. Also the simulations show a strong dependence of the contact resistance on the doping concentrations in the n or p type layers. On the other hand, the contact resistances are variable for different gates biasing, due to the carriers concentration ranging, [15].

The physical parameters of the standard pentacene, noted as Pentacene [14], enhanced new organic semiconductors noted as Organic [15, 19] and polyimide as insu-

lator [20] are included in the Atlas models by the "material" instruction and centralized in table 1. Those parameters that are missing from table 1, for pentacene, organic or insulators, get the default values from the Atlas library, [14]. The sizes and doping concentrations of each layers are selected from a real organic technology [11-21], and they are indicated as main references in table 1. The n-type layer is defined by a Gaussian doping concentration, with a maximum value of 10^{19}cm^{-3}, while the p-type substrate has 10^{17} cm^{-3}.

TABLE I.
INITIAL DEVICE CHARACTERISTICS

Material	Thickness (μm)	E_G (eV)	Mobility (cm^2/Vs)
n-Pentacene	40 [15]	2.11 [21]	1x10^{-5}, [21]
p-Pentacene	60 [9]	2.11 [21]	4x10^{-4}, [21]
n-Organic	40 [15]	1.20 [19]	0.80 [15]
p-Organic	60 [9]	1.21 [19]	0.80 [15]

III. FIRST ATLAS SIMULATIONS

The Atlas input file is prepared to simulate electrical conduction thru organic materials, activating some key parameters in the "model" instruction: pfmob singlet langevin, to activate the Poole-Frenkel mobility model and the Langevin recombination for the existent carriers, [14].

In Atlas 2D output files, the drain currents are expressed in Amperes per 1μm, as default depth. Therefore, in our simulations, the current densities are more relevant than the currents itself.

The potential distribution over the mixed OTFT structure is presented in fig. 3, accordingly with an expecting work regime, for low positive drain voltage and negative top-gate voltage and also negative bottom-gate voltage. In another work regime, the drain voltage is increased, when the mixed device is biased at V_S=0V, V_D=40V, V_{TG}=-10V and V_{BG}=30V, the maximum electric field occurs on a 0.2μm length of oxide, between the edges of top gate and drain electrodes.

Subsequently, the maximum electric field reaches 2.5x10^{6}V/cm, still lower than 1.1x10^{7}V/cm, but under increasing alert for the critical electric field in the right corner of the oxide, near the drain contact. Hence, a limit drain voltage can be +40V ... +50V to avoid the breakdown. A thicker polyimide provides a lower residual current thru polyimide versus oxide, at the same voltages. For the device safety, the gate currents are monitored. After simulations, the top and bottom gate current densities posses few order of magnitudes lower than the drain current, so far away from the breakdown conditions and far away from the loss of the gate control.

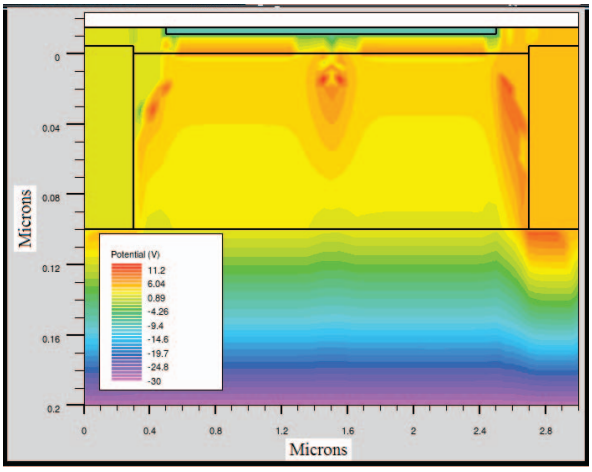
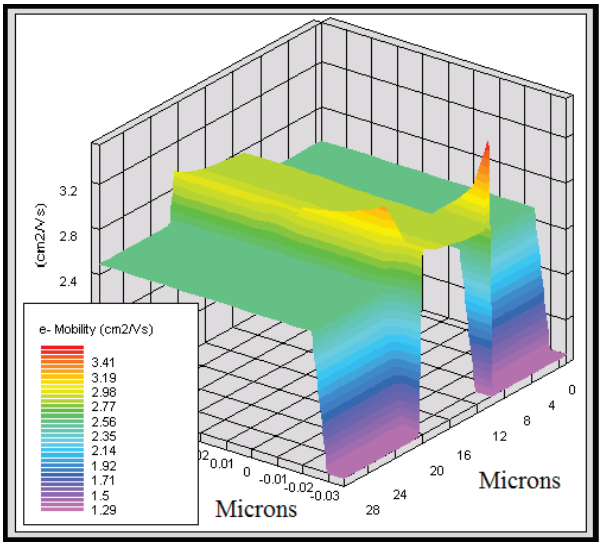


Fig 3. The potential distribution at V_S=0V, V_D=+4V, V_{TG}=-10V and V_{BG}=-30V in mixed OTFT.

Because the mixed OTFT structure comprises a vertical n/p junction, two types of electrical carriers ensure the longitudinal conduction, as in any pn junction.

A top gate biased at negative voltage can foster the holes accumulation. An additional negative bottom gate voltage enhances the holes accumulation, while positive bottom gate voltage depletes the p-type film, fig. 3. Holes accumulation occurs near the polyimide interface for V_{BG}=-30V, up to 2x10^{18}cm^{-3}, higher than the native doping concentration of 10^{17} cm^{-3}, while holes accumulation occurs near the oxide interface for V_{TG}=-10V, up to 9x10^{19}cm^{-3}. In this case, an electrons volume channel coexists with the upper holes surface channel, near the source vicinity. The work regime with positive top gate voltage provides two conduction channels, near oxide and polyimide interfaces, depending on the bottom gate biasing.

Figure 4 presents a comparison between the electrons and holes mobility, under usual biasing conditions.



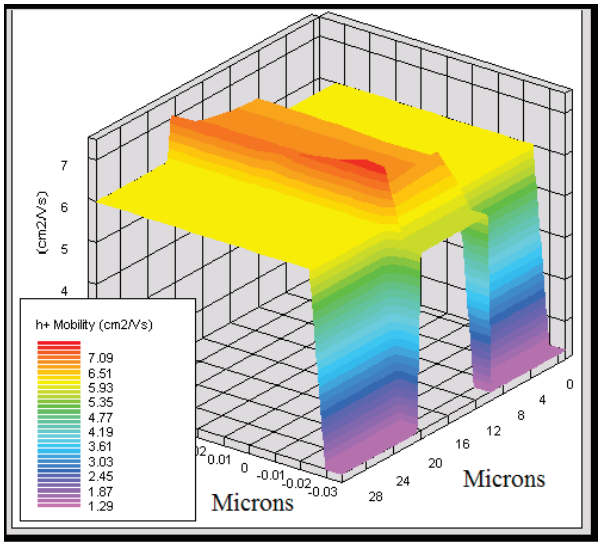


Fig 4. The electrons and holes concentration for different top and bottom gate voltages.

The specific models included in Atlas to capture the organic semiconductors becomes obviously, due to the results with higher holes mobilities and lower electron mobilities (opposite to the inorganic semiconductors), as is specifically encountered in literature, [22].

IV. Statistic Regime Analysis

The output characteristics simulations, I_D-V_{DS}, consists in drain-source voltage ranging from 0V to positive values at maximum +40V, keeping a negative bottom gate voltage and associating different top-gate voltages, fig. 5. In the simulations from fig. 5, the organic semiconductor noted by organic, is envisaged. The current decreases when the negative top or bottom voltages increase in modulus, due to the n-channel diminishing.

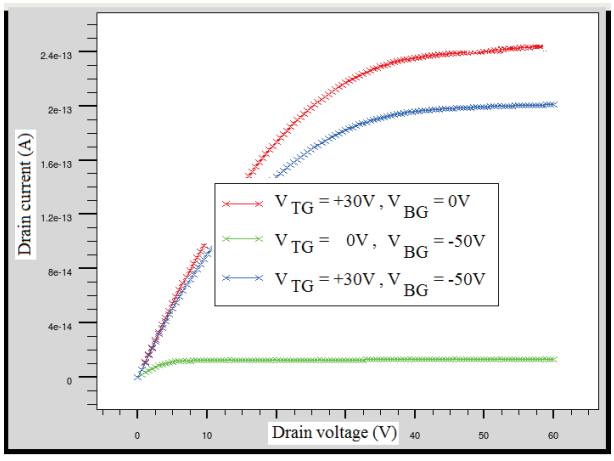


Fig 5. The output characteristics at different top and bottom gate voltages.

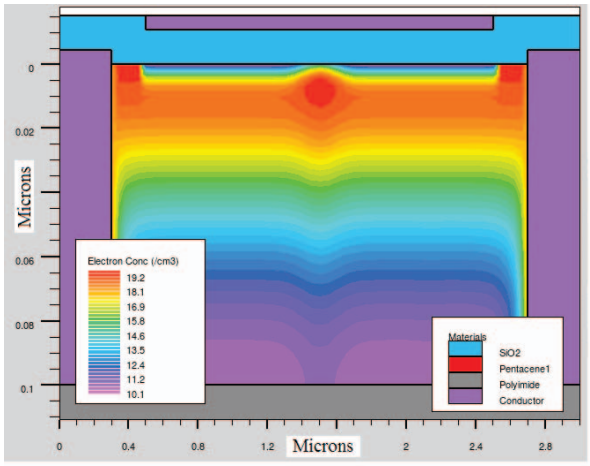
Selecting the optimum "organic" semiconductor, the drain current reaches in the saturation region for a saturation voltage, V_{DSat} of minimum +5V and maximum +42V in fig. 5. The maximum drain current reaches a value of 2.38 x10^{-13}A that is 2.3 times higher than in a previous analysis [11], when I_D was 100fA. Now, the maximum saturated drain current of 238fA occurs for V_{TG}=+30V, V_{BG}=0V, instead old conditions for V_{TG}=+10V, V_{BG}=+50V.

In this study results that a higher positive top gate voltage produces higher drain currents. A lower dependence of the drain current on the bottom gate voltage is simulated.

V. Discussions

The applications of the proposed OTFT are in agreement with the applied voltages in each work regime. Because the n and p layers posses different doping concentrations, the conduction thru the longitudinal n-channel is stronger than the conduction thru the longitudinal p-channel.

The conduction superiority has to be established by the static characteristics analysis, forcing the device to use a p-type channel or a n-type channel. This evolution is emphasized once for a maximum electron concentration reached deeply in the n-type film of 10^{19}cm^{-3}, but rather closer to the oxide layer, fig. 6.a.



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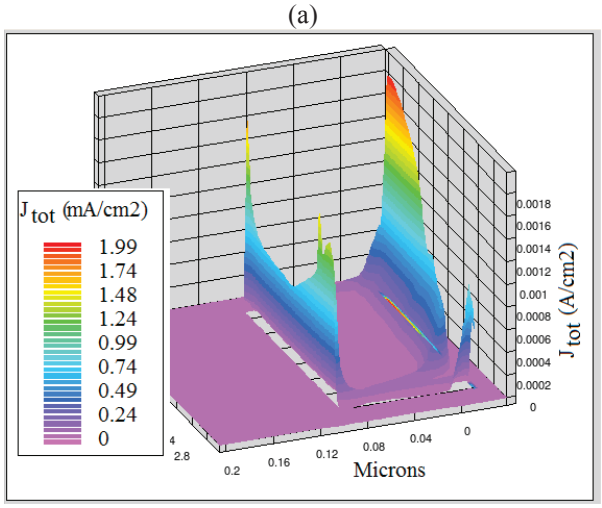

(b)

Fig 6. The electron concentration through the proposed OTFT with overlapped channels as contours traces proving a thin volume channel onset ; two accumulation channels onset at V_S=0V, V_D=40V, V_{TG}=10V.

When positive voltages are applied on both gate terminals, two accumulation channels occur near the interfaces with oxide and with polyimide, fig. 6.b. This work regime with two simultaneous channels acted by two gates represents the main explanation to support a 2.3 higher drain current during the saturation regime.

If the positive voltage is applied on the top-gate, ($V_{TG}>0$), the electron concentration increases in a thin volume channel, at 10nm close under the upper oxide interface (where $n >10^{19}cm^{-3}$), offering the specific volume channel conduction way [4], with a maximum of efficiency now, 2.3 times higher drain current. Weather the work regime is changed ($V_{TG}<0$ or $V_{BG}>0$), the holes channel is onset within the p-type layer and systematically the hole current density rests much lower than the electron current density, due to the initial asymmetry in the doping concentrations. To capture an as favorable as possible work regime for the holes transport, it is necessary to invert the biasing (e.g. for $V_{TG}>0$, $V_{BG}<0$), to increase the hole concentration $p>10^{19}cm^{-3}$ near the polyimide interface, so that two distinct accumulation channels occurs and both get the same order of magnitude for the current density, $j_{p,\ n}$ = 1.2 ... 1.8 mA/cm^2, fig. 6.b. The localization of these two channels is near the oxide interface and near the polyimide interface. In this case, the vertical n/p junction is reverse biased, with two depleted regions, n-type and p-type that touch each other by the median coordinate of the organic mixed layers. This reverse bias prevents any leakage between the upper n-channel and the bottom p-channel, ensuring a firm behavior of the device.

Some comparisons of the main voltages and saturated drain current for the proposed device biased at $V_{TG}>0$, with similar organic thin film transistors, are presented in table 2.

TABLE II.
THE OTFTS DEVICE PARAMETERS

Parameters	**$\|V_G\|$ (V)**	**$\|I_{D,\ max}\|$ (pA)**	**V_{Dsat} (V)**
Actual OTFT	1 ... 30	0.238	2…42
Other OTFT	17... 33 [22]	0.102 [11]	24…54[21-29]

The studied organic OTFTs are suitable for the industrial low power display, due to a low drain current consumption, versus other variants, [22]. Also the organic devices are suitable for any biomimetic applications, which require carriers mobility under 0.1cm^2/Vs, [24] and transducer with organic materials as biocompatible interfaces, [25-29].

The volume channel regime is advantageously when the technology of fabrication of the organic semiconductors on different insulators provides an extremely charged interface, which can degrade the surface currents.

VI. CONCLUSIONS

This paper studied some new configurations of Organic Thin Film Transistors, which usually used a sole p-channel, or a sole n-channel. When a mixed structure with n-type layer on a p-type layer was used in the organic semiconductor region, some novel kinds of conduction channels occurred. The vertical n/p junction arose between the upper n-channel and the bottom p-channel, offers novel physical properties and prevented any interaction among channels.

The device simulations revealed multiple behaviors, depending on the Top and Bottom Gate voltages, if a positive drain-source voltage is applied.

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