Robust Benchmarking Strategy for Organic Thin-Film Transistors

Rodrigo Santos Batista
Centro de Informática
Universidade Federal de Pernambuco
Recife, Brazil
rsb6@cin.ufpe.br

Stefan Blawid
Centro de Informática
Universidade Federal de Pernambuco
Recife, Brazil
ORCID 0000-0001-6982-4575

***Abstract*—Organic thin-film transistors (OTFTs) utilize organic semiconductors to generate electronic responses. Operating with three terminals, these devices control the current flow between the source and drain electrodes by applying voltage to a gate electrode. OTFT technology is evaluated through key parameter reports such as threshold voltage, charge carrier mobility, and series resistance. However, conventional parameter extraction methods adapted for silicon transistors can yield inaccurate results for OTFTs. This study seeks precision in parameter extraction to improve reliability in the production and commercialization of these devices.**

***Index Terms*—Benchmarking, Simulation model, Parameter optimization, Thin-film transistor, Flexible electronics**

I. INTRODUCTION

Ubiquitous computing envisions technology being available everywhere at any time, with flexible electronics playing a crucial role due to their adaptable forms [1]. This enables widespread ambient intelligence, demonstrated in applications such as health, industrial, environmental, agricultural, and structural monitoring [2]. The low cost required for future Internet of Things (IoT) edge devices [3] can be achieved through printed fabrication, involving components like sensors, energy harvesters, displays, and antennas, which often require thin-film transistors (TFTs) as active switches.

TFTs are compared based on threshold voltage, charge carrier mobility, and series resistance. However, conventional MOSFET parameter extraction methods [4] often yield misleading results for organic TFTs [5], due to significant differences in their electrical behavior [6]. A universal model that captures key parameter trends across various materials and structures is necessary. This model must be simple, analytically and physically based, with easily extractable parameters.

Our previous work suggested the OVSED model for TFTs [7], based on the virtual source (VS) emission-diffusion (ED) theory [8]. Here, we combine the model with an efficient algorithm for parameter extraction. Benchmark models based on the VSED framework can replace conventional methods [9] and apply to a wide range of TFT technologies [10].

While empirical models fit device behavior accurately, they involve many parameters, making extraction complex and time-consuming. This work's main contribution is developing a standardized parameter extraction method for organic TFTs using a flexible extraction algorithm implemented on a Python-based software platform. This platform employs a least squares algorithm for model parameter determination, using data from scientific literature and research labs fabricating prototype devices.

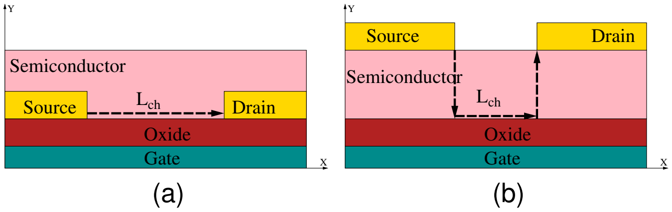


Fig. 1. Schematic cross-sections of (a) a coplanar, and (b) a staggered OTFT. The dashed lines show the expected current paths.

This physical-mathematical model and tool aim to replace traditional methods for extracting parameters like charge carrier mobility and series resistance, which often produce misleading results. Developed with input from thin-film device fabricators, the tool is expected to be widely adopted, ensuring more reliable, standardized extractions.

II. MODEL DESCRIPTION

TFTs are electronic switches where current flows from the source to the drain terminal, controlled by the voltage applied to the gate terminal, see Fig. 1. Benchmark models must consistently reproduce the current-voltage characteristics of TFTs with a minimal number of parameters. This means that the model parameters can be reliably and unambiguously extracted from experimental curves.

The simplest physical representation of the drain current in a TFT involves mobile charges modulated by the gate-to-source voltage, V_{GS}, moving at a velocity influenced by the drain-to-source voltage, V_{DS}. For very high source-drain electric fields, the charge carrier velocity saturates. As the carriers move from the source to the drain, they encounter a potential barrier, which acts as a bottleneck for charge transport. The limited charge injection rate at the top of this potential barrier can be described as a virtual source (VS).

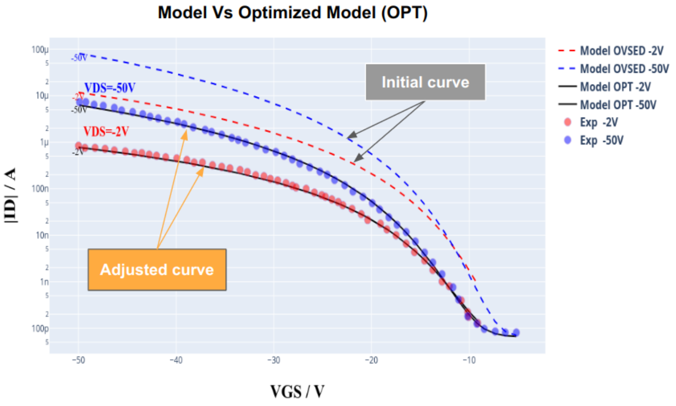


Fig. 2. Transfer characteristics of a p-type transistor. Manual fit vs. optimization

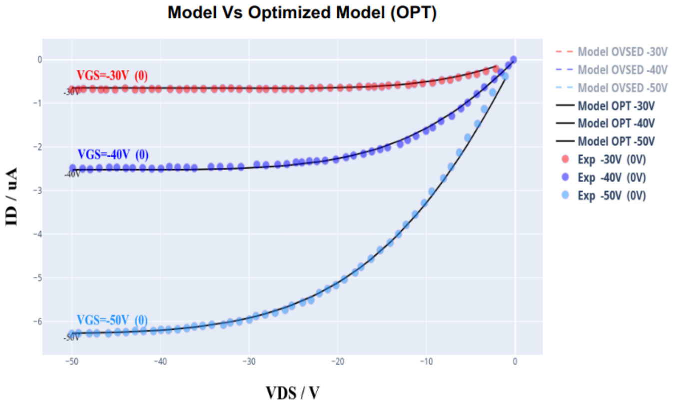


Fig. 3. Output characteristics of a p-type transistor.

Eq. (1) represents the current-voltage model for the drain current J_D of TFTs adapted from previous work [7]:

$$J_\mathrm{D} = J_\mathrm{TH} \left\{ \ln \left[1 + \exp \left(\frac{V_\mathrm{GS} - (V_\mathrm{tho} + \delta \cdot V_\mathrm{DS})}{n V_T} \right) \right] \right\}^l F_\mathrm{sat} \, . \tag{1}$$

In this equation, key parameters include: J_TH, the current transport capacity per gate width; V_tho, the threshold voltage; δ, the drain induced shift of the threshold voltage; n, the gate coupling factor indicating the sensitivity of the drain current to the gate-source voltage; and l, the linearity of the transconductance. Moreover, the function F_sat describing the transition from linear to saturation operation of the TFT is parametrized by $1/\lambda$, the mean free path per gate length, and V_crit, the onset voltage of velocity saturation. More details can be found in [7], [11].

The parameters described in Eq. (1) are essential for forming the objective function, allowing a close fit to the collected experimental data. Subsequently, optimization is employed to achieve the best curve fit. As shown in Fig. 2, we start with an initial fit, and then the optimizer refines the parameter values. We use the Trust Region Reflective (TRF) algorithm [12], which iteratively seeks the best parameters by minimizing discrepancies between predictions and real data, considering reliability constraints to update parameter values.

These parameters are critically analyzed against two types of input data: transfer curves and output curves, characterizing p- and n-type transistors. Fig. 2 and Fig. 3 show transfer and output characteristics, respectively. The optimizer simultaneously adjusts both, ensuring no ambiguities in the obtained values, unlike traditional separate optimization approaches that may yield unreliable values.

III. METHODS

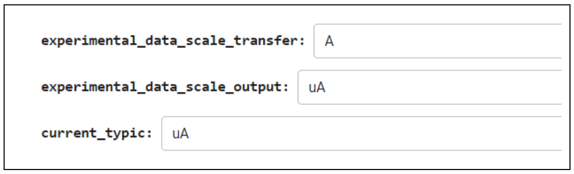
In this study, we utilized the Google Colab platform as a cloud programming environment for Python code development and execution. The specific Python version employed was 3.9.16. Throughout development, we utilized the following libraries:

- **NumPy (1.22.2)**: Efficient for multidimensional array manipulation and numerical calculations. It allowed us to work with experimental data obtained from laboratory measurements, consisting of current points in amperes and voltages in volts. Currents are expressed in amperes without subunits to maintain consistency with the International System of Units (SI).
- **SciPy (1.7.3)**: The SciPy library provides a wide range of advanced mathematical functions and algorithms for scientific data processing and numerical analysis.
- **Curve Fit Algorithm**: For parameter optimization of our model, we employed the curve fit algorithm, which fits a predefined function to the observed data, essential for finding the optimal parameter set.
- **Matplotlib (3.5.1) and Plotly (5.5.0)**: Utilized for result visualization.
- **CSV**: Efficient for storing and manipulating experimental data.

To obtain experimental datasets, we collected laboratory measurements focused on output and transfer curves. We conducted computational experiments using a minimum of one and a maximum of two transfer curves, and a minimum of two and a maximum of four output curves. Our methodology allows parameter extraction with an arbitrary number of each curve type, providing flexibility for various experimental needs.

We organized our code into classes, each with specific responsibilities. One class is dedicated to data handling, organizing, standardizing, and parameterizing them for proper model processing, always using SI units and ensuring an adequate sample quantity. Other classes handle visualization and model optimization. The complete source code, along with the dataset used, is available in our GitHub repository.

A unique feature of the developed notebook is its versatility and intuitive use. Experimental data are selected as transfer and output curves. To enable parameter extraction from the subthreshold operation region, a logarithmic scale may be applied to the transfer curves. Moreover, the user can set a



experimental_data_scale_transfer: A

experimental_data_scale_output: uA

current_typic: uA

Fig. 4. Input parameters interactive mode.

typical current scale for data normalization, see Fig. 4 for an interactive example. The selection of curves, even after loading, can be dynamically adjusted by the user, allowing for the verification of the impact of the number of each curve on the optimization results. We employ a simple configuration strategy for the parameter extraction platform, centered on a file called 'model card' in JSON format. This file contains all configurations and serves as an input for the notebook, as well as a memory repository for already executed models. We provide two versions of the notebook: one fully interactive, with windows and buttons, and another configured exclusively through the 'model card'. The choice between versions depends on the user's preference.

IV. RESULTS

We implemented the OVSED model for organic transistors including charge trapping. We used the mobile and trapped charge fractions to parameterize the model, allowing the description of transistor transfer and output curves with a small number of parameters. The model utilizes the virtual source concept to describe DC current-voltage attributes of organic thin-film transistors. The virtual source is a theoretical model that aids in understanding how charge carriers are drained from the transistor and how this affects its current and voltage. Electrical characteristics of organic transistors are typically analyzed through drift mobility, describing how quickly charge carriers move through the device. It is important to note that mobility can be affected by charge trapping, a phenomenon that can occur in organic devices.

Initially, we executed the model with two transfer curves and three output curves, using pentacene [13] and C16-IDTBT, poly(indacenodithiophene-*co*-benzothiadiazole), [14] technologies. For the first technology, the initial parameter values and the extracted (optimized) ones are reported in Tab. I. The extraction algorithm achieved good performance as demonstrated by the results shown in Fig. 2 and Fig. 3. The parameter extraction for the second technology also proved satisfactory.

Our experiments demonstrated that parameter optimization using two transfer curves and three output curves results in greater consistency and accuracy in the obtained values. In an additional experiment, we removed one of the transfer curves to evaluate the impact on parameter optimization. The results showed a decrease in the threshold voltage $V_{\mathrm{tho}} = 11.2\,\mathrm{V}$, a similar series resistance $R_{\mathrm{S}} = 100\,\mathrm{k\Omega}$ and a decrease in the current carrying capability of the channel $4.38 \times 10^{-6}\,\mathrm{\mu A\,cm^{-1}}$ suggesting a reduced charge carrier mobility. These erroneously extracted benchmark parameter could mislead the technology development to focus on improving the crystallinity of the film instead on reducing the series resistance. Thus, to ensure obtaining the best values, we recommend the use of at least two transfer and three output curves. Although it is possible to obtain satisfactory curve fitting using only a single curve for transfer characteristic data, the effectiveness of this approach depends heavily on the quality and quantity of collected sample points. The suggested extraction protocol offers greater robustness against experimental data variabilities, providing more reliable and accurate results.

TABLE I

BENCHMARKING FOR A PENTACENE TECHNOLOGY AND COMPARISON OF INITIAL VS. OPTIMIZED COEFFICIENTS.

Parameter	**Initial Value**	**Optimized Value**
V_{tho} (V)	-8.57	-12
δ	0.123	0.007
n	108	121
l	3.18	2.34
λ	1490	10000
V_{crit} (V)	32.3	41.5
J_{TH} ($\mathrm{\mu A\,cm^{-1}}$)	1	6.34
R_{S} ($\mathrm{k\Omega}$)	10	100
$J_{\mathrm{TH}}/(\lambda * n)$ ($\mathrm{\mu A\,cm^{-1}}$)	6.21e-6	5.24e-6

By employing the outlined approach, we conducted a rigorous numerical study of essential benchmark parameters, helping us to identify the technology that offers the best performance under specified conditions. It is important to note that while this approach provides valuable quantitative assessment, the final selection of technology should also consider the specific desired application type. Targeted evaluation is essential to ensure that the chosen technology fully meets the needs of the intended use. As an exemplary result, Tab. I provides the benchmark parameters for a OTFT technology based on pentacene. The extracted values suggest that the technology has good gate coupling, decent current transport capacity, but suffers from enhanced series resistance. Additionally, the extracted value of λ indicates that the transistor does not operate at the scattering limit, indicating a certain crystallinity of the thin film. The initial assessment, on the contrary, directed the technology development efforts towards mobility improvements instead of focussing on reducing the parasitic series resistance.

We evaluated the performance of the extraction algorithm employing two control values: first, by assessing the initial cost distance and comparing it with the final cost after the algorithm had iterated a number of steps until parameter convergence. Second, we compared the initial and final relative errors to ensure the quality and reliability of the obtained values. For this, we determined the absolute error, which is the difference between the experimental value and the reference value. Mathematically, for each pair of values $I_{\mathrm{D,ref}}$ and

TABLE II
PERFORMANCE OF THE EXTRACTION ALGORITHM FOR DIFFERENT OTFT TECHNOLOGIES.

Material	Pentacene	C_{16}-IDTBT	FlexOS^{TM}
Geometry	TCBG [13]	BCTG [14]	BCTG [14]
W (cm)	0.1	0.1	0.1115
L_G (µm)	40	70	8.1
Initial Cost	2.364e5	1.91e4	8.463e6
Final Cost	5.076e-1	2.14e1	2.022e3
Initial E_{rel}	1470	266.66	2232
Final E_{rel}	973	190.94	1559
Benchmarking			
V_{tho} (V)	-12	-3.19	+4
$J_{TH}/(\lambda * n)$ ($\mu A\,cm^{-1}$)	5.24e-6	2.51e-5	1.56e-4
R_S (kΩ)	100	239	2.97

$I_{D,exp}$, the absolute error E_{abs} is given by Eq. 2, where $I_{D,ref}$ corresponds to the current points obtained for input voltages received by the model:

$$E_{abs} = \sum |I_{D,ref} - I_{D,exp}| \ . \tag{2}$$

The relative error is then the fraction of the absolute difference normalized by the reference value:

$$E_{rel} = \sum \frac{|I_{D,ref} - I_{D,exp}|}{I_{D,ref}} \ . \tag{3}$$

In Tab. II, we compare the absolute and relative costs after parameter optimization. This comparison covers all available current points, demonstrating that the extraction algorithm provided satisfactory results across a wide range of different OTFT technologies.

V. CONCLUSIONS

To ensure the reliable deployment of thin-film technologies on a large scale, it is imperative to have accurate and robust benchmark strategies for these devices. Traditional parameter extraction methods, adapted from MOSFET analysis, often fail to provide reliable results for TFTs due to their unique electrical characteristics. This work presents a methodology for the comparative evaluation of organic thin-film transistors, aiming to increase the accuracy of parameter extraction and provide a quantitative criterion for technology selection, facilitating decision-making based on concrete data. The robust extraction of benchmark parameter requires a compact model, here based on a virtual-source emission-diffusion archetype, capable of accurately capturing key performance parameters with minimal complexity. Equally important is the standardization of the parameter optimization algorithm and of the experimental electrical characteristics used for benchmarking. We provided a versatile software tool and made it availabe to the community. We suggest to employ at least two transfer curves, one captured in the linear and another in the saturation operation regime, and three output curves of the OTFT. The proposed approach has been validated with empirical data, demonstrating its efficacy in representing the electrical behavior of various OTFT technologies. The combined modeling and extraction procedure ensures that benchmark parameter values are both precise and robust, enabling comparative evaluation and broader application within the TFT research and development community.

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ONLINE RESOURCES

The complete source code of the combined modeling and parameter extraction procedure for OTFT benchmarking, along with the dataset used, is available in our GitHub repository.

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