Compact Modeling and Contact Effects in Thin Film Transistors

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Abstract—A compact model for the current–voltage characteristics of organic thin-film transistors (OTFTs), which includes the effects of the contact regions, is proposed. Different physical and morphological aspects of contacts with organic or other emerging materials such as graphene, semiconducting dichalcogenides such as MoS₂, or NW devices are described. The electrical behavior of the contacts is studied in OTFTs, and circuit models that describe them are reviewed. Two trends are observed in the current-voltage curves of the contacts of different OTFTs: linear and nonlinear, and different models are used to explain them. A unified model for the contact region that reproduces both trends and gathers the different physical and structural features of the contacts is developed. It is described by a single parameter and introduced in a generic analytical model for TFTs. The variability in OTFT structures, materials, and fabrication approaches gives rise to a strong variability in the values of the parameters of the model. In this regard, a characterization technique to determine the value of the parameters of the model from experimental data is also developed. Different physical tests are proposed to validate the results of the technique. The procedure is applied to recent experimental data for different pentacene-based transistors. The good agreement between the experimental data and our analytical results provides a way to relate the parameters of the model with the physical or geometrical origin of the contact effects in OTFTs.

Index Terms—Compact modeling, contact effects, contact modeling, organic thin-film transistor (OTFT), organic transistors, OTFT modeling, thin film transistors (TFTs).

I. INTRODUCTION

E MERGING technologies based on organic or polymeric materials [1]–[3], 2-D materials such as graphene [4], semiconducting dichalcogenides, MoS₂ or WSe₂ [5], or nanowire (NW) devices [6], are promising solutions in the fields of nanoelectronics, sensing, and photonics. Apart from having common applications, these materials share an additional common feature: the connection to the outer world via metal contacts.

In order to treat this common contact problem, we focus on one of these emerging technologies and one of its outstanding devices, the organic or polymeric (hereafter, the term organic is used for both) thin-film transistor (OTFT). These transistors are especially important as drive elements in niche applications such as the displays of mobile devices and televisions using the Active-Matrix Organic Light-Emitting Diode technology. Sensors, smart labels, solar cells, or smart clothing are other emerging and innovative applications where these transistors work as the main or control element. These transistors, and other organic devices, have received considerable attention because of the attractive properties of the materials they use. One key advantage of the organic material is that they can be solution processed [7]. The combination of soluble deposition techniques such as drop casting, spin coating, layer-by-layer, or roll-to-roll on flexible sheets with low-cost patterning equipment, such as ink-jet printers [8], reduces both capital and manufacturing costs compared with conventional crystalline electronics [9].

Contact effects in OTFTs are affected by the materials used for substrates, electrodes, or semiconducting films; the vertical and horizontal layout differences; the different processing steps such as vacuum processing, spin coating, printing, or stamping; the functionalization of interfaces; and the self assembling of organic materials. Though important in all devices, the contact effects are even stronger at the nanoscale [10]. To understand the effects of the contacts in OTFTs, the physical or geometrical origins of these effects are treated jointly in nanoscale and organic-thin-film structures.

The prediction and optimization of the performance of integrated circuits is necessary. For practical applications, compact models for electronic devices play an important role. Compact models must include the effects of beneficial and detrimental mechanisms that affect the device performance. In this paper, we focus on the incorporation of the contact effects in compact models of OTFTs.

This paper begins with the analysis of the properties of the contacts from a general point of view, treating common effects at nano- and large scale (Section II). In Section III, we analyze the advantages and disadvantages of previously developed models that describe the current–voltage curves of OTFTs with contact effects. In Section IV, we propose a compact model for the contact region of OTFTs that unifies different
trends found in the literature. This model is introduced in Section V in a previously developed generic model for OTFTs. In the following sections, the resulting model is applied to describe recent experimental data in OTFTs with contact effects.

II. Properties of Metal Contacts

Although the basic ideas of the metal-semiconductor contacts are reasonably well understood [11], [12], there are many side effects that impact their electrical behavior (Fig. 1). Here, we analyze the role of metal contacts in general terms, distinguishing between physical and geometrical effects.

A. Metal and Semiconductor Work Functions

According to the earliest and simplest models of the metal-semiconductor junction [13], [14], the difference between the metal and semiconductor work functions determines the ohmic or rectifying behavior of the contact. As an example, in graphene, Pd and Ni have been shown to provide a relatively low contact resistance. A higher contact resistance has been observed with Ti, Cr, and Al contacts [15]–[17].

The doping level in the semiconductor, even in bulk metal-semiconductor junctions, determines the position of the Fermi level in relation to the band edges, and thus the semiconductor work-function. Graphene displays an even stronger effect known as metal doping. Since monolayer graphene is gapless, realignment of the Fermi level due to the metal work function and the accompanying charge transfer can produce p-type or n-type behavior. In fact, a very small amount of electron transfer shifts the Fermi level significantly in graphene [18]. Thus, contacts in graphene can be chosen as n-type or p-type by selecting a metal with the suitable work function. When the graphene layer is deposited on a bottom gate, separated from it by a thin insulator layer, and then covered by a top contact (TC), the bottom gate bias has also been found to contribute to the metal-graphene contact resistance by changing the charge density in the graphene layer [15], [16].

B. Quality of the Contact and the Near-Interfacial Region

The position of the Fermi level is also affected by the bond structure of the contact region, with possible bond polarization [19] and/or a high interface state density in the semiconductor gap [20], [21]. A charge neutrality level is defined at the position of the Fermi level at the interface for which the net charge in the interface states is zero. The Fermi level is said to be pinned [22], [23]. It cannot shift very much from this position without a huge charge transfer. Thus, the resulting barrier height may be significantly different from that predicted by using the work functions of the separate materials. There are approaches to de-pin the Fermi-level and tune the metal-organic contact behavior such as the introduction of ultrathin interfacial insulators (Si₃N₄) [24]; the treatment of the contacts with a self-assembled monolayer (SAM) [25]; the introduction of a thin polyelectrolyte layer between the electrodes and the semiconductor [26]; or using a solid electrolyte directly as dielectric layer [27]. These observed reductions in the contact resistance can be explained either by a decrease of the barrier energy or by changes in the surface morphology [25].

Examples of this last effect can also be seen in different materials as graphene, MoS₂, or NWs. Graphene can be subjected to strong modifications originated by charge inhomogeneities induced by the metal [28], [29]. Questions have arisen as to whether the original work function of the graphene is preserved after the contact [17]. Density functional theory calculations have shown that the energetic separation between the Fermi level and the Dirac point in the contacts is a sensitive function of the metal-graphene distance [18]. In [28], it was found that the metal-graphene coupling strength is moderate, resulting in a modification of the graphene density of states (DOS) underneath the contacts small enough so that Fermi level pinning does not occur due to a lack of screening of the gate field. Furthermore, although capacitance-voltage measurements have shown that the original work function of graphene is not preserved, but it is pinned to the work function of the metal when the coupling is strong, the measurement of the quantum capacitance of graphene in the strong accumulation mode seems to prove that the characteristic properties of the graphene DOS are maintained [17].

A further difference in behavior of graphene contacts has been proposed to distinguish between side-bonded [Fig. 1(c)] and end- or edge-bonded [Fig. 1(d)] contacts [30]. While end contacts form strong covalent bonds to the dangling bonds at the edges, top, and bottom contacts (BC) form weaker van der Waals bonds. In both cases, results show that Fermi-level pinning has a small influence in the barrier height, in contrast with what happens in bulk metal-semiconductor junctions.

In the case of contacts to layered MoS₂, the widely used Au contact has been proposed to form a tunnel barrier and be the cause of the low values of the measured mobility [5], while metals with a low work function would efficiently...
inject electrons into the conduction band and would solve this problem. MoS$_2$ transistors with Sc [31] and Ti ohmic contacts [32] have been demonstrated, but the quality of the contacts should be improved in order to achieve the expected advantages of these materials.

While metal-induced gap states often determine the barrier height in bulk contacts, they can have a weaker impact in NWs. The electrostatics at reduced dimensions prevents the Fermi-level from being pinned since a strong band bending cannot be established due to the small size of these nanostructures. The region of a NW under the metal has also been shown to change its electrical properties after the application of a thermal treatment [6], [33].

In the case of OTFTs, the quality of the contacts also depends on the relative position of the source/drain (S/D) contacts, dielectric, and organic films. Bottom-gate OTFTs can be found in two typical structures: TC or staggered configuration [Fig. 1(a)] and BC or coplanar configuration [Fig. 1(b)]. The BC configuration is known to give inferior performance to the TC configuration for a range of deposition conditions and material thickness [34]. This can be attributed to the different arrangement of molecules in the organic material in relation to the proximity with other materials [34], [35].

C. Geometry of the Contact

The size and geometry of the electrodes are other factors that affect the performance of the transistors [36]. The description of the current flow through the contact region often requires a 2-D analysis, in particular for the TC staggered configuration [37], since the electrodes, dielectric, and semiconductor channel are not adjacent to each other [Fig. 1(e)]. A widely used model to deal with these aspects is the transmission-line (or transfer length) model (TLM) [38]. According to this model, instead of the physical length $L$, a contact transfer length, $L_T$, can be defined as the effective length over which injection occurs from the contact edge. In contacts to bulk and thin-film materials, $L_T = \sqrt{\rho_c R_s}$, where $\rho_c$ is the contact resistivity and $R_s$ is the sheet resistance under the contact. The transfer length determines the contact resistance through the relation $R_c = \sqrt{\rho_c R_s \tanh^{-1}(L/L_T)/\omega}$ [38], [39], where $\omega$ is the width of the contact.

The conventional expression of the TLM model has been applied to graphene [40]. To compute the transfer length in this system, a phenomenological expression for the sheet resistance of graphene under the contact [41] has to be used. This sheet resistance underneath the metal contact depends on the mobility, which in turn is strongly dependent on the deposition processes [10]. Experimental values of the contact transfer length in graphene show a dependence with the type of electrode [38]. The dependence on the material can be explained by the strength of the coupling between the metal and the semiconductor, since stronger coupling produces higher electron scattering and thus smaller $L_T$ values. The TLM has also been applied to NWs [42]. However, corrections are introduced due to the small dimensions of these structures: the contact length in many NW devices is typically comparable to the NW length; and the depth of the depleted or accumulated semiconducting region in metal-NW interfaces is typically comparable to the NW radii [43].

D. Transition Region

The region within the semiconductor in which the effects of the contact are still strong is called the transition or access region [Fig. 1(a) and (b)]. The band bending due to the contact can be extended on a length scale of tens of nanometers to micrometers. This region, called depletion layer in bulk junctions, develops beneath the contact, but it can spread out laterally toward the channel in thin films and nanostructures. If the thickness of the depletion layer, $W$, is greater than the film thickness or the radii of the nanostructure, then $W$ becomes size dependent and increases strongly at low doping concentrations. A long-distance band bending has been observed in NWs [44] and graphene [45]. A correct determination of $W$ is important since its value strongly influences the charge-injection in the contact [46]. As in bulk contacts, a heavy doping can be used in end-bonded NWs to reduce $W$, thus allowing electrons to tunnel through the barrier. Nevertheless, this method cannot be used in the case of side contacts since, for this to be useful, $W$ has to be smaller than the section diameter and a high doping level should be required when the NW diameter is reduced [46].

The change in the work function of graphene under metal also leads to band bending from the contact edge toward the channel [45], [47]. In the application of the TLM model to graphene, the contact resistance has been separated into two components: the actual contact resistance at the metal-graphene contact, $R_{CD}$, and the additional resistance due to the metal-contact doping, $R_{CD}$ [40]. This component, $R_{CD}$, arises in the transition region along which the Fermi level varies from the value pinned by the metal due to metal doping to the value in the channel region. Thus, it depends on the type of metal and differs significantly for each metal. The very small DOS around the Fermi level for graphene increases the screening length. The resulting long charge transfer region is a unique characteristic of the metal/graphene contact [10] and was reported to be $\simeq 0.5 \mu m$ [47].

In the transition region of the contacts of OTFTs, another mechanism takes place. The charges that are created near the surface of the electrode move through the organic material due to the electric field and the charge transport is space-charge limited. In the following sections, we discuss contact effects in TFTs.

III. CONTACT EFFECTS IN OTFTs

A. Models of Contact Effects

The objective, when modeling the contacts of OTFTs, is the reproduction of the current-voltage curves in the contact ($I_D-V_C$), where $V_C$ is the voltage drop in the contact region, and their dependences on bias voltages, temperature, and material parameters [48], [49]. The incorporation of physical models of the contacts, [11], [50], into the classical transistor models is not a trivial task because the contact effects interfere with other dependences in OTFTs [1]. In the literature, there are different electrical models that incorporate the voltage drop
and electric field-dependent mobilities have been incorporated into the current–voltage characteristic, and the access resistances at the contacts [Fig. 2(a)]. There are also associated methods to extract this voltage drop from the output characteristics of a transistor [2], [51]–[55].

The low conductivity region close to the contact is usually modeled with a parasitic resistance \( R_C \) [Fig. 2(b)]. Experimental investigations show that the magnitude of \( R_C \) is dependent on the gate bias, temperature, and ambient gas environment [2], [36], [52], [56].

Nonlinear behavior, also observed in the literature, is treated with a drain-voltage-dependent resistance [53], [54]. The slope of the \( I_D-V_C \) curve increases with \( V_D \), thus decreasing the contact resistance, being negligible in the saturation region [57]. This may be one reason for some authors to extract the field-effect mobility from the saturation region using the ideal MOS model [53], [58], [59]. However, this way to model nonlinear behavior can lead to confusion as noted in [60], where a diode was added in series with the contact resistance to model the nonlinear response. A study of the error made in the extracted values of the threshold voltage and mobility when considering the ideal MOS model in saturation is given in Section VI-A and Fig. 3. Better approaches that considers highly nonlinear drain and source contact series resistances and a gate-voltage-dependant mobility, \( \mu \propto (V_G - V_T)^\gamma \), \( \gamma > 0 \), can be found in the literature [51], [60]–[62]. This mobility dependence is extracted from theories such as the charge drift in the presence of tail-distributed traps (TDTs) [63] or variable range hopping (VRH) [64], [65]. In order to simulate nonlinear \( I_D-V_D \) output characteristics for organic BC TFTs, an equivalent BC TFT circuit that consists of the TFT with linear source and drain access resistances \( R_D \) and \( R_S \), respectively, and a pair of anti-parallel leaky Schottky diodes connected to each access resistor in series, see Fig. 2(c), was proposed [51]. Two diodes in parallel are needed to obtain symmetric current–voltage characteristics. The diode nonideality factor, \( \eta \), which is responsible for the steepness of the current–voltage characteristic, and the access resistances are the fitting parameters [51].

Recently, Schottky barriers at both drain and source contacts and electric field-dependent mobilities have been incorporated in 2-D numerical simulations to provide a vision on how the current spreads over the contact electrode [66], [67]. Although this model reproduces experimental data, the authors noted the sub-optimal values of some of the model parameters, such as the barrier height [67] or the diode nonideality factor, \( \eta \) [51]. Our interpretation is that simple electrical models valid for crystalline structures are substituting the two main physical theories that describe the metal-organic structure, injection, and space-charge-limited theories, thus providing suboptimal values for the model parameters.

### B. What is Missing?

Linear or nonlinear contact behaviors are observed experimentally at low-drain voltages in the output characteristics of the transistor. Different physical mechanisms have been proposed to explain such behavior [68], [69]. However, many of the models used to interpret the effect of the contacts on these \( I-V \) curves are reduced to finding a value for the contact resistance.

A suitable OTFT model should incorporate both linear and nonlinear behaviors for the contact \( I-V \) curves, with a method that unifies in some of its parameters the injection and transport mechanisms present in the metal-organic contacts and that considers the dependence of the \( I-V \) curves with the gate voltage and the temperature. In the following sections, we present such a model.

Also needed is a method that can be used to extract, from the \( I-V \) experimental data of a single transistor, [70] the parameters of the transistor, including those associated with the contact region. Many methods to extract the parasitic resistance are based on a set of transistors with different lengths, or on more complex techniques such as the four-probe method or the sophisticated electrical scanning probe microscopy techniques [71]–[73]. In this paper, we combine the proposal of a compact model for OTFTs including contact effects with a method to extract \( I-V \) curves at the contact from output characteristics measured in a single transistor.

### IV. Compact Model for the Contact Region of OTFTs

Different physical ways to inject charge from the metal contact (ohmic contacts, Schottky barriers, tunnel injection)
give way to linear or nonlinear contact behavior. Our method unifies all these physical mechanisms and behaviors by considering them as part of the boundary value for the charge density at the metal-organic interface, $q(0)$. Its value must contain information about the physical, morphological, and/or geometrical features of the contact region. Some of the charges get trapped, with no contribution to the current. The rest, the free-charge density $q \theta p(0)$, where $\theta$ is the ratio of free to total charge density, drifts through localized sites in the transition region of the contact, as mentioned at the end of Section II. Independent of the value of $p(0)$, or how this charge has appeared at the metal organic interface, a relation between the current density $j$ and the applied voltage $V_C$ can be found by solving the transport equations in the semiconductor [55], [68]

$$V_C = (2/3) \left( \right)^{1/2} \left( x_C + x_p \right)^{3/2} - \left( x_p \right)^{3/2}$$

where $x_p = j \epsilon p \left( \right)^{2} \left( 2 \mu q p(0) \right)^{2}$

and a quadratic behavior (Mott–Gurney law) if the characteristic length $x_p$ is much smaller than the contact length $x_C$

$$I_D \approx S \theta p \left( \right)^{2} V_C / x_C \equiv V_C / R_C$$

$$I_D \approx 9 / 8 \epsilon p \left( \right)^{3} V_C \equiv M V_C^2$$

(3)

The two asymptotic situations defined in (2) and (3) also define limit distributions of the free charge density in the contact. $q_\text{P_contact}$ in the case of linear characteristics, $q_\text{P_contact}$ is constant and its value can be represented by the value this variable takes at $x = 0$, $q_\text{P_contact} = \theta q p(0)$, which is the value that appears in (2). The effective area of the contact where the current flows can be expressed as $S = w \times IC$, where $IC$ is an effective thickness, and $w$ is the channel width. Considering the free-charge surface density $\sigma_{\text{contact}} = \theta q p(0) / IC$, the following relation is obtained from (2):

$$\sigma_{\text{contact}} = x_C / (w \mu R_C).$$

(4)

In the case of quadratic behavior, the distribution of the free charge density, not uniform along the contact region [50], is given by

$$q_{\text{P_contact}}(x) = \left( j e \beta \right) \left( 2 \mu x \right)^{1/2}$$

(5)

If the parameter $M$ is known (in Section VI, a parameter extraction method is proposed), $p_{\text{contact}}$ can be evaluated as a function of arbitrary values of the contact voltage $V_{C0}$ and the position $x_0$ close to the contact. This provides physical information about the extracted parameter $M$. In order not to work with the unknown effective thickness $IC$, the free charge surface density is evaluated instead, $\sigma_{\text{contact}} = q_{\text{P_contact}}(x_0) / IC$. Thus, combining (3), (5) and $j = M \times V_{C0}^2 / S$, the following relation results:

$$\sigma_{\text{contact}}(x_0) = (2 M V_{C0}^2) \left( \right)^{1/2} \left( x_C^3 / (x_0 \mu w^2) \right)^{1/2}$$

(6)

The inverse of the contact resistance $R_C$ in (4), and the parameter $M$ in (6) are proportional to the free-charge surface-density $\sigma_{\text{contact}}$. Thus, whatever trend $\sigma_{\text{contact}}$ has with the gate voltage, the parameters $1 / R_C$ and $M$ will have the same trend, except for a multiplying factor.

V. INCORPORATION IN AN OTFT MODEL

The model for the contact region presented above is useful when integrated in a compact model for OTFTs. For this reason, we consider a generic analytical model for the current–voltage characteristics of OTFTs [61], [62]. In that work, the authors related the drain current $I_D$ and the voltages at the borders of the intrinsic transistor, $V_G$, $V_D$, and $V_S$ [Fig. 2(c)]

$$I_D = \left( \right)^{\gamma + 2} / \left( \right)^{\gamma + 2} \left( \right)^{\gamma + 2}$$

(7)

where $C_i = \epsilon_i / \tau_i$ is the gate insulator capacitance per unit area, $\epsilon_i$ is the insulator dielectric constant, $\tau_i$ is the insulator thickness, $V_T$ is the threshold voltage, $w$ is the transistor width, and $L$ the channel length. The result is equivalent to the well-known and widely used generic FET model with a constant mobility. This model is derived considering that the voltage drop at the drain contact is small in comparison to the voltage drop at the source contact [48] [Fig. 2(a)]. Thus, the contact voltage is reduced to the voltage drop between the external source terminal and the internal source ($V_S \equiv V_C$) [Fig. 2(d)]. It also considers that the mobility $\mu$ is written according to the aforementioned common theoretical result [63], [64], [75]

$$\mu = \mu_0 (V_G - V_T - V_S)^2, \quad \gamma = 2 T_0 / T - 2$$

(8)

where $V_S$ is the potential in the semiconducting film of the TFT, $\gamma$ is the mobility enhancement factor, $T_0$ is the specific equivalent temperature that represents the steepness of the DOS exponential tail, and $\mu_0$ is the mobility-related parameter with dimensions $cm^2/(V1s)$. In order to provide a single value for the voltage dependent mobility, the mobility is evaluated at $V_{GT} = V_G - V_T = 1 V$ [61], thus $\mu (V_G = 1 V) = \mu_0$ in $cm^2/(V)$. This model (7) is complemented with a model for the current–voltage curves in the contacts, as defined in (2) or (3). A new parameter, $R_C$ (or $M$), not present in (7), is added to the set of parameters of the model. The parameters $R_C$ and $M$ are expected to depend on the gate voltage, as many experiments have shown the dependence of the $I-V$ curve at the contacts with the gate voltage [2], [52], [76].

To describe this dependence, we analyze the two regions of different conductivity distinguished along the channel of the organic transistor [3], [48], [77]: the low conductivity region close to the contact defined by the free-charge surface-density $\sigma_{\text{contact}}$ and the high conductivity region in the intrinsic
channel defined by its counterpart free-charge surface-density, usually expressed as [78]

\[ \sigma_{\text{channel}} = C_1(V_G - V_T). \]  

(9)

The free charge density in the contact region can be considered as a fraction of the last one: \( \sigma_{\text{contact}} = \sigma_{\text{channel}}/K \). Although \( K \) is an undetermined constant, there is no physical reason to believe that the mobile charges in these two adjacent regions start appearing at very different gate voltages, or follow very different trends, unless local nonuniformities were present just at the contact region. Therefore, \( \sigma_{\text{contact}} \) can be assumed proportional to \( (V_G - V_T) \). Introducing this dependence and the gate voltage dependence of the mobility (8) in (4) and (6), we can write, respectively

\[ 1/R_C = [(mC_1\mu_o)/(Kx_C)](V_G - V_T)^{(1+\gamma)} \]  

(10)

\[ M = \frac{3C_1\mu_o}{2KVC_0} \left[ \frac{x_0w^2}{x_C^2} \right]^{1/2} (V_G - V_T)^{(1+\gamma)} \]

or by defining the parameters \( a_1 \) and \( a_2 \)

\[ 1/R_C = a_1(V_G - V_T)^{(1+\gamma)} \]  

(11)

\[ M = a_2(V_G - V_T)^{(1+\gamma)} \]

Thus, we can express (2) and (3) in a more compact way

\[ V_C = a_m^{-1} I_D^{1/m} (V_G - V_T)^{(1+\gamma)/m}, \quad 1 \leq m \leq 2. \]  

(12)

Although the range \( 1 \leq m \leq 2 \) includes all the cases covered by (1), the practical cases can be restricted to the limit cases \( m = 1 \) and \( m = 2 \). The election of \( m = 1 \) or \( m = 2 \) is decided by a simple linear regression study of the \( I_D - V_D \) curves at low values of \( V_D \).

The combination of (7) and (12) defines a compact relation between the drain current and the external terminal voltages. This model has parameters that can be characterized relatively easily, or even guessed, preventing unnecessary phenomenological fitting parameters or even the use of transistors with different channel lengths. Our model is complemented with an extraction procedure of its parameters \( V_T, \mu_o, \gamma, \) and \( a_m \) or the equivalent \( M(V_{GS}) \) or \( R_C(V_{GS}) \) from the current–voltage curves of an OTFT. It follows the main ideas of the procedure proposed in [61] and [62]. However, some modifications are made in order to eliminate errors in the determination of the model parameters when large contact voltages are present and to extend its application to output characteristics measured in single-length transistors. As different models or different sets of values of our model can reproduce the experimental data, tests are also provided in order to validate the physical meaning of the extracted values for the parameters.

VI. PARAMETER EXTRACTION METHOD

The objective of the extraction method is to determine the values of the parameters \( \mu_o, \gamma, V_T, \) and \( a_m \) that define the compact model for the OTFT (7) including the contact effects (12). The independent determination of \( M \) (or \( R_C \)) for each \( V_{GS} \) is preferred to the determination of the compact parameter \( a_m \). It is slower but more general, since it can be applied to situations where instabilities or trapping effects appear in the transistor [79]. In these cases, the evolution of \( \sigma_{\text{channel}} \) with \( V_G \) (9) can separate from a straight line due to slight modifications in the threshold voltage.

We propose a five step procedure with several tests to check the physical meaning of the results. In a previous work [74], we proposed a method to extract the parameters of this model from experimental \( (I_D - V_D) \) curves including the voltage drop at the contact. It was applied and tested successfully in an hypothetical p-type OTFT with known parameters [80]. It was adapted later to \( I_D - V_D \) curves with hysteresis [81]. In this paper, we compile all the previous ideas to make the method completely general and applicable to OTFTs.

A. Importance of a Compact Model With Contact Effects

Prior to the presentation of our characterization procedure, we highlight the importance of using a proper compact model for OTFTs with contact effects in the determination of essential device parameters such as the mobility \( \mu \) and the threshold voltage \( V_T \). It is deduced from many of the references cited in this paper that the apparent mobility extracted from current–voltage curves with contact effects is different from the real one. However, in many publications, the classical MOS model is still used to characterize the mobility. In saturation, the effects of the contacts are lower than in the linear region of operation. However, the saturation region is not free from errors. In the following, we determine such errors. To do this, we create a set of output characteristics for a hypothetical transistor for which we know all its parameters: \( k_o = \mu_o \gamma w/L, \gamma, V_T, \) and \( M \) (or \( R_C \)). We build the output characteristics of this transistor by combining an intrinsic transistor modeled with the ideal MOS model plus a contact region at the source [Fig. 2(d)]. The classical MOS model can be easily deduced from (7) by assuming \( V_S = 0 \) V and \( \gamma = 0 \). The contact region is modeled by (2) or (3).

Once the output characteristics are created, the ideal MOS equations are used to extract the parameters of such a hypothetical transistor. Fig. 3 represents the errors in this determination in the saturation region. The test is done for different values of \( k, M, \) and \( R_C \) (\( M \) and \( R_C \) are assumed independent of the gate voltage; a dependence with the gate voltage would increase the error). Fig. 3 defines the ranges of these parameters where the relative error is not negligible and the classical MOS model is inaccurate. This figure is also useful since we can establish a relation between the values of \( M \) and \( R_C \) that produce the same effects.

B. Our Extraction Method

The five steps of our extraction procedure are (Fig. 4) now presented.

1) Initial estimation of \( \mu \) and \( V_T \). The experimental data in the saturation region are fitted with the classical MOS model [(7) with \( \gamma = 0 \) and \( V_S = 0 \) V] to determine apparent values for the threshold voltage and the mobility.

2) Initial estimation of \( M \) (or \( R_C \)). The contact model is added to the drain voltage by combining \( V_D = V_{DS} + V_S \) and (3) (or (2)) and assuming \( V_G = V_{GS} \).


[Fig. 4 II]. The resulting equations are used to fit the whole experimental \( I_D(V_D, V_G) \) curves to extract values of \( M(V_G) \) (or \( R_C(V_G) \)). Then, an averaged value for the contact voltage in saturation, \( V_{G_{\text{average}}} \), can be obtained.

3) Extraction of \( V_T \) and \( \gamma \) with the \( H_{VG} \) function [61], [82] applied to the experimental data in saturation. The \( H_{VG} \) function is defined as

\[
H_{VG}(V_G) = \frac{\int_{V_T}^{V_G} I_D dV_G}{I_D(V_G)}.
\]

The \( H_{VG} \) function can be derived from the TFT generic model (7) in the linear and saturation modes. In the saturation mode (\( V_D > (V_G - V_T) \)), \( H_{VG} \) is linear with \( V_G \) [61]

\[
H_{VG}(V_G) = \frac{(V_G - V_T - V_S)}{(\gamma + 3)}.
\]

The values of \( \gamma \) and the threshold voltage \( V_T \) can be extracted easily from the slope of \( H_{VG}(V_G) \) and intercept with the \( V_G \) axis, by assuming \( V_S = V_{G_{\text{average}}} \) in (14).

4) Extraction of \( \mu_0 \) and \( M \) or \( R_C \) (or \( a_m \)). Assuming the previous values of \( V_T \) and \( \gamma \) as correct, the parameters \( \mu_0 \) and \( M \) are iteratively modified until a good fitting is obtained between the theoretical model (7) and (3) [or (2)] and the experimental data. As initial guessed values for the parameters \( \mu_0 \) and \( M \), the ones obtained in steps 1) and 2), respectively, can be used. Since the experimental data are reproduced with a model that depends on several parameters different solutions may be expected. Thus, some tests must be done to validate the solution.

5) Tests of the solution.

a) The values of the parameters \( (\mu_0, \gamma \text{ and } V_T) \) and the experimental data are introduced in the compact model (7). The \( I_D-V_G \) curves at the contact are extracted, and must be consistent with the trends expected by (3) [or (2)]. In case of a negative test, new values of \( \gamma \) and \( V_T \) must be proposed in part 4).

b) Parameters \( M \) (or \( 1/R_C \)) are represented as a function of \( V_G \). These parameters include information about the free charge density at the contact region. Assuming that the free charge density in the channel and contact appears at the same voltage, the evolution of \( M \) (or \( 1/R_C \)) must intercept the \( V_G \)-axis at the value obtained for \( V_T \). In case of a negative test, a new value of \( V_T \) must be proposed in part 4).

VII. RESULTS AND DISCUSSION

To check the validity and applicability of our compact model with contact effects, (7) and (12), and the extraction method, we analyzed published \( I_D-V_G \) experimental curves from pentacene-based OTFTs at different conditions. We analyzed the effects of temperature, contact length, material length, barrier height at the interface, TC and BC configurations, and linear or nonlinear behavior. We also show a situation in which the parameters \( R_C \) or \( 1/M \) do not follow the trend with \( V_G \) indicated in (11). This can be typical of OTFTs with trapping effects.

A. Effects of the Size of the Structure

Fig. 5(a) shows a comparison of experimental data (symbols) with the results of our model (solid lines). They correspond to inverted-staggered OTFTs with thermally evaporated pentacene and Au S/D contacts [83], two different
channel lengths \((L = 100\) and 150 \(\mu m\)) and different thickness of the pentacene semiconductor or contact lengths \((x_C = 50, 100\) and 150 \(nm\)). The whole set of curves is reproduced with our model with the same set of parameters: \(V_T = -3.14 \text{ V}\), \(\gamma = 0.59\), \(\mu_0 = 0.09 \text{ cm}^2/(V\text{s})\), and \(a_2 = 3.9 \times 10^{-8} \times (50 \text{ nm}/x_C) \text{ A/}V^{3+\gamma}\). A convergence test is made to validate these parameters [Fig. 5(b)]. Combining in (7) the above values of \(\mu_0\), \(\gamma\), and \(V_T\) with the experimental values \((I_D, V_D)\) corresponding to \(x_C = 50 \text{ nm}\) of Fig. 5(a), then the current-voltage curves at the contact can be obtained [symbols in Fig. 5(b)]. In the same figure, the curves \(I_D-V_C\) calculated from (3) and (11) with \(a_2 = 3.9 \times 10^{-8} \times (50 \text{ nm}/x_C) \text{ A/}V^{3+\gamma}\) are shown in solid lines. The matching of the symbols and solid lines indicates that the solution is physically acceptable. Table I shows the values of the parameters of the model extracted during the different steps of the fitting procedure. The value of the threshold voltage is modified in the different steps. This value depends on the model employed and whether contact effects are included or not. Actually, the value extracted from the \(H_{VG}\) is valid only when the averaged contact voltage \(V_S = V_{\text{average}}\) is considered in (14). The value of the mobility is also altered during the fitting procedure, from a constant value with the ideal MOS model to a gate-voltage dependent relation modeled by \(\mu_0\) and \(\gamma\). In the table, the value of the mobility obtained with the ideal MOS model is greater than the one obtained for \(\mu_0\) with the compact model. The value of \(\mu_0\) must be understood as the value of the mobility at \(V_{GT} = 1 \text{ V}\). The value at \(V_{GT} = 40 \text{ V}\) is \(\mu = 0.61 \text{ cm}^2/(V\text{s})\). For these samples, the value obtained with the compact model represents an averaged value, since the averaged contact voltage is not too large \(V_{\text{average}} \approx -2.4 \text{ V}\).

The value of \(\mu_0\) is in agreement with the value reported in [83] for the mobility in the conducting channel, in the range of 0.3–0.5 cm²/Vs. In [83], the path that the current follows from the TC down to the conducting channel is modeled with a factor about 3 lower mobility, attributed to an anisotropic mobility. The anisotropic conduction in the contact region and in the intrinsic channel is also compatible with our model. Assuming the same value for the mobility in the contact region and in the conducting channel and introducing the value extracted for \(a_2\) and the geometrical parameters of the OTFTs [83] in (3) and (11), the free to total charge ratio \(\theta\) is found to be greater than one. Thus, a lower value of the mobility is necessary to obtain values of \(\theta\) with a physical meaning. A value around \(10^{-4}\) cm²/Vs, as provided in [83], results in values of \(\theta\) in the range \([-20, -60]\) V.

### Table I

<table>
<thead>
<tr>
<th>Model</th>
<th>Ideal</th>
<th>(H_{VG} (V_T = 0))</th>
<th>(H_{VG}) Compact</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_T \text{ (V)})</td>
<td>-10.31</td>
<td>-0.79</td>
<td>-3.14</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>0</td>
<td>0.49</td>
<td>0.49</td>
</tr>
<tr>
<td>(\mu_0 \text{ (cm}^2/(V\text{)}^{1+\gamma}s))</td>
<td>0.65</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**B. Transistor with Instabilities**

Fig. 6(a) and (b) shows, with symbols, the output characteristics with hysteresis measured in a top gate staggered pentacene OFET with Au S/D electrodes [84]. The gate dielectric is Poly(vinyl alcohol) (PVA), known to produce hysteresis in OTFTs. The dielectric thickness is \(t_1 = 1 \mu m\), the channel length \(L = 100 \mu m\), the transistor width \(w = 1 \text{ mm}\) and the organic-film thickness \(t_0 = 100 \text{ nm}\). These current-voltage curves in the forward scan (FS) and the backward scan (BS) are compared with the compact model (7) in combination with the linear model (2). Our numerical results are shown in solid lines in Fig. 6(a) and (b). The parameters obtained from the fitting procedure are: \(\mu_0 = 0.0041 \text{ cm}^2/(V^{1+\gamma}s)\), \(k_0 = 1.4 \times 10^{-10} \text{ A/}V^{3+\gamma}\), \(\gamma = 0.05\), \(V_{FS} = 5.18 \text{ V}\), and \(V_{BS} = 3.55 \text{ V}\). The values of \(1/R_C\) in (2) are represented as a function of \(V_G\) for the FS and BS in Fig. 6(c). Since the charge density in the contact is proportional to \(1/R_C\), this figure shows how the threshold voltages of the charge density in (4) coincide with the values of \(V_{FS}\) and \(V_{BS}\) found in the fitting procedure. Thus, the values of the fitting parameters are coherent among themselves and the solution can be considered physically acceptable.

At higher voltages, the evolution of the charge density at the contact deviates from the linear trend. The free charge density usually follows a linear trend with the gate voltage (9). However, in situations where instabilities or trapping effects appear in the transistor, the threshold voltage can vary and \(\sigma_{\text{channel}}\) can deviate from this trend. In cases of slight modifications of the threshold voltage, our model is still valid [81]. Instead of combining (7) and (12), (7) must be combined with (2) or (3). In these cases, the independent determination of \(M\) or \(R_C\) for each \(V_{GS}\) is preferred to the determination of the compact parameter \(\sigma_m\). We have reported how information of the trapping processes during hysteresis can be extracted with the analysis of the contact region of the transistor [81].

**C. Effects of the Temperature**

In Fig. 7, we analyzed experimental data measured at different temperatures on bottom gate evaporated-pentacene based OFETs with top Au S/D contacts, \(L = 100 \mu m\) and \(w = 700 \mu m\) [58]. The thickness of the SiO\(_2\) is 270 nm and the
pentacene thickness, which is the same as contact length $x_C$, is 70 nm. The experimental curves have been reproduced with our model with the parameters shown in Table II. On the one side, the variation of the threshold voltage with temperature can be considered large. This variation can be attributed to propagation of errors in the determination of the contact voltage. In any case, the result improves the much greater variation obtained in [58]. Studies focusing on OTFTs without contact effects obtain an even lower variation of the threshold voltage [85]. On the other side, the parameter $\gamma$ follows the trend with the temperature given in (8) with $T_0 = 373.8$ K, and $\mu_o$ also follows the trend with temperature proposed in [64, eq. (15)] with $\sigma_0 = 10^8$ S/cm and $\alpha^{-1} = 0.31 \AA$, thus validating our results.

The average contact voltage is estimated from these parameters, resulting in $V_{C_{\text{average}}} = -1.8$, $-0.4$, $-0.1$ V at 300, 325, and 350 K, respectively. The contact effects decrease when the temperature increases. Another way to analyze the effects of the contacts with the temperature is by evaluating the surface free-charge density at the contact region. Assuming $V_{C_0} = -1$ V in (6), the surface concentration of free charges at the contact can be compared with the surface concentration of free charges along the channel. Fig. 7(d) shows this comparison evaluated at $V_G = -20$ V. At 350 K the effect of the contact region is almost negligible since the free charge density is almost uniform along the whole structure. However, at 300 K, the free charge density in the contact region is almost four orders of magnitude lower than in the channel.

D. Effects of the Energy Barrier

In Fig. 8, we analyzed the experimental data measured in a BC pentacene TFT with Au-Pd contacts [2]. The dimensions of the transistor are $L = 10 \mu m$, $w = 220 \mu m$, and the gate dielectric is SiO$_2$ with 290-nm thickness. Fig. 8(a) corresponds to the configuration Au-source/Pd-drain, and Fig. 8(b), to the configuration Pd-source/Au-drain. The solid lines in both figures show the results of our model using the parameters: $V_T = 16$ V, $\gamma = 0.18$, and $\mu_o = 0.47$ cm$^2$/V$^2$s, ($k_0 = 5.02 \times 10^{-8}$ A/V$^{2+\gamma}$). The effect of changing the electrode only affects the value of the parameter $\alpha_2$: $\alpha_2(Au) = 2.61 \times 10^{-10}$ A/V$^{3+\gamma}$ and $\alpha_2(Pd) = 2.62(Au)/5.19 = 5.04 \times 10^{-10}$ A/V$^{3+\gamma}$. However, the use of the classical MOS model to characterize the transistor in Fig. 8 gives different values for the mobility and the threshold voltage: $\mu = 0.63$ and 0.42 cm$^2$/Vs and $V_T = 15$ and 14 V for Fig. 8(a) and (b), respectively [2]. The importance of using a proper compact model that includes the contact effects of OTFTs is again demonstrated. On average the voltage drop at the contacts is $V_{C_{\text{average}}} = -9.64$ V.

VIII. IDEAS FOR FUTURE WORK

One of the strengths of our model is the capability to separate the charge density at the contact region from the charge density in the channel. We have seen that changes in the temperature lead to small changes in the free charge density in the channel but large changes in the contact region [Fig. 7(d)]. Some of the niche applications where OTFTs play an important role are as sensors [86], [87] or photodetectors [88], for example. Monitoring the free charge density in the contact region under the presence of different atmospheres or irradiation might help to explain the sensing characteristics of these devices. In this regard, our model is a potential tool for this task.

In fact, these suggestions agree with recent studies of chemical sensors [87] and phototransistors. [88]. The generation of charges by different physical or chemical mechanisms and
the trap charging in the contact regions decrease the contact resistance. The chemical or irradiation effects on the TFT parameters such as the off-current, threshold voltage, bulk mobility, and field-effect mobility can be investigated using our model. A link between the contact resistance and the threshold voltage would open the possibility of designing the source and drain contacts using different metals or incorporating SAMs to optimize $R_C$ and maximize the sensing effect in organic TFTs.

Another strength of our model is its applicability to OTFTs that differ in structure and morphology. The parameter $a_m$ added to the generic drift MOS model is enough to quantify the effects of the contacts. One step forward in the improvement of OTFTs would be to find the relation between this parameter and structural variations in the active organic material, such as grain boundaries, interface states or defects. This would help to achieve good reproducibility in the fabrication of OTFTs.

We have seen in this paper an example of what is found in the state-of-the-art OTFTs: a great variability in the characteristics of similar OTFTs. Until the technology achieves good reproducibility in the fabrication of OTFTs, simple and tunable compact models such as the one presented in this paper must run in parallel with high accuracy measurements [71], [72].

### IX. Conclusion

By carefully inspecting past and current achievements in modeling the contact effects of OTFTs, we have proposed a model for the current–voltage curves at the contact region that unifies different trends found in experimental data. This model, which is characterized by only one parameter, has been embedded in a generic charge drift model that also includes a gate voltage-dependent mobility. The model is easily reduced to the generic FET model with a constant mobility and no contact effects.

We have proposed a characterization procedure to extract the values of the parameters of the OTFT model, which does not need major reassessment as compared to those for crystalline FETs. We have obtained reliable and good fitting of the TFT generic model to experimental data. We have checked the consistency in the bridge between physical origin of the contact effects and the parameters of the model. The proposed model is a powerful tool to describe the large amount of different structures or fabrication processes the same type organic material in an OTFT can be subjected to.

The model captures, in a consistent and relatively simple way, the essential behavior of transistors when temperature, channel length, and width and different energy barriers at the contact region are varied. It also provides information about the free charge density along the transistor channel.
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