Organic Thin-Film Transistors Modeling; Simulation and Design of a Fully Organic AMOLED Pixel Circuit

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***Abstract*—In this paper we implement the simulation and design of a fully organic AMOLED pixel in which OLED current driving and pixel selection is performed by organic thin-film transistors (OTFTs). An empirical SPICE-like OTFT model has been developed. A pixel with sandwich structure in which the OLED is deposited on top of the rest of the circuit has been simulated and designed.**

Keywords-Organic Thin-Film Transistors; OTFT; modeling; SPICE; simulation; AMOLED; Pixel

I. Introduction

The development of Organic Thin Film Transistors (OTFTs) has been remarkably progressed since early 1990s. During the recent years, thanks to the progress in the field of material chemistry and device optimization, the performance of organic transistors has significantly improved [1]. The charge carrier mobility, one of the OTFTs' main performance indicators [2], has increased over several orders of magnitude during the last 20 years, reaching values up to 0.1-10 $cm^2.V^{-1}.s^{-1}$ for various materials. However, the low conductivity of organic materials makes OTFTs to resemble more closely to amorphous silicon thin-film transistors (a-Si:H TFTs) rather than to the conventional crystalline silicon metal-oxide-semiconductor field effect transistors (MOSFETs). The interest towards the development of OTFTs (and organic electronic devices in general) is due to the possibility of low cost and low temperature deposition of organic materials which provides compatibility to plastic substrates and printing deposition techniques. Consequently, due to the recent advances in their performance, OTFTs are gaining more and more attention in large area electronics applications such as RFID tags and AMOLED displays.

The increasing interest towards OTFTs raises the need of SPICE-like OTFT modeling to provide the simulation and analysis of OTFT-based circuits. Such models should be accurate enough to ensure the functionality of OTFTs while simple enough to be executed on usual simulation platforms.

II. Evaporated Pentacene Bottom-gate OTFTs

With the objective to make fully organic AMOLED pixels, we have developed organic thin-film transistors (OTFTs) in a bottom-gate bottom-contact structure, using evaporated pentacene as the active layer [3, 4]. Benzocyclobutene (BCB) film prepared by spin-coating was used as the gate insulator of the OTFTs. The OTFTs are fabricated on glass substrate and gold (Au) is used for the realization of drain and source contacts, while the gate is fabricated with aluminum (Al). The mean field-effect mobility and the current on/off ratio of the pentacene OTFTs were measured to be 0.25 $cm^2/V.s$ and higher than 10^5, respectively. Electrical stress was applied to check the compatibility of pentacene OTFTs for AMOLED displays. After 11.5 days of stress, the off-current was even reduced and the mobility drifted less than 5%. The electrical performance of the fabricated pentacene OTFTs is thus sufficient for application in OLED addressing.

III. OTFT Model Specifications

Since *G. Horowitz* and *P. Delannoy* have introduced their analytical model for OTFTs in 1991 [5] many efforts have been made to provide appropriate model simulations for OTFTs [6, 7]. However, due to the still incomplete knowledge of the nature of the carrier transport mechanism in organic semi-conductors, efforts to develop appropriate models to describe OTFTs' characteristics are still scarce [8]. Moreover, these rare models are still far away from representing OTFTs in usual circuit analysis (due to their incompleteness and/or their complexity that implies convergence issues and/or long computation time).

It is known that OTFTs' current-voltage characteristics are mostly similar to those of amorphous silicon based TFTs (a-Si:H TFTs). This fosters the idea that modifying the existing models for a-Si:H TFTs is a good way to represent

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the characteristics of OTFTs [9]. In order to perform such modifications several model fitting parameters should be introduced and extracted from the device characteristics.

We have developed our basic model, which we aim to evaluate up to a specific SPICE-like OTFT model, in Verilog-A language and based on an adapted MOSFET model for amorphous silicon TFTs (AIMSPICE Level 15) [10]. It is also provided with a complete and efficient parameter extraction procedure.

Applying the extracted parameters into the model, the result of simulation would represent the general functionality of the OTFTs. The mismatch would be due to the fact that although a-Si:H TFTs show the nearest characteristics to our OTFTs the physical mechanisms of the two devices are still too different. Further parameter fitting would be thus needed in order to better represent the characteristics of the OTFTs. For this, we have used the Agilent's ICCAP (Integrated Circuit Characterization and Analysis Program) software [11]. Applying parameter values resulting from the fitting step into our model, the simulation result is reasonably close to the experimental characteristics. The model was capable of correctly representing the OTFTs' characteristics in the leakage and above-threshold regimes while its performance in the sub-threshold regime was more critical. Thus we have replaced the equations describing the drain-source current of the OTFT in the sub-threshold regime with those of the Polycrystalline TFT model where the current dependence in gate-source voltage is introduced by a power law expression as follow:

$$I_{sub-threshold} = \frac{W}{L} C_{ox} \mu_{sub} \left(\frac{k_B T}{q}\right)^2 \exp\frac{q(V_{GS} - V_{FB})}{\eta k_B T} \left(1 - \exp\frac{-qV_{DS}}{\eta k_B T}\right) \quad (1)$$

in which W and L are the channel width and the channel length, C_{ox} is the dielectric's capacitance per area, V_{FB} is the flat-band voltage of the transistor, and η is a parameter concerning density of states in the semiconductor. In this expression, having the dimension of mobility ($cm^2.V^{-1}.s^{-1}$), μ_{sub} does not represent the charge mobility in this regime.

Although the model showed a better behavior, it still needs improvements in this regime to better represent OTFTs. The results of the application of our model to our pentacene OTFTs are shown in Fig. 1 and Fig. 2.

Fig. 1.a shows the application of our model to an OTFT with (W/L = 100 µm / 10 µm) after a fitting procedure on the device's transfer characteristic using the ICCAP software. Fig 1.b represents the relative simulation error rate according to the measurement data in percentage. It can be seen that the error rate is limited to 6% (except for a few points in the leakage regime which is not critical).

The reproduction of device characteristics is not sufficient to justify the use of the model in circuit design. For that, the model should also be able to predict the characteristics of devices with similar functionality but different physical or bias conditions. A model verification procedure should thus be introduced in order to justify the predicting capability of the model. We have examined a two step model validation procedure. First we have analysed the model including fitted parameters (using a transfer characteristic of a specific transistor) on another transistor with different bias conditions. Then the model has been checked to respond to change in physical dimensions of the transistor (while maintaining the same values for other parameters). The results of these tests are shown in Fig. 2.a and Fig. 2.b, respectively.

As it can be seen in Fig. 2 the model can represent and predict correctly the OTFTs' behaviour in the leakage and the above-threshold regimes while its functionality remains critical in the sub-threshold regime. Fortunately this does not affect the simulation of our OTFT-based pixel circuit in which OTFT transistors are only biased in the leakage or the above-threshold regimes (they are either turned ON or turned OFF). We can thus apply the introduced model in order to simulate our pixel circuit.

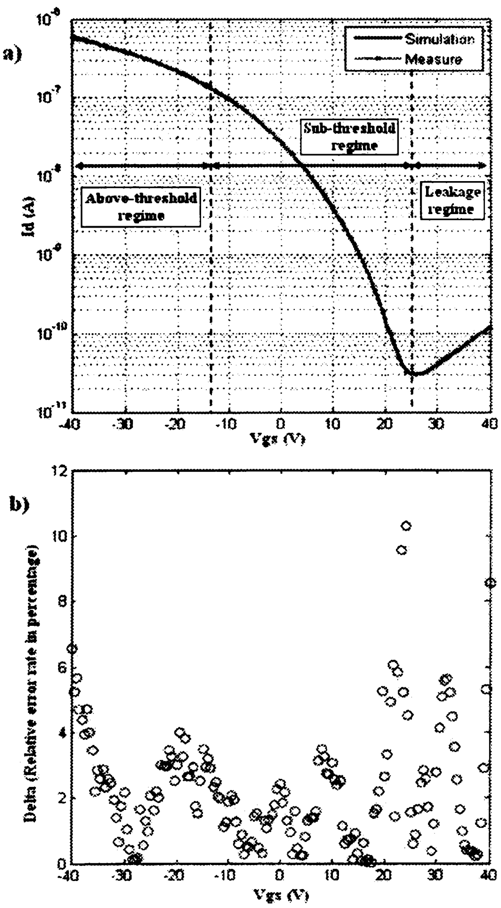

Fig. 1. Application of the model on a OTFT with W/L= 100 µm / 10 µm and V_{ds}= -20 V: a) Transfer characteristic from the simulation result and experiment, b) the relative error rate between the simulation and the measurement results (in percentage)

IV. Pixel Circuit Design

A. The Pixel circuit

Our objective is to design an 8×8 pixel matrix using totally organic display pixels in which OLEDs are driven in each pixel by two OTFTs. A schematic view of a unit active matrix pixel circuit is shown in Fig. 3. Here, V_{data}, V_{select}, V_{cap}, V_{dd} and V_k mean data voltage, selection voltage, capacitor voltage, power supply voltage, and cathode voltage, respectively. The pixel consists of an organic light emitting diode (OLED), a storage capacitor and two organic transistors (which are p-type): the switching transistor (Sw-OTFT) and the driving transistor (Dr-OTFT). The OTFTs are fabricated according to the specifications explained in section II. The switching transistor is turned on by the line selection in the matrix (V_{Select}) while the driving transistor is controlled by the

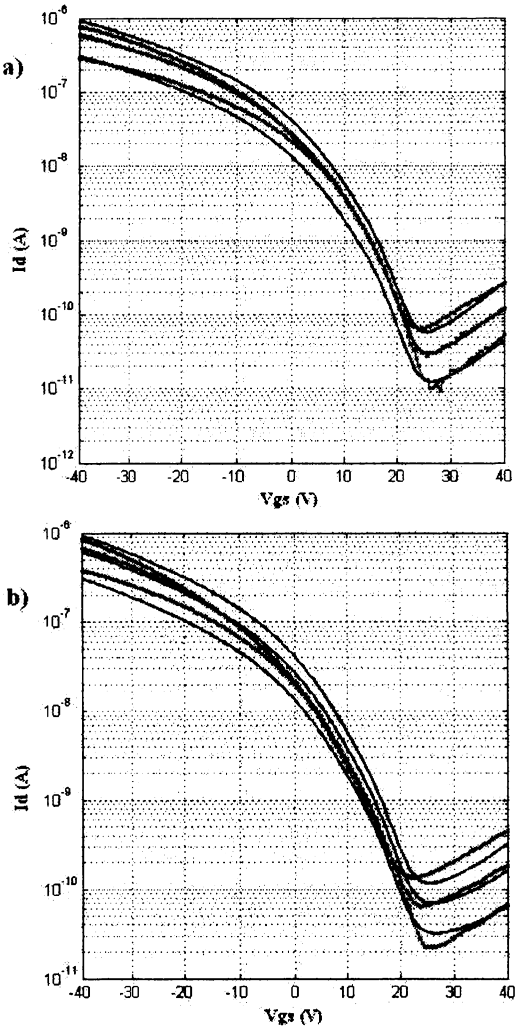

Fig. 2. Model verification: a) Application of the fitted parameters on an OTFT with same W and L but different biases (V_{ds} = -10, -20 and -30 V); b) Application of the fitted parameters on an OTFT with W/L= 500 µm / 50 µm and V_{ds}= -10, -20 and -30 V

column selection of the pixel (V_{Data}). The driving transistor should also provide the OLED current.

V_{data} and V_{select} are the pixel's column and line selection commands in the total display matrix while the main task of V_{cap} is to maintain the driving OTFT ON once the pixel is commanded (after the selection step). During the selection period of a given pixel, the gate-source voltage of the SW-OTFT ($V_{gs1}= V_{select}- V_{cap}$) and thus V_{select}, should be negative enough to ensure the required current for a rapid charging of the capacitance (biased in the above-threshold regime). In addition, during the activation of the driving OTFT, V_{data} should be negative enough in order to ensure that Dr-OTFT turns on (biased in the above-threshold regime). Similarly, during the non-selection of the pixel, V_{select} and V_{data} should be high enough to guarantee that the SW-OTFT and the Dr-OTFT are blocked (they should be biased in their leakage regimes).

The low conductivity of organic semiconductors, pentacene in our case, which turns into low mobility of OTFTs, implies the use of greater OTFT dimensions in order to ensure the required current in the pixel circuit. In the other hand the choice of BCB as the insulator layer requires a big capacitor size in order to ensure the correct functionality of the circuit. However the total size of the whole pixel circuit including the OLED is restricted. We have therefore chosen a sandwich structure in which the OLED is stacked upon the rest of the circuit. Fig. 4 represents the proposed structure.

B. Design criteria

The pixel circuit should respond to the following criteria:

1. The conventional size of a display pixel is limited to 500 µm × 500 µm.
2. An OLED current density greater than 50 mA/cm² would destroy the OLED. A current density of 15-20 mA/cm² would be suitable.
3. The degradation of the OLED current after a total sweep of the pixel matrix should be less than 5%.
4. The *Select* and *Data* command voltages should be as low as possible.

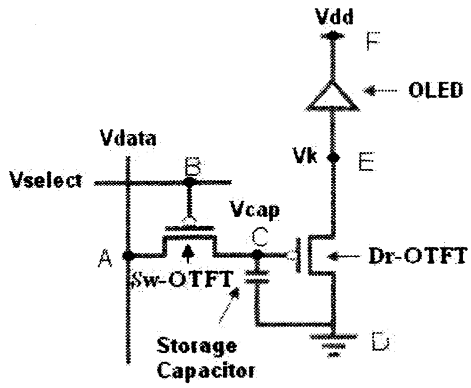

Fig. 3. Schematic diagram of a unit OTFT driven AMOLED pixel circuit.

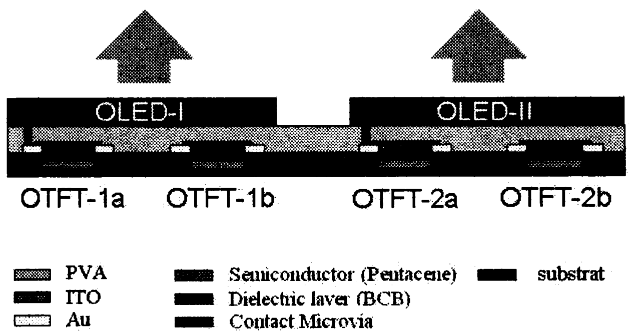

Fig. 4. Layout structure of two adjacent pixels in the sandwich structure.

In view of the above criteria we have designed and tested a pixel circuit with the following specifications:

- The pixel size was set to 400 µm × 400µm which requires an OLED current of 24-32 µA.
- The OTFTs' size was chosen as follow:
    - $(W/L)_{Sw\text{-}OTFT} = 130\ \mu m / 5\ \mu m$
    - $(W/L)_{Dr\text{-}OTFT} = 2500\ \mu m / 5\ \mu m$.
- The capacitor's size was chosen: 360 µm × 360 µm.
- The *Select* and *Data* command voltages were chosen as follow:
    - $V_{Select\text{-}High} = 15$ V, $V_{Select\text{-}low} = -50$ V
    - $V_{Data\text{-}High} = 30$ V, $V_{Data\text{-}low} = -50$ V.

C. *Simulation results*

With the above specifications for the pixel circuit and using our OTFT model we have simulated the pixel circuit in CADENCE environment. We have also used a specific OLED model developed in Verilog-A language [12]. The pixel commands as well as the capacitor's voltage are shown in Fig. 5.a while the resulting OLED current is presented in Fig. 5.b. An appropriate OLED current with 5% of degradation over the whole matrix sweep can be observed in Fig. 5.b.

V. CONCLUSIONS

In this paper we have first developed an empirical model for OTFTs. We have then designed and simulated a fully organic pixel circuit using the developed model. The simulation results show that the designed circuit covers well the desired performance and design criteria.

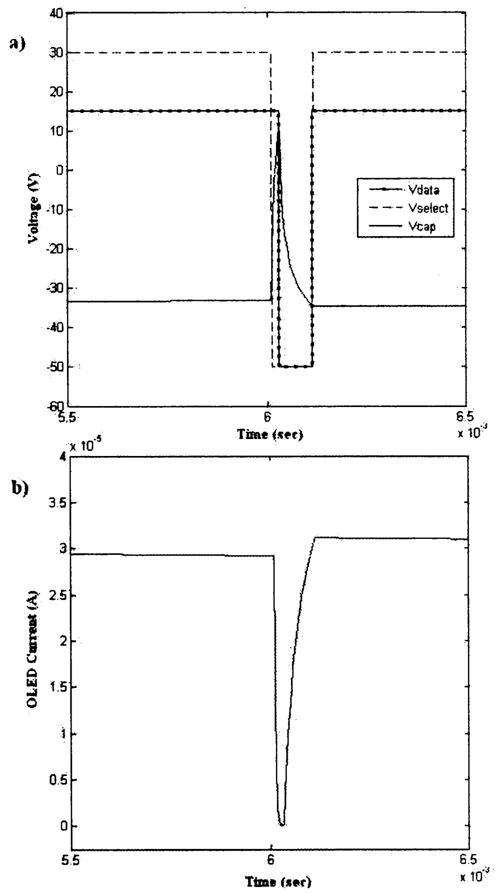

Fig. 5. Simulation results for an OTFT-based AMOLED pixel circuit: a) Command voltages; b) OLED current.

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