Abstract—A generic analytical model for the current–voltage characteristics of organic thin-film transistors (OTFTs) is derived. Based on this generic model, a TFT compact dc model that meets the requirements for compact modeling, including for computer circuit simulators, is proposed. The models are fully symmetrical, and the TFT compact dc model covers all regimes of TFT operation—linear and saturation above threshold, subthreshold, and reverse biasing. The empirical fitting parameters are mostly eliminated from the characteristic equations. The developed models are also in close correspondence to several physical, parametric, and limiting models for current–voltage and mobility characteristics. An essential practical feature of the TFT compact dc model is that the model is both upgradable and reducible, allowing for easier implementation and modifications and also simultaneously allowing for separation of characterization techniques. This allows for systematic fitting of experimental data with large scattering in the values, but at the same time, preserving consistently the OTFT behavior in the model.

Index Terms—Compact modeling, experimental characterization and symmetric models for TFT, organic thin-film transistors (OTFTs), polymeric thin-film transistors (PTFTs).

I. INTRODUCTION

ORGANIC or polymeric thin-film transistors (OTFTs or PTFTs, but hereafter, both are referred to as OTFTs) are mainly intended for application in low-cost, large-area, and flexible integrated circuits. Perhaps, in the future, it will be feasible to “print” disposable organic circuits in a similar fashion as to print on paper. Thus, it is highly desired to have compact models that can be used in simulators to predict and also to optimize the performance of the organic integrated circuits.

It is observed many times, and explained at different depths and rigor in the literature (for example in [1] and [2]), that the OTFTs behave similarly to crystalline field-effect transistors (c-FETs) and amorphous thin-film transistors (a-TFTs). The similarity between OTFT and MOSFET has allowed for adapting the MOS model for computer simulations a long time ago, e.g., in [1] in 1992, where one can see one among the first compact models for OTFTs with contact and bulk leakage resistances included. The recent review of organic transistors in [2] noted that there are significant differences between organic and c-FETs, although a similarity in the current–voltage and other characteristics in these transistors exists. The “deviation” of OTFT characteristics from the “ideal” FET characteristics causes difficulties to define a unified compact model for OTFTs as a counterpart to the unified compact models for crystalline transistors. Scattering in the characteristics of individual OTFTs can be caused by several factors, such as contact effects interfering with carriers moving in the intrinsic TFT channel, bias-dependent mobility, and other factors that are discussed in detail in [2]. In addition, there is a wide range of fabrication approaches for OTFTs, including the use of different materials for substrates, electrodes, semiconducting films, and gate insulators; vertical and horizontal layout differences; variations in processing steps ranging from vacuum processing, through spin coating, to printing and stamping; functionalization of interfaces; and self-assembling of organic materials. In fact, there is no “standard” or “classical” OTFT structure that can be regarded as a counterpart of MOSFET or JFET generic structures. Consequently, many models are proposed for OTFTs to reflect one or another specific charge transport or feature assumed for the particular OTFT.

Currently, the significant variability in experimental data for similar devices and time-dependent characteristics makes the dc modeling quite challenging, and one can find many models in the literature (see Section V-B for more details). Therefore, we look at the trends and transferability of different models in order to define a sustainable dc model, which we will denote as “generic model.” This model captures the common points, providing the base of a compact model. These common points are stated in Section II in connection with the features that are desired for compact dc modeling of OTFTs. The implementation of the OTFT compact dc model follows. In Section III, we first present the simple derivation of a generic model for the current in OTFTs, based on the most common point that the charge carrier mobility $\mu$ is bias dependent, and it increases when the gate bias increases, which is in contrast to c-FETs. We also show the main correspondence to the generic MOS model in this section. Then, in Section IV, we discuss the details of converting the TFT generic model into a symmetric TFT compact dc model by adding the subthreshold regime and several effects observed in OTFTs, e.g., channel length modulation and contact resistance. The correspondence of the derived generic charge drift model and the TFT compact dc model to other TFT models is given in Section V. Section VI provides a brief summary and conclusions.
The validation of the TFT compact dc model in all ranges of TFT operation, from saturation and ohmic regimes above threshold, down to subthreshold and reverse biasing, is presented in Part II [3] in conjunction with relevant characterization and parameter extraction techniques.

II. FEATURES OF OTFT COMPACT MODELS

The channel current in crystalline MOSFETs and a-TFTs can be described by the simple expressions

\[ I_D = \frac{W}{L} \mu C_I \left( V_G - V_T - \frac{1}{2} V_D \right) V_D, \]

where \( C_I \) is the gate insulator capacitance per unit area, \( W \) is the channel width, \( L \) is the channel length, \( \mu \) is the charge carrier mobility, \( V_T \) is the threshold voltage, \( V_G \) is the bias voltage of the gate, \( V_D \) is the bias voltage of the drain, and the bias voltage of the source is zero, i.e., \( V_S = 0 \). This model of (1) is generic; it captures the essence of the dc operation of MOS transistors above threshold at idealized assumptions. All compact and computer MOS transistor dc models can be reduced to these equations, but simultaneously, the compact and, particularly, the computer models for MOS transistors are much more complicated in order to describe details of the operation of real transistors in other regimes and to provide the balance between gate and substrate capacitances, electric field degradation of mobility, and access contact impedances. This paper is on the compact dc modeling of OTFTs. Therefore, it is reasonable to state what a compact model is, since one may see differences in interpretations in the past. In this paper, first, we define the requirements for compact OTFT models as follows.

1) It must represent consistently the behavior of OTFTs.
2) It must be symmetrical to reflect the symmetry of the OTFT structure.
3) It has to be analytical, without differentials or integrals. It could be in matrix format but must not be a finite element model.
4) It has to be simple and easily derivable. No compromises with the essence in the overall OTFT behavior, but some freedom for simplifications should be allowed, neglecting details that deviate from experimental trends, are insignificant in magnitude, or are not reproducible in identical devices. In other words, one should have a generic model for OTFTs that is analogous to (1) used for MOS transistors.
5) It has to have parameters that can be characterized relatively easily, or even guessed.
6) It has to be upgradable and reducible. Consequently, it should be possible to replace different portions and dependences (e.g., on temperature) in the model with different models. Thus, the different portions in the model are extensions of each other, and the portions communicate between each other only by values of parameters or values for quantities, but the relations in the different portions must remain separated.
7) It has to have relations that can be physically justified.
8) It should have similar form and correspondence to compact models for other FETs.
9) It should be tunable to inaccurate (or uncertain) experimental data. Consequently, scaling rules can be left external, since these rules can be obscured by individual devices and different measurements.

The above requirements for OTFT compact models can be simultaneously emphasized and criticized, or graded in different order, considering the many approaches for modeling proposed in the literature. Our arguments for the particular list of requirements are the following. Despite the pronounced variations, there is a common point in the behavior of different OTFTs, and the common point is the mobility enhancement at higher gate overdrive voltage, which is behind requirement 1). Although asymmetric TFTs are used in research, the OTFTs mostly have symmetric structures. The drain and source are interchangeable, and so, the requirement 2) reflects the symmetrical structure of OTFT in the symmetric model. Requirement 3) guarantees the compact form of the model, making it also platform independent and convertible between computer simulators and other methods to use the model. Requirement 4) is to encourage an understanding of the origin of the analytical expressions, preventing unnecessary complications that arise from derivations based on physical assumptions followed by unnecessary complex expressions. Requirement 5) restricts and minimizes the set of model parameters only to significant parameters, whose impact on the model is known and predictable, preventing unnecessary phenomenological fitting parameters and dependences that may not be possible to adjust consistently, or interfere strongly with other parameters. Requirement 6) is very specific for OTFTs, since the different dependences and relations are not very certain and vary between different OTFT designs. For example, from a collection and statistical analysis of numerous experimental data [4], it has been observed that the effective carrier mobility tends to depend inversely on the product \( t_{organic} \times C_I \) of organic film thickness \( t_{organic} \) and gate capacitance per unit area \( C_I \). In addition, requirement 6) states the method of communication between different portions in the compact model so that the overall reassessment of the model is avoided; thus, the reusability of code in computer simulators is increased, while the reduction allows for separating of characterization techniques by parameter value extraction. Requirement 7) reflects the cumulative experience that empirical models are limited to specific cases, whereas models derived on physical basis usually sustain in the practice, and also, the physically linked models provide a feedback to OTFT design and fabrication. Requirement 8) guarantees continuity in modeling and also helps to compare OTFTs to other devices without major recalculation of model parameters. Requirement 9) reflects the current state-of-the-art OTFTs, in particular, the poor reproducibility in fabrication, and variability by experiments, as compared to the established crystalline devices. We believe that this requirement will be omitted in the future when
the fabrication of OTFTs reaches maturity. Until then, simpler and tunable compact models are more efficient, as compared to complicated “accurate” models, which are fitted to overall not very accurate data. Thus, the theoretical accuracy of the model is lost in the practice.

Perhaps, it is worth mentioning that compact modeling of TFTs is not difficult to achieve, but at the same time, an agreement for a unique TFT model is problematic. The main difficulties are the variability or lack of complete sets of systematic experimental data. Mostly processed data are available in the literature. The deviations in experimental data do not allow for automatic parameter extraction, since the variations are large and the cases are many, and the extraction and optimization procedures need to be manually guided in order to avoid unrealistic values for the model parameters. Nevertheless, there are common points and relations, and with the first one, the bias enhancement of mobility, we present the simple derivation of a TFT generic charge drift model.

III. DERIVATION OF TFT GENERIC CHARGE DRIFT MODEL

There are different theories for OTFTs, and the widely accepted theories are based on charge drift in the presence of tail-distributed traps (TDTs) [5] and variable range hopping (VRH) [6]. The common point in the theoretically derived expressions for the mobility is that \( \mu \propto (V_G - V_T)^\gamma \), \( \gamma > 0 \), which is significant for compact modeling and therefore is used here. Since the primary goal of compact models is the electrical which is significant for compact modeling and therefore is used here. Thus, the large expressions deduced from the physics are omitted. The derivation of the TFT generic charge drift model is now given, using the well-established concept for charge drift, by which the current per unit width \( (I_D/W) \) in the TFT is

\[
\frac{I_D}{W} = \mu_x Q_x |E_x| \tag{2}
\]

where \( W \) is the width of the TFT conduction channel. At given position \( x \) in the channel, \( 0 \leq x \leq L \), \( \mu_x \) is the mobility, and \( Q_x \) is the areal charge density given by

\[
Q_x = C_I (V_G - V_T - V_x), \tag{3}
\]

and is written so that Gauss’ law for the free carriers is satisfied by the gate voltage overdrive \( (V_G - V_T) \). The gate dielectric capacitance per unit area is \( C_I \), and \( |E_x| = \partial V_x/\partial x \) is the magnitude of the electric field, since we have explicitly given the direction of the current flow. Here, \( V_G, V_T, \) and \( V_x \) are the gate bias voltage, threshold voltage, and potential in the semiconducting film of the TFT, respectively. From the aforementioned common theoretical result [5], and [6], we write for mobility that

\[
\mu_x = \mu_{oo}(V_G - V_T - V_x)\gamma \tag{4}
\]

where, as suggested in [7], \( \mu_{oo} = \mu_{oo}/(V_G)\gamma \) is the mobility at the gate overdrive voltage \( (V_G - V_T) = V_G \), \( \mu_{oo} \) is in unit different from \( \text{cm}^2/\text{V} \cdot \text{s} \), but the value will correspond to the low-field mobility \( \mu_{oo} \) by choosing, as a reference, the low gate overdrive \( (V_G - V_T) = V_G = 1 \text{ V} \). The substitution of (3) and (4) in (2) yields

\[
\frac{I_D}{W} = [\mu_{oo}(V_G - V_T - V_x)]_{\mu_{oo}} \times [C_I(V_G - V_T - V_x)]_{C_I} \times \frac{\partial V_x}{\partial x} \tag{5}
\]

The current is constant along the channel, and \( dV_x = (\partial V_x/\partial x)dx \). Therefore, integration along the channel length coordinate \( x \) in a manner similar to that in [5], and [8] yields

\[
I_D = \frac{L}{0} \int (I_D) dx = \mu_{oo}C_I \int_{0}^{L} (\partial V_x/\partial x) dx = \mu_{oo}C_I \int_{V_S}^{V_D} dV_x \tag{6}
\]

\[
I_D = -\mu_{oo}C_I \frac{1}{\gamma + 2} (V_G - V_T - V_x)^{\gamma + 2} \bigg|_{V_x = V_S} \tag{7}
\]

\( V_S \) is the potential of the channel at the source side of the TFT. \( V_D \) is the potential of the channel at the drain side, when operating in the linear regime, or the drain saturation voltage \( V_{SAT} \approx (V_G - V_T) \) in the saturation regime. Finally, we obtain the expression for the TFT generic charge drift model as

\[
I_D \frac{L}{W} = \mu_{oo}C_I (V_G - V_T - V_S)^{\gamma + 2} - (V_G - V_T - V_D)^{\gamma + 2} \bigg|_{\gamma + 2} \tag{8}
\]

Since the derivation here is based on the common point for bias enhancement of mobility, the derivation is generic, and so, it is reflected in the name of the model. Note that all equations are written for n-channel TFTs. Normally, OTFTs are p-channel transistors, for which the polarities of voltages and currents have to be inverted.

The main features of the model are symmetry and direct correspondence to the MOS charge model: \( I_D/K = [(Q_S/C_{ox})^2 - (Q_D/C_{ox})^2]/2\alpha \) (see, e.g., [9, eq. (4.3.29)]), with \( \alpha = d(Q_{inv}/C_{ox})/d\Psi_{surface} \approx 1 + dV_T/dV_{body} \) (where (4.3.27) \( \approx (4.5.41) \) in the same book). Complicated derivations in other publications, with various assumptions for physical origin, have arrived essentially at the same result with a difference of a constant multiplier (see [5, eq. (52)]) or with a difference in terms that are insignificant in magnitude (see [10, eqs. (35) and (37)]).

The TFT generic model suggests a “normal” scaling rule, via \( I_D \propto K = \mu_{oo}C_I W/L \), but the rule is highly obscured in real OTFTs, owing to different factors such as contact “resistance” with a different scaling rule. Therefore, one should allow for some variability in the values of \( \mu_{oo}, V_T, \) and \( \gamma \) in identical samples and between different measurements. In addition, the scaling rules for these quantities should be kept external for the TFT generic model, according to rule 6) for compact modeling of OTFTs that was discussed in Section II. Another feature of the TFT generic model is that the model allows for modifications when building compact models, as discussed in the next section.
IV. TFT Compact DC Model (Level 1)

At normal biasing, $V_D > V_S$, the term $(V_G - V_T - V_D)$ in (8) of the TFT generic model has to be taken only with positive values in the linear regime of OTFT operation, and in the saturation regime, $(V_G - V_T - V_D) \approx 0$. With this detail and also by taking $\gamma = 0$, thus neglecting mobility enhancement, it can be shown that the model reduces to the generic FET model of (1). Similarly, if the TFT is biased in reverse, $V_D < V_S$, the term $(V_G - V_T - V_S) \geq 0$, and this follows from the symmetry in the TFT generic model. Thus, the TFT generic model becomes a solid initial base for developing the TFT compact dc model, by introducing the details in the operation of real OTFTs that are described immediately hereinafter.

The subthreshold regime is not considered in the TFT generic model, but it can be easily added by an asymptotically interpolation function, which results in

$$I_D \frac{L}{W} = \mu_e C_l \times \left[ \frac{f(V_G - V_T - V_S)}{V_S} \right]^{(\gamma + 2)} - \left[ \frac{f(V_G - V_T - V_D)}{V_S} \right]^{(\gamma + 2)} \gamma + 2$$

where, with either $V = V_D$ or $V = V_S$, the function $f(V_G, V)$ can be regarded as effective voltage overdrive ($V_{\text{EODR}}$) that is given by

$$V_{\text{EODR}}(V) = f(V_G, V) = V_{SS} \ln \left[ 1 + \exp \left( \frac{V_G - V_T - V}{V_{SS}} \right) \right]$$

$$\approx V_{SS} \exp \left( \frac{V_G - V_T - V}{V_{SS}} \right),$$

when $(V_G - V_T - V) < -V_{SS}$,

$$\approx (V_G - V_T - V),$$

for subthreshold regime

$$\approx (V_G - V_T - V),$$

when $(V_G - V_T - V) > V_{SS}$,

$$\text{for above-threshold regime.}$$

A similar interpolation is used for MOS transistors (please see [9, p. 176] for MOS and [11] and [12] for other FETs). The function for the overdrive voltage can also be modified to include other factors such as the bias dependence of the threshold voltage (see [3, eq. (10)]).

The value for the voltage parameter $V_{SS}$ is related to the steepness of the subthreshold characteristics of the TFT. Therefore, in the subthreshold saturation regime, one has $[(V_G - V_T - V_S) < -V_{SS}]$. Thus, $\exp(-V_D/V_{SS}) \ll \exp(-V_S/V_{SS})$, and (9) can be rewritten in a logarithmic form as

$$\ln(I_D) + \ln \left( \frac{L}{W} \right) \approx \ln(\mu_e C_l) + (\gamma + 2) \ln(V_{SS})$$

$$+ \frac{V_G - V_T - V_S}{V_{SS}} (\gamma + 2).$$

Consequently, from (11), it follows that

$$\frac{\partial \ln(I_D)}{\partial V_G} \mid_{V_S < V_T} \approx \frac{(\gamma + 2)}{V_{SS}}.$$ 

Therefore, having the subthreshold slope $SS$ determined in unit $[V/\text{decade}(I_D)]$ from the slope of the semilogarithmic plot of the measured transfer $I_D - V_G$ curve in saturation ($V_D \geq V_{SS} \approx 1 - 10 \text{ V}$), the parameter $V_{SS}$ can be estimated as

$$V_{SS} = \frac{\partial V_G}{\partial \ln(I_D)} \approx 0.43(\gamma + 2)SS \sim SS.$$ 

Please see [3, eq. (7)] for a simple practical rule that can be used to obtain an initial value of $V_{SS}$.

A useful detail is that the TFT generic model allows for consistently adding other phenomena that take place in OTFTs. One example to add is the channel “length” modulation, by rewriting (8) as

$$I_D \frac{L - \Delta L}{W} = \mu_e C_l \times \left( \frac{V_G - V_T - V_S}{\gamma + 2} \right)^{(\gamma + 2)}$$

and by introducing the channel “length” modulation coefficient $\lambda$ [in unit, e.g., %/V] from

$$L \left( 1 - \frac{\Delta L}{L} \right) = L \left[ 1 - \lambda(V_D - V_{\text{SAT}}) \right] \approx \frac{L}{1 + \lambda(V_D - V_{\text{SAT}})}.$$ 

The last term is arranged so that it preserves the symmetry inherent for the TFT generic model, but when tested with measured data, we found that $\Delta L/L$ is a sublinear function of drain bias, having a decreasing slope along the semilogarithmic plot of $\partial \ln(I_D)/\partial V_D$ when $V_D$ increases above the saturation voltage $V_{\text{SAT}} \approx (V_G - V_T)$. A better model is given by (31) in the Appendix, where the coefficient $\lambda$ is empirically found to be suitable, because at low drain bias $|V_D - V_S| \ll (V_G - V_T)$, the modulation is suppressed, while $|V_D - V_S| \approx V_{\text{SAT}},$ the ratio is 2/3, decreasing to 1/2 when $V_D$ increases above $V_{\text{SAT}}$. In addition, the constraint $(V_G - V_T) \geq 10 \text{ mV}$ avoids a division by zero. Indeed, several of our data suggest that other formulations for channel length modulation are also feasible for compact modeling, e.g., $\Delta L$ originating from space-charge-limited conduction (SCLC). However, these formulations are stated under investigation in the Appendix, since they are not confirmed by the existing published literature.

The TFT generic model also allows the incorporation of the voltage drop $V_C$ across the contacts at the TFT terminals. As reviewed in detail in [2], it is observed [7], [13]–[17] that the carrier injection contact (source terminal of the OTFT) is dominant, so $V_S = V_C$. Assuming a functional model of the carrier injection as $V_C = f_c(I_D) = V_C(I_D)$, the TFT generic model of (8) becomes

$$I_D \frac{L}{W} = \mu_e C_l \times \left( \frac{V_G - V_T - V_C(I_D)}{\gamma + 2} \right)^{(\gamma + 2)}.$$ 

Again, the TFT generic model provides simple ways to add diverse effects when building the TFT compact dc model, and the parameters and characteristic equations are summarized in

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the Appendix. Denoting the TFT generic model as the initial Level 0 in symmetric TFT models, then the TFT compact dc model can be placed at Level 1, as the first step in the all-region compact modeling of TFTs.

V. LINKS TO TFT GENERIC CHARGE DRIFT MODEL AND TFT COMPACT DC MODEL

In this section, we provide the physical origin of the parameters used in the TFT generic charge drift model and the TFT compact dc model and the correspondence between these models and other models, which are currently used in the practice of compact modeling of TFTs.

A. Physical Interpretation of Parameters

We have mentioned in Section III that the bias dependence of the mobility, i.e., $\mu \propto \mu_o (V_{GDR})^2$, has been theoretically elaborated from assumptions for TDTs [5] and VRH [6]. In both theoretical approaches, one has assumed energy states distributed in some way in the “forbidden” energy gap. The difference between the two theories is in the transport mechanism assumed for the mobile charge. The charge transport is scattering-like in the quasi-conduction or quasi-valence band in the TDT theory, whereas the charge transport is due to charge hopping in a percolation-like manner between the states in the VRH theory.

Both derivations in [5], and [6] consider exponentially decaying density of states (DOS) with an exponential distribution of DOS given by

$$\text{DOS}(\Delta E) = \frac{N_S}{k_BT_o} \exp\left(-\frac{\Delta E}{kT_o}\right) = \frac{N_S}{E_o} \exp\left(-\frac{\Delta E}{E_o}\right)$$

(17)

where \text{DOS} is in unit of cm$^{-3}$ eV$^{-1}$, so that $N_S = \int \text{DOS} \text{dE}$ is the concentration of states in unit of cm$^{-3}$, $\Delta E = E - E_{\text{ref}}$ is the difference of the energy $E$ of the states with respect to the reference energy $E_{\text{ref}}$, e.g., $E_{\text{ref}}$ could be chosen as the energy of the conduction (or valence) band edge, or the Fermi energy, the HOMO or the LUMO level; $k$ is Boltzmann’s constant; and $T_o$ is the specific equivalent “temperature” that represents the steepness (or effective energy width $E_o = kT_o$) of the DOS exponential tail.

The theory in [5] for TDTs assumes that some significant portion of charge ($N_{\text{localized}}$) is localized (thus, trapped) in the exponential tail. Therefore, the mobile charge ($n_{\text{free}}$) attributed to the “conduction” (or “valence”) band is only a portion of the total charge, and the effective mobility $\mu$ becomes proportional to the ratio of free-to-trapped charge, i.e., $\mu \propto n_{\text{free}}/N_{\text{localized}}$. Note that the energy of the band edge is the threshold condition for conduction in the TDT (some authors redefine the TDT model as the mobility edge model [18] by modifying the tail shape).

The theory in [6] for VRH in tail-distributed states does not separate between free and localized charges. Excess charge is induced in the states by the gate bias voltage in terms of Gauss’ law. Then, charge hopping occurs from occupied to nonoccupied states in a percolation network, and conduction occurs when the spatial concentration of occupied states reaches the threshold condition for sustainable percolation. Thus, although in different manners, both theories have defined threshold conditions for conductivity. In addition, both theories predict a field-temperature enhancement of the mobility in the form of

$$\mu = \mu_o (V_G - V_T)^{\frac{2\gamma\sigma_T^2}{T_o^2} - 2} = \mu_o (V_G - V_T)^\gamma$$

(18)

where $T$ is the absolute temperature, and there is a slight difference in otherwise very similar expressions for the mobility prefactor $\mu_o$. It can be shown that the expressions for $\mu_o$, derived in the TDT [5] and VRH [6] theories differ by two constant multipliers [19].

Equation (18) suggests that the mobility enhancement factor depends on the characteristic energy width $E_o$ of the tail distribution, and

$$\gamma + 2 = \frac{T_o}{T} = \frac{E_o}{kT}.$$ 

(19)

By assuming a Gaussian (normal) distribution of $\text{DOS}(\Delta E) \propto \exp(-\Delta E^2/2\sigma^2)/\sigma E$, it is found again for the effective width of the distribution that $\sigma E \sim (1 \ldots 2) E_o$, as shown in [20], and [21], for example. Confusion may arise from (18) and (19) by setting $T_o \leq T$ or $E_o \leq kT$ for narrow distributions or high temperatures. This setting violates the conditions for proper use of the infinite integration limit in the gamma function in the theoretical derivations in [5], and [6]. This problem was recently identified in [22].

The physical models generally capture the behavior of the mobility with temperature and bias. However, the variability in the characteristics of OTFTs is large, as mentioned earlier, and in practice, there is always some discrepancy between idealized assumptions on which the models are derived and the experimentally acquired data. In addition, the compact models do not allow for confusions as that at $T_o \leq T$. Therefore, until the details in the mobility models are resolved, it would be better if the mobility models are kept separate from the electrical compact models, but with proper interfacing through selected parameters, e.g., by $\mu_o$ and $\gamma$ for the TFT compact dc model.

B. Correspondence Between Different DC Models for TFTs

The variety of models for OTFTs is large, ranging from simple phenomenological models based on similarities to crystal FETs, e.g., (1), to finite-element models of the TFT structure [23], and from the adaptation of a-TFT charge sheet models [11] to limiting models [2]. Each of these models has advantages and disadvantages, addressing different issues such as complexity, accuracy, repeatability, physics, characterization techniques, or convergence. On the other hand, the object of the models is the same accurate prediction of the electrical characteristics of OTFTs. Thus, it is important to know the correspondence between the different models.

In this section, we look at the parametric electrical dc models, since these are the basis for compact modeling. However, we will not address finite-element models, which ideally are able to predict the behavior of the TFT from detailed description of the TFT layers and other entities, such as the properties
of the materials for the films and contacts, sizes, bias, and by appropriate selection of charge transport principles.

Perhaps, the most popular TFT parametric model is the charge model. It assumes that the gate voltage induces simultaneously free carrier charge \( Q_S \) and trapped charge \( Q_T \) in the exponential DOS. The free charge at the source side is then given by the so-called unified charge control model [11], and [12]

\[
Q_S = 2Q_o \ln \left( 1 + \frac{1}{2} \exp \left( \frac{V_G - V_T}{\eta \varphi_t} \right) \right) \\
\approx 2C_1 \left[ \eta \varphi_t \ln \left( 1 + \frac{1}{2} \exp \left( \frac{V_G - V_T}{\eta \varphi_t} \right) \right) \right]
\]

(20) where \( \eta \) is a numeric parameter that can be attributed to the ratio \( Q_S/Q_T \). By comparison with (10) for the effective overdrive \( V_{EODR} \), one sees that \( V_{SS} \) in the TFT generic/compact model corresponds to \( \eta \varphi_t \) in the TFT charge models. Further correspondence between the TFT generic/compact model and the TFT charge models can be seen when looking at the different terms in the equation for the drain current in the TFT charge model [24], given by

\[
I_D = \frac{W}{L} \mu_o C_1 \left( \frac{V_G - V_T}{V_A^\gamma} \right)^{1+\gamma} \frac{V_{DS}(1+\lambda V_D)}{\left[ 1 + \left( \frac{V_D}{\alpha_s (V_G-V_T)} \right)^m \right]^\frac{1}{m}} \\
\times \frac{1}{1+R_C \frac{W}{L} \mu_o C_1 \left( \frac{V_G-V_T}{V_A^\gamma} \right)^{1+\gamma}}.
\]

(21) The mobility enhancement factor \( \gamma \) and the low-field mobility \( \mu_o \) are the same in both models. The values for the reference voltages are proportional, i.e., \( V_A^\gamma = V_c (2 + \gamma) \). Thus, \( V_A^\gamma \) and \( V_c \) have the same meaning. In both models, the channel length modulation factor \( \lambda \) scales the current, but beyond this point, there are several essential differences between the TFT generic/compact model and the TFT charge model.

The first difference is that the empirical parameter \( m \), which is used to tune the sharpness of the transition from linear to saturation regimes in the TFT charge model, is removed from the TFT generic/compact model. The main reason for this is that \( V_D^m \) interferes with \( \lambda V_D \) when varying \( V_D \), which can cause physically unrealistic estimates for the channel length modulation, for example, negative values for \( \lambda \) [25]. Therefore, a separate model for the channel length modulation \( \Delta L/L \) is considered in the TFT compact model (see (31) in the Appendix), which can be modified independently of all other parts of the model, if necessary.

The second difference between the TFT generic/compact model and the TFT charge model is in the modeling of the contact effects. It is assumed in the TFT charge model that the contact resistance \( R_C \) is nearly constant, and therefore, it was placed in the product with the conductance of the source terminal \( g_s = (W/L) \mu_o C_1 (V_G - V_T)^{1+\gamma}/V_A^\gamma \) in the last term of (21), which reduces the drain current by degenrating current feedback at the source terminal. In contrast, and also more reasonable, the contact resistance has a separate model in the TFT compact model (see (35) in the Appendix), since the contact materials can be diverse in OTFTs, and the contact effects in OTFTs can be prominent. In addition, the voltage drop across the contact is consistently attributed to the carrier injection electrode of the TFT (see (36) in the Appendix), by subtracting this contact voltage drop from the biasing of the injecting electrode (normally from \( V_S \), but could be from \( V_D \) in the case of reverse biasing, when \( V_D < V_S \)). This is because the contact effects are more important for carrier injection, as compared to carrier extraction in OTFTs (see again (16) in Section IV). Consequently, the fitting parameter \( \alpha_s \), which is used in the TFT charge model normally to reduce the saturation point of \( V_D \) to less than \( (V_G-V_T) \), is not used in the TFT generic/compact model since \( \alpha_s \) is found to be redundant and the characterization techniques for \( \alpha_s \) are not very certain.

The third difference is that the TFT generic/compact model is symmetrical, as required by compact modeling, whereas the TFT charge model is source referenced, and the TFT charge model can be used only if the potential of the source terminal is taken as zero potential.

One common problem in all TFT compact models is that the drain current is an implicit function of the contact resistance at the source terminal and that the dependence of the current on the biasing voltages becomes different in different regimes—exponential dependence in the subthreshold regime, nearly linear dependence in the ohmic regime, and nearly quadratic dependence in the saturation regime above threshold. In the TFT generic/compact model, one uses smoothing functions \( \ln(1+\exp(V_G-V_T)) \) and \( (V_S^2+V_D^2)/(1-\Delta L/L) \) that asymptotically tend to the dependences in the different regimes, which is one of the interpolation approaches in compact modeling.

The interpolation is found to have sufficient accuracy to describe the behavior of the TFT, and it is appropriate for the models in computer simulators in which the numerical iterations resolve also the problem with implicit functions. However, the interpolation approach is not very convenient at the characterization stage, since the parameters and dependences dominating in one regime also interfere with other regimes, and the interpolation is not the only approach possible. Another approach is to arrange the different terms of the model in a limiting equation, so that the dominant term limits the overall behavior of the equation. The general form of the limiting equation is in the expression of a harmonic mean, and it is given by

\[
1/U = a_x/X + a_y/Y - a_z (\pm \mu_a V ...)
\]

(22) where \( X, Y, Z(V, ...) \) are different functions for one quantity, e.g., mobility or current; \( U \) is the resulting value for the same quantity; \( a_x, a_y, a_z \ldots \) are weighting parameters, usually taken as unity; and the sign \((+)\) is used to limit, whereas the sign \((-)\) is used to enhance the value of \( U \). A well-known application of the limiting model is Matthiessen’s rule for mobility, i.e., \( 1/\mu = 1/\mu_a + 1/\mu_b \), where \( \mu_a \) and \( \mu_b \) are mobilities of two different scattering mechanisms, e.g., impurity and lattice scattering.

The limiting modeling approach was used several times for silicon TFTs [11] to describe the mobility enhancement at high
gate overdrive and to match and combine subthreshold and above-threshold drain currents, respectively, by
\[
\frac{1}{\mu} = \frac{1}{\mu_o} + \frac{1}{\mu_l} \left( \frac{V_G - V_T}{\eta \tau_l} \right)^\gamma
\]
\[
I_D = \frac{1}{I_{\text{D}_{\text{subVT}}} + I_{\text{D}_{\text{aboveVT}}}}
\tag{23}
\]
where \( I_{\text{D}_{\text{subVT}}} \propto \exp[(V_G - V_T)/\eta \phi I] \) and \( I_{\text{D}_{\text{aboveVT}}} \propto (V_G - V_T)^{1+\gamma} \) are the currents under gate biasing below and above the threshold voltage \( V_T \), given by their simple expressions. The limiting approach was also used in the injection–drift-limited model (IDLM) for organic transistors in the form of expressions. The limiting approach was also used in the injection–drift-limited model (IDLM) for organic transistors [2], in the form of
\[
\frac{1}{I_D(\text{injection} \& \text{drift})} = \frac{1}{I_D(\text{injection})} + \frac{1}{I_D(\text{drift})}
\tag{24}
\]
where \( I_D(\text{drift}) = I_D(\text{MOS}) \) and \( I_D(\text{injection}) \propto (V_G)^{2+m} \) are asymptotic limits for the current \( I_D(\text{injection} \& \text{drift}) \) flowing through the OTFT. Note again that the components \( I_D(\text{drift}) \) and \( I_D(\text{injection}) \) are given with their simple expressions for the MOS transistor and for organic diodes, respectively. Thus, one can split the different relations in the TFT compact dc model into explicit equations.

The first explicit equation (25), shown at the bottom of the page, for the TFT current is the TFT generic charge drift model interpolated for subthreshold regime, see (9), with effective overdrive by (10) and the contact voltage drop and channel length modulation neglected.

The second explicit equation is for the channel length modulation enhancement in the simplified form of (15) as
\[
\frac{\Delta L}{L} \approx \lambda |V_D - V_S|.
\tag{26}
\]

The third explicit equation is for the voltage drop at the injecting contact
\[
V_C \approx I_{\text{TFT}} R_T(I_{\text{TFT}})
\tag{27}
\]
where the value of \( R_T \) is calculated explicitly from \( I_{\text{TFT}} \), not implicitly by \( I_D \), according to the model of the contact (see (35) in the Appendix). Then, the explicit relations can be combined, in terms of the IDLM, as
\[
\frac{1}{I_D} = \frac{1}{I_{\text{TFT}}} \frac{\Delta L}{L} I_{\text{TFT}} + 2 \frac{2}{I_{\text{TFT}}} \times \frac{V_C}{(V_G - V_T)} \left[ \max \left( 1, 2 \frac{V_G - V_T - V_D/2}{V_G - V_T + V_D/2} \right) \right]
\tag{28}
\]
where the first term is the drift limit, the second term is the enhancement due to channel length modulation, and the third term is the injection limit, the weighting parameter of which is chosen so that it limits more strongly when \( V_C \) is larger. The function in the square brackets provides a smooth transition between the linear and saturation regimes. In this way, one obtains the drain current \( I_D \) by a calculation without iteration loops.

A comparison of the two approaches of calculation, an iteration procedure by the TFT compact dc model and in terms of IDLM, is shown in Fig. 1, when using the same data and parameters from [3, Fig. 2]. One can see a satisfactory agreement between the different calculation approaches, which indicates that both approaches are feasible for compact modeling of OTFTs.

Note that the accuracy of the TFT compact dc model is higher at low drain biases around the origin of the output \( I_D-V_D \) characteristic. Therefore, the TFT compact dc model should be preferred in circuit simulators, particularly in the linear regimes of TFT operation, but the IDLM can be used to accelerate the convergence of numerical methods for solving implicit relations, providing a reasonable estimate for the first iteration by an explicit calculation.

**VI. CONCLUSION**

By careful inspection of past and current achievements in modeling TFTs, we have determined a common point, namely, that the mobility enhancement in a-TFTs and OTFTs can be embedded in compact models consistently in a functional form of
\[
\mu(x) = \mu_o(V_G - V_T - V_x)^\gamma,
\]
where \( V_x \) is the potential at coordinate \( x \) along the channel length of the TFT. This allowed

\[
I_{\text{TFT}} = \frac{W}{L} \mu_o C_T V_{\text{SS}}^{\gamma+2} \left\{ \ln \left[ 1 + \exp \left( \frac{V_G - V_T - V_S}{V_{\text{SS}}} \right) \right] \right\}^{\gamma+2} - \left\{ \ln \left[ 1 + \exp \left( \frac{V_G - V_T - V_D}{V_{\text{SS}}} \right) \right] \right\}^{\gamma+2}
\tag{25}
\]
us to derive a TFT generic charge drift model with a mobility enhancement factor $\gamma > 0$, which is equivalent to the well-known and widely used generic FET model with a constant mobility. The TFT generic model is symmetric, as required for TFT compact models, and its specific parameters, namely, the low-field mobility $\mu_o$ and the mobility enhancement factor $\gamma$, have a well-established physical interpretation from a tail distribution of localization states in a-TFTs. Thus, the TFT generic model becomes a bridge between physics-based modeling and compact modeling of OTFTs, capturing the essence in the behavior of these transistors in a consistent and relatively simple way.

We have demonstrated approaches for incorporating channel length modulation, subthreshold operation, and contact effects in the TFT generic model, so that the modifications closely reflect the characteristics of the OTFTs. The modifications resulted in a TFT compact dc model that is applicable to all regions of operation of the TFT. In Part II [3], we will discuss the available characterization techniques for OTFTs and their application to the extraction of the values of the parameters of the TFT generic model. We have obtained reliable and good fitting of the TFT generic model to experimental data, without excessive fitting parameters or smoothing functions, thus preserving the consistency in the bridge between physical and compact models for OTFTs. Therefore, we propose Level I for the TFT compact dc model. Finally, we have shown a close correspondence between several parameters in the TFT compact dc model and the presently available charge models and limiting models for TFTs and have pointed out some differences.

APPENDIX

TFT COMPACT DC MODEL

This Appendix summarizes the TFT compact dc model of Level I. The model is applicable for all regions of operation

**TABLE I**

MODEL PARAMETERS USED IN TFT COMPACT DC MODEL

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Notation</th>
<th>Unit [value]</th>
<th>Comments</th>
<th>Model (Level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of FET</td>
<td>[n, p, -p]</td>
<td>cm</td>
<td>p-channel OTFT, Invert polarity of voltages and currents by calculations</td>
<td>TFT Generic (0) and above</td>
</tr>
<tr>
<td>Channel Width</td>
<td>W</td>
<td>cm</td>
<td>Default: 0.01 cm=100 $\mu$m</td>
<td>TFT Generic (0) and above</td>
</tr>
<tr>
<td>Channel Length</td>
<td>L</td>
<td>cm</td>
<td>Default: 0.001 cm=10 $\mu$m</td>
<td>TFT Generic (0) and above</td>
</tr>
<tr>
<td>Gate Capacitance</td>
<td>$C_g$</td>
<td>F/cm$^2$</td>
<td>35 nF/cm$^2$, corresponding to 100 nm SiO$_2$</td>
<td>TFT Generic (0) and above</td>
</tr>
<tr>
<td>Threshold Voltage</td>
<td>$V_{TH}$ or $V_T$</td>
<td>V</td>
<td>Value is extrapolated from above-threshold regime, corresponds to zero bias, Invert polarity for p-channel OTFT.</td>
<td>TFT Generic (0) and above</td>
</tr>
<tr>
<td>Low-Field Mobility</td>
<td>$\mu_o$</td>
<td>cm$^2$/V$\cdot$s</td>
<td>Value corresponds to voltage overdrive $V_{GDD}(V_D-V_D)$(V_D-V_T)</td>
<td>TFT Generic (0) and above</td>
</tr>
<tr>
<td>Voltage overdrive for $\mu_o$</td>
<td>$V_D$</td>
<td>V</td>
<td>Default=1V. The value corresponds to overdrive $V_{GDD}(V_D-V_D)$(V_D-V_T) for which the value of $\mu_o$ is given.</td>
<td>TFT Generic (0) and above</td>
</tr>
<tr>
<td>Mobility Enhancement Factor</td>
<td>$\gamma$</td>
<td>number</td>
<td>The actual mobility is $\mu_o\times(V_{GDD}(V_D-V_D))$ Temperature dependence $2\gamma=1/T$, eq. (19)</td>
<td>TFT Generic (0) and above</td>
</tr>
<tr>
<td>Channel Length Modulation Factor</td>
<td>$\lambda$</td>
<td>1/V or %/V</td>
<td>0.05%/V, refers to the concept for channel length modulation in saturation, $\Delta L/L\times V_D$</td>
<td>TFT Compact (1)</td>
</tr>
<tr>
<td>Selector for Channel Length Modulation Model</td>
<td>$n_{SCLC}$</td>
<td>[0, 1, 2, 3]</td>
<td>Default=1. Associated models $n_{SCLC}=0$; $n_{SCLC}=1$; $n_{SCLC}=2$; $n_{SCLC}=3$: Mott-Gurney SLIC, $\lambda=I_{D}(V_D-V_{DD})^{1/2}$</td>
<td>Empirical models $n_{SCLC}=0$: inacurate, obsolete $n_{SCLC}=1$: TFT Compact (1) $n_{SCLC}=2$: under investigation $n_{SCLC}=3$: under investigation</td>
</tr>
<tr>
<td>Subthreshold Slope Voltage</td>
<td>$V_{SS}$</td>
<td>V</td>
<td>For asymptotic interpolation model, $V_{GDD}=V_{SS}ln[1+exp(V_D-V_D/(V_D-V_{SS})]; V_D=V_D(V_D,V_S)$</td>
<td>Empirical, can be changed</td>
</tr>
<tr>
<td>$V_T$ Sensitivity to Bias</td>
<td>$\delta_{VT}$</td>
<td>V/V or %</td>
<td>Threshold voltage sensitivity to bias voltages, $\delta_{VT}=\Delta V_D/\Delta V_T$ (±10% usually); $V_D=V_D(V_D,V_S)$</td>
<td>Empirical, can omit</td>
</tr>
<tr>
<td>Minimum (contact) Resistance</td>
<td>$R_C$</td>
<td>$\Omega$</td>
<td>Should obey $1/W$ scaling rule, but it is implemented as absolute value</td>
<td>TFT Compact (1)</td>
</tr>
<tr>
<td>Maximum (contact) Resistance</td>
<td>$R_{Cmax}$</td>
<td>$\Omega$</td>
<td>Note: the maximum resistance at low currents is $R_{C}=R_{Cmax}$</td>
<td>TFT Compact (1)</td>
</tr>
<tr>
<td>Max. Current for $R_{Cmax}$</td>
<td>$I_{Cmax}$</td>
<td>A</td>
<td>The actual contact resistance is given by $R_{C}=R_{Cmax}(I_{Cmax}/(I_{Cmax}+I_0))^{1/2}$</td>
<td>TFT Compact (1)</td>
</tr>
<tr>
<td>Reduction exponent for $R_{Cmax}$</td>
<td>$n_{RC}$</td>
<td>number</td>
<td>Meaningful values for $n_{RC}$ are between 0.5 (SCLC) and 1 (constant voltage at contact)</td>
<td>TFT Compact (1)</td>
</tr>
<tr>
<td>Resistance Field Reduction</td>
<td>$n/a$</td>
<td>$n/a$</td>
<td>To be implemented to cover cases for OTFTs with high voltage barrier at injection contact</td>
<td>under investigation</td>
</tr>
</tbody>
</table>
of OTFTs. The scaling rules are assumed external. The internal model variables (voltages and currents) are denoted with italic fonts, and the model parameters are denoted with bold fonts (Table I). Some parameters can be either constants or variables, so they are in fonts (Table I). Some parameters can be either constants or variables, so they are in fonts (Table I). Some parameters can be either constants or variables, so they are in fonts (Table I). Some parameters can be either constants or variables, so they are in fonts (Table I). Some parameters can be either constants or variables, so they are in fonts (Table I). Some parameters can be either constants or variables, so they are in fonts (Table I). Some parameters can be either constants or variables, so they are in fonts (Table I). Some parameters can be either constants or variables, so they are in fonts (Table I).

Characteristic Equations for TFT Compact Model (Level 1)

Source-side overdrive voltage

\[ V_{EODR} = V_{DS} \ln \left(1 + \exp \left[ \frac{V_G - V_{D0} - (V_G - V_{SI}) \delta VT}{V_{SS}} \right] \right), \]

\[ V_{SI} \text{ is internal source potential.} \quad \text{(29)} \]

Drain-side overdrive voltage

\[ V_{EODR} = V_{SS} \ln \left(1 + \exp \left[ \frac{V_G - V_{D0} - (V_G - V_{DI}) \delta VT}{V_{SS}} \right] \right), \]

\[ V_{DI} \text{ is internal drain potential.} \quad \text{(30)} \]

Channel length modulation \((n_{SCLC} = 1)\)

\[ \frac{\Delta L}{L} = \lambda \frac{V_{DS}}{2V_{DS} + V_{GT}\Delta L} \geq 0 \]

\[ V_{DS} = |V_D - V_S| \]

\[ V_{GT}\Delta L = \max[(V_G - V_{TO}).10 \text{mV}]. \quad \text{(31)} \]

Drain current

\[ I_D = \frac{W}{L(1 - \frac{\Delta L}{L})} \left( \frac{\mu_0}{C} \right)(V_T)^{\gamma} \times \left[ (V_{EODR})^{2+\gamma} - (V_{EODR})^{(2+\gamma)} \right] \frac{2 + \gamma}{2} \quad \text{(32)} \]

Source current

\[ I_S = -I_D. \quad \text{(33)} \]

Gate and leakage currents are omitted, since they vary between different approaches of fabrication and require external modeling

\[ I_G = 0. \quad \text{(34)} \]

Terminal (contact) resistance: current model, \( R_C \) and \( R_{C_{\text{max}}} \)

to be modified for field dependence

\[ R_T = R_C + R_{C_{\text{max}}} \left[ \frac{I_{C_{\text{max}}} - |I_D|}{I_{C_{\text{max}}} + |I_D|} \right]^{\gamma_{\text{MC}}}. \quad \text{(35)} \]

Internal potentials \( V_{SI} \) and \( V_{DI} \) of source and drain, respectively

\[ V_D > V_S \Rightarrow \begin{cases} V_{SI} = V_S + R_T \times |I_D|, & V_{DI} = V_D \\ V_{DI} = V_D \end{cases} \]

\[ V_D < V_S \Rightarrow \begin{cases} V_{SI} = V_{DI} = V_D \end{cases} \]

with terminal contact voltage drop attributed to injecting electrode.

References


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Ognian Marinov was born in Sofia, Bulgaria, in 1962. He received the M.Sc. and Ph.D. degrees in electronics from the Technical University of Sofia, Sofia, in 1986 and 1996, respectively.

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Organic Thin-Film Transistors: Part II—Parameter Extraction
M. Jamal Deen, Fellow, IEEE, Ognian Marinov, Ute Zschieschang, and Hagen Klauk

Abstract—A parameter extraction methodology and a verification of a generic analytical model and a thin-film transistor (TFT) compact dc model for the current–voltage characteristics of organic TFTs are presented. The verification shows that the proposed models meet the requirements for compact modeling and for computer circuit simulators. The models are fully symmetrical, and the TFT compact dc model is validated in all regimes of operation—linear and saturation above threshold, subthreshold, and reverse biasing. Suitable characterization techniques for parameter extraction of mobility, threshold voltage, and contact resistance are provided. Approaches are elaborated for the essential practical feature of upgradability and reducibility of the TFT compact dc model, allowing for easier implementation and modification, as well as separation of characterization techniques.

Index Terms—Compact modeling, experimental characterization and symmetric models for thin-film transistor (TFT), organic TFTs (OTFTs), polymeric TFTs (PTFTs).

I. INTRODUCTION

In compact modeling of the electrical characteristics of transistors, not only the model should be sound and physically based but also the associated parameter extraction should provide physically reasonable parameter values in as simple and straightforward a manner as possible. The field of parameter extraction and modeling in organic/polymeric thin-film transistors (OTFTs or PTFTs, respectively, but hereinafter, both are referred to as OTFTs) dates back almost two decades. In [2], one can find from 1992 an early computer-based model with the associated parameter extraction technique for PTFTs. This model was implemented in SPICE, and good agreement with the associated parameter extraction technique for PTFTs. Some important features of this early publication were the incorporation of resistances associated with contacts at the source and drain terminals, a bias-dependent parasitic leakage current through the bulk of the polymer and in parallel with the channel current, and channel-length modulation effects.

In a more recent publication [3], a more elaborate model for the dc electrical characteristics of OTFTs and associated parameter extraction was described. This model was based on amorphous TFTs and presented procedures for extracting parameters associated with above-threshold linear and saturation regions of operation. However, using the model and parameter extraction method [3], unphysical parameters, such as negative channel length modulation, positive or negative mobility enhancement parameters, and sometimes zero parasitic source resistance, were obtained.

Concerning the important contact effects, two recent publications [4], [5] presented a physical model and parameter extraction technique [4] and a compact model and parameter extraction technique [5] based on the forward and reverse modes of operation of OTFTs. In [4], a detailed discussion on the importance of interrelating different physical phenomena, such as charge injection, redox reactions, and charge drift, was presented. Both publications showed that the contact resistance decreased with increasing absolute gate biasing and that if the contact effects are not properly accounted for, then the extracted mobility and threshold voltage can be in significant error.

In [1, Part I], we have described details for the derivation and development of compact models for the current–voltage characteristics of OTFTs/PTFTs. These models are fully symmetrical and cover all regimes of TFT operation—linear and saturation above threshold, subthreshold, and reverse biasing. We have showed that the models developed are in close correspondence to several physical, parametric, and limiting models for current–voltage and mobility characteristics. An important practical feature of the TFT compact dc model is that it is both upgradable and reducible, allowing for its easier implementation and modifications, and also simultaneously allowing for separation of characterization techniques. In the TFT generic charge drift model in [1, Part I], the relation between channel current $I_D$ and biasing voltages is

$$I_D = \frac{L}{W} \mu \gamma C_I \left( V_G - V_T - V_S \right)^{(\gamma+2)} - \left( V_G - V_T - V_D \right)^{(\gamma+2)}$$

where $C_I$ is the gate insulator capacitance per unit area, $W$ is the channel width, $L$ is the channel length, $\mu = \mu_0 \left( V_G - V_T \right)^\gamma$ is the charge carrier mobility, $\gamma$ is the mobility enhancement factor, $V_T$ is the threshold voltage, $V_G$ is the bias voltage of the gate, $V_D$ is the bias voltage of the drain, and $V_S$ is the bias voltage of the source. Since the derivation is based on the common point for bias enhancement of mobility, it is generic. Note that the equations in [1] and here are written for n-channel TFTs. However, since OTFTs are normally p-channel transistors, then the polarities of voltages and currents have to be inverted. Also, the $V_D$ and $V_S$ in the TFT generic charge drift model do not exceed the gate voltage override ($V_G - V_T$).

The TFT generic charge drift model is for the operation of OTFTs above threshold ($V_G > V_T$). For operation in the
subthreshold regime, with either \( V = V_D \) or \( V = V_S \), the terms \( (V_G - V_T - V) \) in (1) are interpolated with the effective overdrive voltage \( (V_{EODR}) \), which is given by

\[
V_{EODR}(V) = f(V_G, V) = V_{SS} \ln \left[ 1 + \exp \left( \frac{V_G - V_T - V}{V_{SS}} \right) \right].
\]

(2)

As shown in [1, Part I], further modifications that reflect the characteristics of OTFTs are implemented in the TFT generic charge drift model. The modifications resulted in a TFT compact dc model that is applicable to all regions of operation of the TFT. The TFT compact dc model is summarized in [1, Part I, Appendix]. Here, we discuss the available characterization techniques for OTFTs and their application to the extraction of the values of the parameters of the TFT generic model and the TFT compact dc model.

II. PARAMETER EXTRACTION FOR THE TFT GENERIC CHARGE DRIFT MODEL AND THE TFT COMPACT DC MODEL

A. Extraction of Mobility Enhancement Factor \( \gamma \)

Looking closer at the characteristic equation (1) of the TFT generic model, one sees that parameter extraction techniques that are well established for FETs can be used and that only an additional extraction technique for the value of mobility enhancement factor \( \gamma \) is needed. An appropriate technique is proposed in [6], by the so-called \( H_{VG} \) function, which extracts the values of \( \gamma \) and threshold voltage \( V_T \) from the linear regime of operation of the OTFT. The \( H_{VG} \) function is the ratio of the integral of the drain current over the gate bias divided by the drain current. The corresponding equation for the \( H_{VG} \) function derived from the TFT generic model is (3), shown at the bottom of the page. In these equations, as stated in [6], \( H_{VG} \) becomes a linear function of gate overdrive \( (V_G - V_T) \) by setting \( S = 0 \), while \( W, L, \mu_0 \), and \( C_J \) are canceled, which is the advantage of the method. Accordingly, the value of mobility enhancement factor \( \gamma \) is obtained from the slope of the \( H_{VG} \) versus-\( V_G \) plot.

A typical plot of \( H_{VG} \) is shown in Fig. 1 for an OTFT with solution-deposited poly(3-hexadecylthiophene) as the semiconductor. The TFT was made on a degenerately doped silicon wafer with a thermal SiO2 gate insulator, where \( C_{ox} = 12 \text{ nF/cm}^2 \), \( W = 1.67 \text{ cm} \), and \( L = 10 \mu \text{m} \). Several observations in Fig. 1 can be made. First, a linear dependence on gate bias voltage \( V_G \) is present. Second, the slope is steeper for the linear regime of operation, as predicted by (3) derived from the TFT generic model. However, one sees that the different plots in the linear regime have different slopes and intercepts, owing to the error term in (3), while the plots for the saturation regime overlap, allowing for both \( \gamma \) and \( V_T \) to be reliably determined, and this is also predicted by (3). Thus, the integral function \( H_{VG} \) suggested in [6] is useful, and the TFT generic model helps one to realize that the \( H_{VG} \) function has to be used with data from the saturation regime of operation of the OTFT, not with data from the linear regime, as initially proposed in [6]. Note that there are also other methods for the extraction of \( \gamma \), e.g., based on differentiation of transfer \( I-V \) curves [7].

B. Extraction of Contact \( I-V \) Characteristics

The usefulness of the TFT generic model can be further illustrated by extraction of the \( I-V \) curves of the contacts in OTFTs. The extraction method is suggested in [8] on the basis of using the generic FET model with constant mobility, which is given by (1) with \( \gamma = 0 \). The method comprises a reduction technique, assuming that the contact voltage drop is at the source terminal \( (V_S = V_C) \), as discussed in the previous section, and then, one determines a unique \( I_D/W - V_C \) curve for several devices with different channel lengths, but otherwise identical, or at several biasing conditions in the linear regime, by only varying the mobility in the following equation (4):

\[
I_D/W = \mu C_I \left( (V_G - V_T)(V_D - V_C) - \frac{1}{2} (V_D^2 - V_C^2) \right).
\]

(4)

\[
H_{VG}(V_G) = \frac{\int_{V_T}^{V_G} I_D(V_G) dV_G}{I_D(V_G)} = \frac{1}{\gamma + 3} \frac{(V_G - V_T - V_S)^{\gamma + 3} - (V_G - V_T - V_D)^{\gamma + 3}}{(V_G - V_T - V_S)^{\gamma + 2} - (V_G - V_T - V_D)^{\gamma + 2}}
\]

\[
= \frac{V_G - V_T}{\gamma + 3}, \quad \text{in the saturation regime, when } V_D > V_G - V_T
\]

\[
\approx \frac{V_G - V_T}{\gamma + 2} \left[ 1 - \text{Error} \left( \frac{V_D}{V_G - V_T} \right) \right], \quad \text{in the linear regime, when } V_D \ll V_G - V_T
\]

(3)
From (4), the contact voltage drop \( V_C \) is

\[
V_C = V_S = (V_G - V_T) - \sqrt{(V_G - V_T - V_D)^2 + \frac{2I_D L}{\mu C T W}}. 
\]

(5)

The aforementioned equations apply for FETs, in which the mobility variation with the bias is low, i.e., \( \gamma \approx 0 \). Unfortunately, this is a rare case for OTFTs, and for cases when \( \gamma > 0 \), the method is now enhanced by utilizing the TFT generic model.

Note that (1) of the TFT generic model reduces to (4) when \( \gamma = 0 \). When \( \gamma > 0 \), \( V_S \) can explicitly be obtained from the TFT generic model in a form of (5), and the equation for the contact voltage drop \( V_C = V_S \) becomes

\[
V_G = V_S = (V_G - V_T) - \sqrt{(V_G - V_T - V_D)^2 + \frac{2I_D L}{\mu C T W}}. 
\]

(6)

with \( (\Delta L/L) \) being given in [1, Part I, eq. (15) or eq. (31)] for channel-length modulation.

To check the validity of the extraction method for the contact voltage drop with the TFT generic model included in (6), we use data from low-temperature-processed OTFTs with high-capacitance gate dielectric [9]. A high-mobility small-molecule organic semiconductor [10], deposited by vacuum evaporation, is utilized in these OTFTs. The result of the parameter extraction is shown in Fig. 2. The mobility enhancement factor \( \gamma \) and threshold voltage \( V_T \) were determined first from the \( H_{V_G} \) plot using data from the saturation regime according to (3), and then, the \( I_D-V_C \) characteristics of the ohmic contacts were obtained, as shown in Fig. 2, by taking a constant value for channel-length modulation factor \( \lambda = 3.5\% / \text{V} \) in the simpler relation \( \Delta L/L = \lambda |V_D - V_S| \) (see [1, Part I, eq. (15)]) as the first-order approximation, and only low-field mobility \( \mu_o \) was varied until overlap between the \( I_D-V_C \) curves at different \( V_G \)'s occurred. The snapback in the extracted \( I_D-V_C \) characteristics is spurious, owing to the use of a constant value for \( \lambda \) and the simpler equation \( \Delta L/L = \lambda |V_D - V_S| \) for channel-length modulation. Despite this, the fit of the TFT generic model to the measured data is very good, as shown in the inset of Fig. 2, by using the values of the model parameters, also shown in the figure. Evidently, the TFT generic model allowed us to characterize reliably this high-mobility OTFT with nearly constant contact resistance, even when the contact was ohmic and did not cause nonlinearity at the origin of the \( I_D-V_D \) output characteristic. This was not possible by using (4) and (5) for the simplified generic FET model with constant mobility. Thus, we demonstrate that the extraction procedure suggested in [8] is applicable for OTFTs with \( \gamma > 0 \), once one uses the TFT generic model in the procedure, showing that the TFT generic model becomes vital for OTFT compact dc models.

C. Extraction of Subthreshold Slope Voltage Parameter \( V_{SS} \)

Regarding the introduction of the subthreshold regime in the TFT generic model by (2) for the effective voltage overdrive \( (V_{EODR}) = f(V_G, V) \), two details have to be
carefully considered with regard to device characterization. In particular, the function causes an overestimate of the overdrive near the threshold voltage (well known from interpolation models for MOS transistors; for example, see [11, p. 177 and 426] and [12]), as shown in Fig. 3(a). Also, one may not be able to obtain accurate measurement data in the deep subthreshold regime, owing to leakage in the OTFT. Therefore, there may be a problem of using the relation $V_{SS}$ near the threshold voltage (well known from interpolation function given by (2)). One effect is the variation of threshold voltage $V_T$ with biasing. One usually observes that $V_T$ varies with drain bias voltages, and the sensitivity in this dependence can be denoted as

$$\delta_{VT} = \frac{\partial V_T}{\partial V_D} \approx \pm (0\% - 10\%).$$

The value is normally small in magnitude. The parameter $\delta_{VT}$ for the bias sensitivity of threshold voltage can be included by empirically modifying (2) for effective overdrive voltage $V_{EODR}$ as

$$V_{EODR} = f(V_G, V) = V_{SS} \ln \left(1 + \exp \left(\frac{(V_G - V_T - V) + (V_G - V) \times \delta_{VT}}{V_{SS}}\right)\right),$$

with $V = V_D$ or $V = V_S$.  

In this modification, effective threshold voltage $V_{T,eff} = V_T + (V_G - V_T) \times \delta_{VT}$ in the expression for effective overdrive voltage $V_{EODR}$ can physically be justified as a variation of the quasi-Fermi level (also known as IMREF) by variation of the gate bias voltage for the case of tail-distributed states [13]. However, the empirical introduction of $\delta_{VT}$ causes tradeoffs in characterization, as discussed in the following example.

The example is for modeling of all-region operation of a P3OT PTFT, and it is shown in Fig. 4. The measured dc curves are shown with lines in this figure, as reported in [14, Fig. 7]. The circles in Fig. 4 are calculated using the TFT compact dc model summarized in [1, Part I, Appendix] using the model parameters listed in Table I. The TFT is a p-channel transistor, and it was measured and modeled in all regions of biasing—normal biasing ($-V_D > -V_S = 0$) from linear to saturation regimes, both above and below threshold voltage, and reverse biasing ($-V_D < -V_S = 0$). A negative
Fig. 4. All-region modeling by the TFT compact dc model. The device is a p-channel TFT (see Table I for details). The voltages and currents are shown with their polarities, which are negative at normal biasing and positive at reverse biasing. (a) Output characteristics showing the complete set of data at bias voltages $V_D = \{-15 \text{ V to } +15 \text{ V, step 0.5 V}\}$, $V_G = \{-12 \text{ V to } +2 \text{ V, step 2 V}\}$, and $V_S = 0 \text{ V (ground)}$. (b) Subset of the data arranged as transfer characteristics at $V_D = \{15 \text{ V, 13.5 V, 12 V, 10.5 V, 9 V, 7.5 V, 6 V, 4.5 V, 3 V, 1.5 V, 0.5 V, } -0.5 \text{ V, } -3 \text{ V, } -15 \text{ V}\}$ from bottom to top.

TABLE I

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of FET</td>
<td>p</td>
<td></td>
</tr>
<tr>
<td>Channel width</td>
<td>W</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>Channel length</td>
<td>L</td>
<td>10 $\mu$m</td>
</tr>
<tr>
<td>Gate insulator capacitance</td>
<td>$C_G$ or $C_{ox}$</td>
<td>17.3 nF/cm$^2$</td>
</tr>
<tr>
<td>Threshold voltage</td>
<td>$V_T$ or $V_{TD}$</td>
<td>-6.1 V</td>
</tr>
<tr>
<td>Low-field mobility</td>
<td>$\mu_0$</td>
<td>$1.5 \times 10^{-4} \text{ cm}^2$/Vs</td>
</tr>
<tr>
<td>Voltage overdrive for $\mu_0$</td>
<td>$V_T$</td>
<td>1 V</td>
</tr>
<tr>
<td>Mobility enhancement factor</td>
<td>$\gamma$</td>
<td>1.1</td>
</tr>
<tr>
<td>Channel modulation factor</td>
<td>$\lambda$</td>
<td>0.05 %/V</td>
</tr>
<tr>
<td>Subthreshold slope voltage</td>
<td>$V_{SS}$</td>
<td>2 V</td>
</tr>
<tr>
<td>Sensitivity of $V_T$ to bias</td>
<td>$\delta_{VT}$</td>
<td>-0.05 V/V</td>
</tr>
<tr>
<td>Min (contact) resistance</td>
<td>$R_C$</td>
<td>16 M$\Omega$</td>
</tr>
<tr>
<td>Max (contact) resistance</td>
<td>$R_{C_{max}}$</td>
<td>39 M$\Omega$</td>
</tr>
<tr>
<td>Max. current for $R_{C_{max}}$</td>
<td>$I_{C_{max}}$</td>
<td>3 nA</td>
</tr>
<tr>
<td>Reduction exponent for $R_{C_{max}}$</td>
<td>$n_{BC}$</td>
<td>0.8</td>
</tr>
</tbody>
</table>

drain current denotes normal biasing, when the current exits from the drain terminal of the p-channel TFT. All voltages are given with their polarities referenced to the source terminal; the latter was always connected to ground ($V_S = 0 \text{ V}$). Therefore, the gate voltage is given with respect to the source terminal, ($V_G \equiv V_{GS}$).

The complete sets of the measured and modeled data are shown in Fig. 4(a), arranged as $I_D$–$V_D$ output characteristics for different $V_G$ values. We observe consistent behavior in the characteristics—ohmic and saturation regimes under normal biasing and diode-like characteristics under reverse biasing. Currents decrease in magnitude when changing $V_G$ from negative to positive values, causing clockwise “rotation” in the characteristics. We note good overlap between the model and the measured data when using the TFT compact dc model, whereas we have observed discrepancies by applying the MOS model with constant mobility, i.e., (1) with $\gamma = 0$.

Fig. 4(b) shows part of the data arranged as transfer characteristics, i.e., $I_D$ versus $V_G$ for different $V_D$ values. In this plot, we observe again very good matching between the measurement and the model. While under normal biasing, the characteristics intercept the horizontal axis at a nearly constant
voltage $V_T \approx -6$ V, the intercept moves toward positive gate voltages under reverse biasing since the roles of the drain and source terminals are interchanged under reverse biasing, and the gate voltage overdrive becomes approximately $\approx (V_G - V_T - V_D)$, so it varies when varying the drain bias voltage. We observe that the transfer characteristics under reverse biasing are equally spaced (shifted along the $V_G$-axis), as expected from term $V_{on} \approx (V_G + V_D)$, with $V_T < 0$ and $V_D > 0$ under reverse biasing, but the spacing is less than the step in $V_D$, and we have used the reduced spacing to determine parameter $\delta_{VT} = -5\%$ for sensitivity of $V_T$ to bias. However, one needed to compromise between $V_{GS}, \delta_{VT}, \gamma, V_T$, and contact resistance by fitting the dc curves since these parameters depend on the particular unknown shape of the distribution of tail states. The empirical introduction of parameter $\delta_{VT}$ was accompanied with problems when evaluating the parameter, as mentioned in [1, Part I, Sec. II] with a relation to requirement 5) for minimizing the set of model parameters, although it might be necessary to have such empirical parameters in OTFT compact models in some cases, for example, here, for a wide range of gate overdrive voltages.

III. Conclusion

By the examples in this paper, we have demonstrated the robustness of the proposed TFT compact dc model in [1, Part I], which is based on the symmetric TFT generic charge drift model. Overall, the characterization techniques do not need major reassessment as compared to those for crystalline FETs. The TFT generic model has clarified the ranges and procedures for parameter extraction, so that we have obtained reliable and good fitting of the TFT generic model to experimental data, without excessive fitting parameters or smoothing functions. Therefore, denoting the TFT generic model as the initial Level-0 model in symmetric TFT models, then the TFT compact dc model can be placed at Level 1 as the first step in all-region compact modeling of TFTs. The parameters and characteristic equations of the TFT compact dc model are summarized in [1, Part I, Appendix].

REFERENCES

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