Compact Modeling for the Drain Current of an “Extrinsic" Organic Field-Effect Transistor Based on an Improved Smoothing Function

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Abstract

Previously we proposed a new smoothing function to bridge the transition between the linear regime and the saturation regime, for the “intrinsic” (neglecting the contact resistances) MOSFET [1,2]. In contrast to the traditional smoothing function, this approach gives a monotonic decrease of the differential conductance from the maximum value in the linear regime to the minimum value in the saturation regime. We also proposed a linear approximation for an “extrinsic” (accounting for the source and drain resistances) MOSFET drain current dependence on the drain bias in the saturation regime [3]. Finally, by using this approximation and the new smoothing function we developed an “extrinsic” MOSFET above the threshold drain current compact model [4]. We now use a similar approach for the “extrinsic” organic field-effect transistor (OFET) compact modeling. In [5] the approach, previously developed for a MOSFET in [1,2], was applied for yielding linear approximations for the output characteristics in the linear and saturation regimes for the “intrinsic” OFET. Next, we proposed an approximate equation for the “extrinsic” OFET saturation current [6]. In addition, we proposed a linear approximation for an “extrinsic” OFET drain current dependence on the drain bias in the saturation regime [7]. As a basis, in our work, we use the compact model of a p-channel OFET proposed in [8,9] and developed on the basis of the traditional MOSFET compact models. Now we present an “extrinsic” compact model for the above threshold drain current of an OFET based on a new smoothing function, on a new approximate equation for the saturation current, and on a new linear approximation for a drain current in the saturation regime [10]. This model takes into account the source and drain resistances and provides a monotonic decrease in the differential conductance with the drain bias rise.
As a basis, in our work we use the compact model of p-channel OFET proposed in [1] and developed on the basis of the compact model MOSFET Level 1 for a long-channel MOSFET. Typical parameters of pentacene OFET with p-type channel and parameters of its compact model are given in Table 1.

### Table 1. Typical parameters of pentacene OFET with p-type channel [1].

<table>
<thead>
<tr>
<th>$\gamma$</th>
<th>$V_{\text{th}}$ (V)</th>
<th>$\mu_{\text{FET}}$ (cm$^2$/V·s) ($V_{GS} = -50$ B)</th>
<th>$\alpha_S$</th>
<th>$R_T$ (kΩ)</th>
<th>$\lambda$ (V$^{-1}$)</th>
<th>$L$ (μ)</th>
<th>$W$ (μ)</th>
<th>$C_i$ (nF/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.91</td>
<td>-12</td>
<td>0.13</td>
<td>0.46</td>
<td>24</td>
<td>1.2 · 10$^{-3}$</td>
<td>40</td>
<td>1000</td>
<td>3.3</td>
</tr>
</tbody>
</table>

$\mu_0$ is the conversion mobility set to 1 cm$^2$/V·s and with parameter $V_{aa} = 358$ V.

In our work, the value of the total resistance of the contacts $R_T = 2.4$ MΩ ($R_S = R_D = 1.2$ MΩ) was chosen sufficiently large to more clearly demonstrate the influence of the contact resistance on the calculation results.

In our calculations, we used a relatively large hypothetical value $\lambda = 0.01$ V$^{-1}$ to emphasize the effect of nonzero differential conductance in saturation regime on OFET characteristics.
The "intrinsic" OFET in the linear (ohmic) regime

For linear regime we have:

$$I_{\text{LIN}} = g_{\text{LIN}}V_{DS}$$  \hspace{2cm} (1)

The overdrive voltage:

$$V_{GT} = V_{GS} - V_{th}$$  \hspace{2cm} (2)

The transconductance parameter:

$$\beta = K \mu_{\text{FET}}$$  \hspace{2cm} (3)

Mobility taking into account the field effect ($\mu_0$ is the conversion mobility set to 1 cm$^2$/V·s and with parameter $V_{aa} = 358$ V):

$$\mu_{\text{FET}} = \frac{\mu_0}{V_{aa}} V_{GT}^\gamma$$  \hspace{2cm} (4)

The parameter of the geometry of the gate capacitor and material characteristics (here $L$ and $W$ are the transistor channel length and width, $C_i$ - insulator capacity per unit area):

$$K = \frac{W}{L} C_i$$  \hspace{2cm} (5)

The insulator capacity per unit area ($\varepsilon_{\text{ox}}$ - dielectric permittivity of the gate dielectric, $\varepsilon_0$-electric constant, $d_{\text{ox}}$-thickness of the gate dielectric.):

$$C_i = \frac{\varepsilon_{\text{ox}}\varepsilon_0}{d_{\text{ox}}}$$  \hspace{2cm} (6)

The differential conductance:

$$g_{\text{LIN}} = \frac{\partial I_{\text{LIN}}}{\partial V_{DS}}\bigg|_{V_{DS},V_{GS}}$$

$$g_{\text{LIN}} = \beta V_{GT} = K \frac{\mu_0}{V_{aa}} V_{GT}^\gamma V_{DS}$$  \hspace{2cm} (7)

The output resistance:

$$R_{\text{LIN}} = \frac{1}{g_{\text{LIN}}}$$  \hspace{2cm} (8)

The transconductance:

$$g_{m\text{,LIN}} = \frac{\partial I_{\text{LIN}}}{\partial V_{GS}}\bigg|_{V_{DS},V_{GS}}$$

$$g_{m\text{,LIN}} = (\gamma + 1) K \frac{\mu_0}{V_{aa}} V_{GT} V_{DS}$$  \hspace{2cm} (9)
The “saturation point” for the “intrinsic” OFET

<table>
<thead>
<tr>
<th>The saturation voltage :</th>
<th>( V_{SAT} = \alpha_s V_{GT} ) (10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The saturation current :</td>
<td>( I_{SAT} = g_{LIN} V_{SAT} = \alpha_s K \frac{\mu_0}{V_{aa}} V_{GT}^{\gamma+2} ) (11)</td>
</tr>
<tr>
<td>( b_{m,SAT} = \frac{\partial V_{SAT}}{\partial V_{GS}} \bigg</td>
<td><em>{V</em>{GS}} )</td>
</tr>
<tr>
<td>The transconductance: ( g_{m,SAT} = \frac{\partial I_{SAT}}{\partial V_{GS}} \bigg</td>
<td><em>{V</em>{GS}} )</td>
</tr>
<tr>
<td>The equation linking ( I_{SAT} ) and ( V_{SAT} ) :</td>
<td>( I_{SAT} = \alpha_s^{-\frac{\gamma+1}{\gamma+2}} K \frac{\mu_0}{V_{aa}} V_{SAT}^{\gamma+2} ) (14)</td>
</tr>
</tbody>
</table>
The drain current asymptotic in the saturation regime accounting for the nonzero differential conductance

<table>
<thead>
<tr>
<th>The drain current asymptotic in the saturation regime:</th>
<th>$I_{ASY} = I_{SAT} \cdot [1 + \lambda \cdot (V_{DS} - V_{SAT})]$, Here $\lambda = 1/V_{E}$ (the value of $V_{E}$ is similar to the well-known Early voltage from the theory of bipolar transistors)</th>
<th>(15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The differential conductance $g_{ASY} = \frac{\partial I_{ASY}}{\partial V_{DS}}</td>
<td>V_{DS},V_{GS}$</td>
<td>$g_{ASY} = \lambda \cdot I_{SAT} = \lambda \cdot \alpha_s K \frac{\mu_0}{V_{aa}} V_{GT}^{y+2}$</td>
</tr>
<tr>
<td>The output resistance:</td>
<td>$r_{ASY} = \frac{1}{g_{ASY}}$</td>
<td>(17)</td>
</tr>
<tr>
<td>The transconductance: $g_{m ASY} = \frac{\partial I_{ASY}}{\partial V_{GS}}</td>
<td>V_{DS},V_{GS}$</td>
<td>$g_{m ASY} = g_{m SAT} + \lambda \cdot [g_{m SAT} \cdot (V_{DS} - V_{SAT}) + I_{SAT} \cdot b_{m SAT}]$</td>
</tr>
</tbody>
</table>
The equivalent circuits for the “intrinsic” OFET in the linear (ohmic) regime and in the saturation regime.

**Figure 1.** Schematic for “intrinsic” OFET connected in the common source configuration.

**Figure 2.** Static circuit model (equivalent circuit) of an “intrinsic” OFET operated in its linear (ohmic) regime.

**Figure 3.** A large-signal circuit model (equivalent circuit) for an “intrinsic” OFET biased to operate in its saturation regime.

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The output characteristics of the “intrinsic” OFET in the piecewise linear approximation

Figure 4. Output characteristics for “intrinsic” OFET in piecewise linear approximation. Upper curve for $V_{GT} = -30 \text{ V}$, then $-35 \text{ V}$, $-40 \text{ V}$, $-45 \text{ V}$, $-50 \text{ V}$.

Figure 5. Dependence of differential conductance on “intrinsic” source-to-drain bias $V_{DS}$ for “intrinsic” OFET with output characteristics presented on Figure 4.
The transfer characteristics of the “intrinsic” OFET in the piecewise linear approximation

Figure 6. Transfer characteristics for “intrinsic” OFET in piecewise linear approximation. Upper curve for $V_{DS} = -5 \, V$, then $-10 \, V$, $-15 \, V$, $-20 \, V$, $-25 \, V$.

Figure 7. Dependence of transconductance on “intrinsic” source-to-gate bias $V_{GS}$ for “intrinsic” OFET with transfer characteristics presented on Figure 6.
Smoothing function for bridging the transition between the linear and the saturation regimes in case of the “intrinsic” OFET in case $\lambda=0$ (zero differential conductance in saturation regime)

The smoothing function that is used to bridge the transition between the linear and the saturation regimes:

$$I_0 = \frac{I_{\text{LIN}} I_{\text{SAT}}}{[I_{\text{LIN}}^m + I_{\text{SAT}}^m]^{\frac{1}{m}}}$$  \hspace{1cm} (19)

The differential conductance

$$g_0 = \left( \frac{I_0}{I_{\text{LIN}}} \right)^{m+1}$$

$$g_{\text{LIN}} = \frac{g_{\text{LIN}}}{1 + \left( \frac{I_{\text{LIN}}}{I_{\text{SAT}}} \right)^m}$$

$$g_{\text{SAT}} = \frac{\beta V_{\text{GT}}}{1 + \left( \frac{V_{\text{DS}}}{\alpha_s V_{\text{GT}}} \right)^m}$$  \hspace{1cm} (20)

The transconductance

$$g_{m0} = \left( \frac{I_0}{I_{\text{LIN}}} \right)^{m+1}$$

$$g_{m\text{LIN}} = g_{m\text{LIN}} + \left( \frac{I_0}{I_{\text{SAT}}} \right)^{m+1}$$

$$g_{m\text{SAT}} = \frac{g_{m\text{LIN}} + g_{m\text{SAT}}}{1 + \left( \frac{I_{\text{LIN}}}{I_{\text{SAT}}} \right)^m}$$

$$g_{m\text{LIN}} + g_{m\text{SAT}} = \frac{g_{m\text{LIN}} + g_{m\text{SAT}}}{1 + \left( \frac{V_{\text{DS}}}{\alpha_s V_{\text{GT}}} \right)^m}$$  \hspace{1cm} (21)
The traditional smoothing function for bridging the transition between the linear and the saturation regimes in the case of the “intrinsic” OFET in the case $\lambda \neq 0$ (nonzero differential conductance in the saturation regime)

The traditional interpolation expression is used to bridge the linear and the saturation regimes:

$$I = \frac{I_{LIN} I_{ASY}^{\frac{1}{m}}}{(I_{LIN} + I_{SAT}^{\frac{1}{m}})} = \frac{I_{LIN} I_{SAT}^{\frac{1}{m}}}{(I_{LIN} + I_{SAT}^{\frac{1}{m}})} \cdot (1 + \lambda \cdot (V_{DS} - V_{SAT})) = I_0 \cdot (1 + \lambda \cdot (V_{DS} - V_{SAT}))$$

Here $I_0 = \frac{I_{LIN} I_{SAT}^{\frac{1}{m}}}{(I_{LIN} + I_{SAT}^{\frac{1}{m}})}$

The differential conductance:

$$g = g_0 \cdot [1 + \lambda \cdot (V_{DS} - V_{SAT})] + \lambda I_0 = \beta V_{GT} \cdot \frac{1 + \lambda \cdot \left(2 + \left(\frac{V_{DS}}{\alpha_s V_{GT}}\right)^m\right) V_{DS} - \alpha_s V_{GT}}{\left[1 + \left(\frac{V_{DS}}{\alpha_s V_{GT}}\right)^m\right]^\frac{1}{m+1}}$$

Here $g_0 = \left(\frac{I_0}{I_{LIN}}\right)^{m+1} g_{LIN}$

The transconductance:

$$g_m = g_{m0} \cdot [1 + \lambda (V_{DS} - V_{SAT})] - \lambda I_0 b_{mSAT} = g_{m0} \left[1 + \lambda \left(V_{DS} - \alpha_s V_{GT}\right)\left\{1 + \frac{1 + \left(\frac{V_{DS}}{\alpha_s V_{GT}}\right)^m}{\gamma + 1 + (\gamma + 2) \left(\frac{V_{DS}}{\alpha_s V_{GT}}\right)^m}\right]\right]$$

Here $g_{m0} = \left(\frac{I_0}{I_{LIN}}\right)^{m+1} g_{m LIN} + \left(\frac{I_0}{I_{SAT}}\right)^{m+1} g_{m SAT}$

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The use of the traditional smoothing function to the bridging the linear and the saturation regimes in the case of the “intrinsic” OFET. Output characteristics

Figure 8. Output characteristics for “intrinsic” OFET calculated with traditional interpolation expression. Upper curve for \( V_{GT} = -30 \), then \(-35 \text{ V}, -40 \text{ V}, -45 \text{ V}, -50 \text{ V}\).

Figure 9. Dependence of differential conductance on “intrinsic” source-to-drain bias \( V_{DS} \) for “intrinsic” OFET with output characteristic presented on Figure 8. We can see a significantly nonmonotonic behavior of the differential conductance for small drain-to-source bias.

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The use of the traditional smoothing function to the bridging the linear and the saturation regimes in the case of the “intrinsic” OFET. Transfer characteristics

Figure 10. Transfer characteristics for “intrinsic” OFET calculated with traditional interpolation expression. Upper curve for $V_{DS} = -5$, then $-10 \, V, -15 \, V, -20 \, V, -25 \, V$.

Figure 11. Dependence of transconductance on “intrinsic” source-to-gate bias $V_{GS}$ for “intrinsic” OFET with transfer characteristics presented on Figure 10.
The improved smoothing function for bridging the transition between the linear and the saturation regimes in the case of the “intrinsic” OFET in the case $\lambda \neq 0$ (nonzero differential conductance in the saturation regime)

The improved interpolation expression, that provides a smooth transition between the drain current before and after saturation with the proper monotonic decrease of the differential conductance:

$$I = \frac{l_{LIN}l_{ASY}^{\lambda}}{(l_{LIN}^{m}+l_{ASY}^{m})^{\frac{1}{m}}}$$  \hspace{1cm} (25)

The equation for the drain current “modified” asymptotic in the saturation regime $I_{ASY}^{*}$ (the drain current asymptotic in the saturation regime $I_{ASY B}$ was used in calculations):

$$I_{ASY}^{*} = k I_{ASY} = \frac{g_{LIN}}{(g_{LIN}^{m}-g_{ASY}^{m})^{\frac{1}{m}}} I_{ASY} = \frac{g_{LIN}}{(g_{LIN}^{m}-g_{ASY}^{m})^{\frac{1}{m}}} \cdot I_{SAT} \cdot (1 + \lambda \cdot \frac{(V_{DS} - V_{SAT})}{g_{LIN}})$$

Here $k = \frac{g_{LIN}}{[g_{LIN}^{m}-g_{ASY}^{m}]^{\frac{1}{m}}}$  \hspace{1cm} (26)

The differential conductance:

$$g = \frac{g_{LIN} + k \cdot g_{ASY} \cdot \left(\frac{l_{LIN}}{l_{ASY}}\right)^{m+1}}{1 + \left(\frac{l_{LIN}}{l_{ASY}}\right)^m}$$  \hspace{1cm} (27)

The transconductance:

$$g_{m} = \frac{g_{m \cdot LIN} + \left(\frac{k \cdot g_{m \cdot ASY}}{v_{GT}} + \frac{l_{ASY}}{v_{SAT}} \cdot \left(\frac{v_{SAT}}{v_{E}}\right)^{m} \cdot I_{ASY}^{*}\right)^{m+1}}{1 + \left(\frac{l_{LIN}}{l_{ASY}}\right)^{m}}$$  \hspace{1cm} (28)
The use of the improved smoothing function to the bridging the linear and the saturation regimes in the case of the “intrinsic” OFET. Output characteristic

Figure 12. Output characteristic for “intrinsic” OFET calculated with improved interpolation expression. Upper curve for $V_{GT} = -30$, then $-35, -40, -45, -50$ V.

Figure 13. Dependence of differential conductance on “intrinsic” source-to-drain bias $V_{DS}$ for “intrinsic” OFET with output characteristic presented on Figure 12. We see a monotonous decrease in the differential conductance for the entire range of the drain-to-source bias.

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The use of the improved smoothing function to the bridging the linear and the saturation regimes in the case of the “intrinsic” OFET. Transfer characteristics

Figure 14. Transfer characteristics for “intrinsic” OFET calculated with improved interpolation expression. Upper curve for $V_{DS} = -5$, then $-10, -15, -20, -25$ V.

Figure 15. Dependence of transconductance on “intrinsic” source-to-drain bias $V_{GS}$ for “intrinsic” OFET with transfer characteristics presented on Figure 14.
The “extrinsic” OFET

The “extrinsic” overdrive voltage:

\[ V_{gt} = V_{gs} - V_{th} \] \hspace{1cm} (29)

The relations between the “extrinsic” and “intrinsic” overdrive voltages:

\[ V_{GT} = V_{gt} - IR_S \] \hspace{1cm} (30)

The relations between the “extrinsic” and “intrinsic” drain-to-source voltages:

\[ V_{DS} = V_{ds} - IR_T \] \hspace{1cm} (31)

Total contacts resistance:

\[ R_T = R_S + R_D \] \hspace{1cm} (32)

Figure 16. Schematic of an “extrinsic” OFET connected in the common source configuration
The “extrinsic” OFET in the linear (ohmic) regime

<table>
<thead>
<tr>
<th>Topic</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>The implicit nonlinear (NL) equation for the transformation of the equation (1) for the “intrinsic” OFET drain current in linear regime into “extrinsic” case:</td>
<td>( I_{\text{lin NL}} = K \frac{\mu_0}{V_{aa}} \cdot (V_{gt} - I_{\text{lin NL}} R_S)^{\gamma+1} \cdot (V_{ds} - I_{\text{lin NL}} R_T) ) &lt;br&gt; here the argument of function ( g_{\text{LIN}} ) is ( V_{GT} = V_{gt} - I_{\text{lin NL}} R_T ) (33)</td>
</tr>
<tr>
<td>From (24), by considering limit ( V_{ds} \to 0 ), we can obtain the linear approximation for an “extrinsic” OFET drain current dependence on “extrinsic” drain-to-source bias:</td>
<td>( I_{\text{lin}} \approx g_{\text{lin}} V_{ds} ) (34)</td>
</tr>
<tr>
<td>In (25) the differential conductance of an “extrinsic” MOSFET in linear regime is given by this equation (here ( \tilde{g}<em>{\text{LIN}} ) mean that the argument of function ( g</em>{\text{LIN}} ) is not intrinsic value ( V_{GT} ), but extrinsic ( V_{gt} )):</td>
<td>( g_{\text{lin}} = \frac{\tilde{g}<em>{\text{LIN}}}{1 + R_T \tilde{g}</em>{\text{LIN}}} = \frac{K \frac{\mu_0}{V_{aa}} V_{gt}^{\gamma+1}}{1 + R_T K \frac{\mu_0}{V_{aa}} V_{gt}^{\gamma+1}} ) (35)</td>
</tr>
<tr>
<td>The differential output resistance ( R_{\text{lin}} = 1/g_{\text{lin}} ):</td>
<td>( R_{\text{lin}} = \tilde{R}<em>{\text{LIN}} + R_T = \frac{1}{\tilde{g}</em>{\text{LIN}}} + R_T ) &lt;br&gt; here the argument of function ( R_{\text{LIN}} ) is ( V_{GT} = V_{gt} ) (36)</td>
</tr>
<tr>
<td>The transconductance of the “extrinsic” OFET in linear (ohmic) regime</td>
<td>( g_{m \text{ lin}} = \left( \frac{g_{\text{lin}}}{\tilde{g}<em>{\text{LIN}}} \right)^2 \tilde{g}</em>{m \text{ LIN}} = \frac{\tilde{g}<em>{m \text{ LIN}}}{(1 + R_T \tilde{g}</em>{\text{LIN}})^2} ) (37)</td>
</tr>
</tbody>
</table>

Here \( \tilde{g}_{\text{LIN}} \) and \( \tilde{g}_{m \text{ LIN}} \) mean that the argument of these functions is not intrinsic value \( V_{GT} \) and \( V_{DS} \), but extrinsic \( V_{gt} \) and \( V_{ds} \).
The “saturation point” for the “extrinsic” OFET (1)

The implicit nonlinear equation for transformation of the “intrinsic” equation for the saturation current into “extrinsic” case:

\[ I_{\text{sat}} = I_{\text{SAT}}(V_{gt} - I_{\text{sat}} R_S) = \alpha_S \frac{\mu_0}{V_{aa}} (V_{gt} - I_{\text{sat}} R_S)^{\gamma + 2} \]  

(38)

We can solve equation (28) by the method of bisection. But this equation is also suitable for calculating the saturation current \( I_{\text{sat}} \) by the iterative method. For the value of the saturation current at zero iteration \( i = 0 \) we take the zero value of the saturation current:

\[ I_{\text{sat}} + 1 = I_{\text{SAT}}(V_{gt} - I_{\text{sat}} i R_S) = \alpha_S \frac{\mu_0}{V_{aa}} (V_{gt} - I_{\text{sat}} i R_S)^{\gamma + 2} \]

\[ I_{\text{sat}} 0 = 0 \]

(39)

For compact modeling, equations are needed that can be solved by quadrature. To obtain such an equation (28) can be linearized. In this case, the value of the current \( I_{\text{sat}} \), that is obtained after \( i \) iterations, is taken as the initial value of the saturation current for the linearization:

\[ I_{\text{sat}} CM i = \frac{I_{\text{SAT}}(V_{gt} - I_{\text{sat}} i R_S) + g_{m\text{SAT}}(V_{gt} - I_{\text{sat}} i R_S) I_{\text{sat}} i R_S}{1 + g_{m\text{SAT}}(V_{gt} - I_{\text{sat}} i R_S) R_S} \]

Taking as the initial value \( I_{\text{sat}} 0 = 0 \) we have:

\[ I_{\text{sat}} CM 0 = \frac{I_{\text{SAT}}(V_{gt})}{1 + g_{m\text{SAT}}(V_{gt}) R_S} = \frac{I_{\text{SAT}}}{1 + g_{m\text{SAT}} R_S} \]

We use equation for \( I_{\text{sat}} CM 0 \) in further calculations. Hence, if we use further the notation \( I_{\text{sat}} \) it means \( I_{\text{sat}} CM 0 \) mostly.

The equation for saturation voltage for “extrinsic” OFET:

\[ V_{\text{sat}} = V_{\text{SAT}} + I_{\text{sat}} R_T = \alpha_S (V_{gt} - I_{\text{sat}} R_S) + I_{\text{sat}} R_T \]

Here the argument of function \( V_{\text{SAT}} \) is \( V_{GT} = V_{gt} - I_{\text{sat}} \cdot R_S \)

(41)
### The “saturation point” for the “extrinsic” OFET (2)

The transconductance \( g_{m \text{ sat}} = \frac{\partial I_{\text{sat}}}{\partial V_{gs}} \) : 

\[
g_{m \text{ sat}} = \frac{g_{m \text{ SAT}}}{1 + g_{m \text{ SAT}} R_S} \quad \text{or} \quad \frac{1}{g_{m \text{ sat}}} = \frac{1}{g_{m \text{ SAT}}} + \frac{1}{R_S}
\]

Here the argument of function \( g_{m \text{ SAT}} \) is \( V_{GT} = V_{gt} - I_{\text{sat}} \cdot R_S \)

\[ b_{m \text{ sat}} = \frac{\partial V_{\text{sat}}}{\partial V_{gs}} \bigg|_{V_{gs}} \]

\[
b_{m \text{ sat}} = \tilde{b}_{m \text{ SAT}} + g_{m \text{ sat}} \cdot (R_T - \alpha_s R_S) = \alpha_s + g_{m \text{ sat}} \cdot (R_T - \alpha_s R_S)
\]

Here \( \tilde{b}_{m \text{ SAT}} \) mean that the argument of these functions is not intrinsic value \( V_{GT} \) and \( V_{DS} \), but extrinsic \( V_{gt} \) and \( V_{ds} \). Really, in our case \( b_{m \text{ SAT}} \tilde{=b}_{m \text{ SAT}}=\alpha_s \)

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The “extrinsic” OFET in the saturation regime

The implicit nonlinear equation (NL) for transformation of the “intrinsic” equation for the drain current asymptotic in the saturation regime into “extrinsic” case:

\[ I_{asy \ NL} = I_{SAT}(V_{gt} - I_{asy \ NL} R_S) \cdot \left( 1 + \lambda \cdot \left( V_{ds} - I_{asy \ NL} R_T - V_{SAT}(V_{gt} - I_{asy \ NL} R_S) \right) \right) \]  \hspace{1cm} (44)

Definition of the differential conductance in saturation regime for “extrinsic” case

\[ g_{asy \ NL} = \frac{1 + g_{m SAT} R_S I_{asy \ NL}/I_{SAT} + g_{asy} \cdot (R_T - b_{m SAT} R_S)}{1 + g_{m SAT} R_S + g_{asy} \cdot (R_T - b_{m SAT} R_S)} \]

here the argument of functions \( g_{ASY}, g_{m SAT}, I_{SAT}, b_{m SAT} \) is \( V_{GT} = V_{gt} - I_{asy} R_S \)

\( I_{asy \ NL} \) can be obtained by numerical method

The differential conductance in “saturation point”:

\[ g_{asy} = \frac{1 + g_{m SAT} R_S + g_{asy} \cdot (R_T - b_{m SAT} R_S)}{1 + g_{m SAT} R_S} \]

here the argument of functions \( g_{ASY}, g_{m SAT} \) and \( b_{m SAT} \) is \( V_{GT} = V_{gt} - I_{sat} \cdot R_S \)

The linear approximation for the OFET drain current in saturation regime dependence on the “extrinsic” drain-to-source bias \( V_{ds} \) and gate-to-source “extrinsic” bias \( V_{gt} \):

\[ I_{asy} = I_{sat} + g_{asy} \cdot (V_{ds} - V_{sat}) \]

\[ g_{asy} = (R_{asy})^{-1} \]  \hspace{1cm} (47)
The equivalent circuits for the “extrinsic” OFET in the linear (ohmic) regime and in the saturation regime

Figure 17. Schematic for “extrinsic” OFET connected in the common source configuration

Figure 18. Static circuit model (equivalent circuit) of an “extrinsic” OFET operated in its linear (ohmic) regime

Figure 19. A large-signal circuit model for an “extrinsic” OFET biased to operate in its saturation regime.
The output characteristics of the “extrinsic” OFET in the piecewise linear approximation

Figure 20. Output characteristics for “extrinsic” OFET in piecewise linear approximation. Upper curve for $V_{gt} = -30\, \text{V}$, then $-35\, \text{V}$, $-40\, \text{V}$, $-45\, \text{V}$, $-50\, \text{V}$.

Figure 21. Dependence of differential conductance on “extrinsic” source-to-drain bias $V_{ds}$ for “intrinsic” OFET with output characteristics presented on Figure 20.
The transfer characteristics of the “extrinsic” OFET in the piecewise linear approximation

Figure 22. Transfer characteristics for “extrinsic” OFET in piecewise linear approximation. Upper curve for $V_{ds} = -5 \, \text{V}$, then $-10 \, \text{V}, -15 \, \text{V}, -20 \, \text{V}, -25 \, \text{V}$.

Figure 23. Dependence of transconductance on “extrinsic” source-to-gate bias $V_{gs}$ for “extrinsic” OFET with transfer characteristics presented on Figure 22.
Smoothing function for bridging the transition between the linear and the saturation regimes in case of the “extrinsic” OFET in case $\lambda = 0$ (zero differential conductance in saturation regime)

The “traditional” interpolation expression is used to bridge the transition between the linear and the saturation regimes:

$$I_{0\,ex} = \frac{I_{lin}I_{sat}}{(I_{lin}^m + I_{sat}^m)^{\frac{1}{m}}}$$

Here $I_{asy} = I_{sat} + g_{asy\,sat} \cdot (V_{ds} - V_{sat}) = I_{sat}\left(1 + \lambda_{ex} \cdot (V_{ds} - V_{sat})\right)$,

$$\lambda_{ex} = \frac{g_{asy\,sat}}{I_{sat}} = \left(R_{asy\,I_{sat}}\right)^{-1},$$

The differential conductance $g_{0\,ex} = \frac{\partial I_{0\,ex}}{\partial V_{ds}}$:

$$g_{0\,ex} = \frac{g_{lin}}{\left[1 + (I_{lin}/I_{sat})^m\right]^{\frac{1}{m+1}}}$$

(49)

The transconductance $g_{m\,0\,ex} = \frac{\partial I_{0\,ex}}{\partial V_{gs}}$:

$$g_{m\,0\,ex} = \frac{g_{m\,lin} + g_{m\,sat} \cdot (I_{lin}/I_{sat})^{m+1}}{\left[1 + (I_{lin}/I_{sat})^m\right]^{\frac{1}{m+1}}}$$

(50)
The traditional smoothing function for bridging the transition between the linear and the saturation regimes in the case of the “extrinsic” OFET in the case $\lambda \neq 0$ (nonzero differential conductance in the saturation regime)

The traditional interpolation expression is used to bridge the transition between the linear and the saturation regimes:

$$I = \frac{I_{\text{lin}} I_{\text{asy}}}{I_{\text{lin}}^m + I_{\text{sat}}^m} = I_{0 \text{ ex}} \cdot (1 + \lambda_{\text{ex}} \cdot (V_{ds} - V_{\text{sat}}))$$

Here

$$I_{\text{asy}} = I_{\text{sat}} + g_{\text{asy sat}} \cdot (V_{ds} - V_{\text{sat}}) = I_{\text{sat}} \left(1 + \lambda_{\text{ex}} \cdot (V_{ds} - V_{\text{sat}})\right),$$

$$\lambda_{\text{ex}} = \frac{g_{\text{asy sat}}}{I_{\text{sat}}} = \left(R_{\text{asy}} I_{\text{sat}}\right)^{-1},$$

$$I_{0 \text{ ex}} = \frac{I_{\text{lin} I_{\text{sat}}}}{(I_{\text{lin}^m + I_{\text{sat}}^m})^m} \quad (51)$$

The differential conductance

$$g = \frac{\partial I}{\partial V_{ds}} \bigg|_{V_{ds}, V_{gs}}$$

$$g = R_{\text{asy}}^{-1} = g_{0 \text{ ex}} \left[1 + \frac{g_{\text{asy}}}{I_{\text{sat}}} (V_{ds} - V_{\text{sat}})\right] + g_{\text{asy}} \frac{I_{0 \text{ ex}}}{I_{\text{sat}}} \quad (52)$$

The transconductance

$$g_m = \frac{\partial I}{\partial V_{gs}} \bigg|_{V_{ds}, V_{gs}}$$

$$g_m = g_{m0 \text{ ex}} \left[1 + \frac{g_{\text{asy}}}{I_{\text{sat}}} (V_{ds} - V_{\text{sat}})\right] - \frac{I_{0 \text{ ex}}}{I_{\text{sat}}} \left[g_{\text{asy}} \frac{g_{\text{sat}}}{I_{\text{sat}}} + \frac{\partial g_{\text{asy}}}{\partial V_{gs}} \right] (V_{ds} - V_{\text{sat}})$$

Here

$$g_{m0 \text{ ex}} = \frac{g_{m\text{lin}} + g_{m\text{sat}} \cdot (I_{\text{lin}}/I_{\text{sat}})^{m+1}}{[1 + (I_{\text{lin}}/I_{\text{sat}})^m]^m} \quad (53)$$

$$\frac{\partial g_{\text{asy}}}{\partial V_{gs}} = (\gamma + 2) \frac{g_{\text{asy}}}{V_{gt}} \left(1 - g_{\text{asy}} \cdot \left[R_T + \left(\gamma + 1\right) \frac{V_E}{V_{gt}} - \alpha_s\right] R_S\right)$$
The traditional approach to the bridging the transition between the linear and the saturation regimes in case of the “extrinsic” OFET. Output characteristic

Figure 24. Output characteristic for “extrinsic” OFET calculated with traditional interpolation expression. Upper curve for $V_{GT} = -30$, then $-35 \text{ V, } -40 \text{ V, } -45 \text{ V, } -50 \text{ V}$. 

Figure 25. Dependence of differential conductance on “intrinsic” source-to-drain bias $V_{DS}$ for “extrinsic” OFET with output characteristic presented on Figure 24. We see a significantly nonmonotonic behavior of the differential conductance for small drain-to-source bias

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The traditional approach to the bridging the transition between the linear and the saturation regimes in the case of the “extrinsic” OFET. Transfer characteristics

Figure 26. Transfer characteristics for “extrinsic” OFET calculated with traditional interpolation expression. Upper curve for $V_{DS} = -5, -10, -15, -20, -25$ V.

Figure 27. Dependence of transconductance on “extrinsic” source-to-gate bias $V_{GS}$ for “extrinsic” OFET with transfer characteristics presented on Figure 26.
The improved smoothing function for bridging the transition between the linear and the saturation regimes in the case of the “extrinsic” OFET in the case $\lambda \neq 0$ (nonzero differential conductance in the saturation regime)

<table>
<thead>
<tr>
<th>The improved interpolation expression is used to bridge the transition between the linear and the saturation regimes:</th>
<th>$I = \frac{I_{\text{lin}} I_{\text{asy}}^*}{\left[I_{\text{lin}}^m + I_{\text{asy}}^m \right]^{\frac{1}{m}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Here $I_{\text{asy}}^* = k_{\text{ex}} I_{\text{asy}}$, $k_{\text{ex}} = \frac{g_{\text{lin}}}{\left[g_{\text{lin}} - g_{\text{asy}}\right]^{\frac{1}{m}}}$, $I_{\text{asy}} = I_{\text{sat}} + g_{\text{asy}} \cdot (V_{ds} - V_{sat})$</td>
<td></td>
</tr>
<tr>
<td>The differential conductance $g = \left. \frac{\partial I}{\partial V_{ds}} \right</td>
<td><em>{V</em>{ds}, V_{gs}}$</td>
</tr>
<tr>
<td>$g = R_{asy}^{-1} = \frac{g_{\text{lin}} + (I_{\text{lin}}/I_{\text{asy}})^{m+1} k_{\text{ex}} g_{\text{asy}}}{\left[1 + (I_{\text{lin}}/I_{\text{asy}})^m \right]^{\frac{1}{m+1}}}$</td>
<td></td>
</tr>
<tr>
<td>The transconductance $g_m = \left. \frac{\partial I}{\partial V_{gs}} \right</td>
<td><em>{V</em>{ds}, V_{gs}}$</td>
</tr>
<tr>
<td>$g_m = \frac{g_{\text{lin}} \cdot m + (k_{\text{ex}} \cdot g_{m \text{ asy}} + I_{\text{asy}} \cdot \frac{\partial k_{\text{ex}}}{\partial V_{gs}}) \cdot (I_{\text{lin}}/I_{\text{asy}})^{m+1}}{1 + (I_{\text{lin}}/I_{\text{asy}})^m} \left[1 + (I_{\text{lin}}/I_{\text{asy}})^m \right]^{\frac{1}{m+1}}$</td>
<td></td>
</tr>
<tr>
<td>Here $\frac{\partial k_{\text{ex}}}{\partial V_{gs}} = k_{\text{ex}}^{m+1} \left(\frac{g_{\text{asy}}}{g_{\text{lin}}}\right)^m \left(1 - \frac{\partial g_{\text{asy}}}{\partial V_{gs}} - \frac{1}{g_{\text{lin}}} \frac{\partial g_{\text{lin}}}{\partial V_{gs}}\right)$</td>
<td></td>
</tr>
<tr>
<td>$\frac{\partial g_{\text{asy}}}{\partial V_{gs}} = (y + 2) \frac{g_{\text{asy}}}{V_{gt}} \left{1 - g_{\text{asy}} \cdot \left[R_T + \left(y + 1\right) \frac{V_E}{V_{gt}} - \alpha_s\right] R_S\right}$</td>
<td></td>
</tr>
</tbody>
</table>

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The improved smoothing function to the bridging the transition between the linear and the saturation regimes in the case of the “extrinsic” OFET. Output characteristics

Figure 28. Output characteristic for “extrinsic” OFET calculated with improved interpolation expression. Upper curve for $V_{GT} = -30$, then $-35$ V, $-40$ V, $-45$ V, $-50$ V.

Figure 29. Dependence of differential conductance on “extrinsic” source-to-drain bias $V_{DS}$ for “extrinsic” OFET with output characteristic presented on Figure 28. We see a monotonous decrease in the differential conductance for the entire range of the drain-to-source bias.

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The improved smoothing function to the bridging the transition between the linear and the saturation regimes in the case of the "extrinsic" OFET. Transfer characteristics

Figure 30. Transfer characteristics for "extrinsic" OFET calculated with improved interpolation expression. Upper curve for $V_{DS} = -5$, then $-10\,V, -15\,V, -20\,V, -25\,V$.

Figure 31. Dependence of transconductance on "extrinsic" source-to-drain bias $V_{GS}$ for "extrinsic" OFET with transfer characteristics presented on Figure 30.
Conclusion

In this report, we are presenting calculations of the output characteristics, dependence of differential conductance on source-to-drain bias and dependence of transconductance on source-to-gate bias for the “intrinsic” and “extrinsic” OFET obtained with piecewise linear approximation, with traditional smoothing function and with improved smoothing function. Finally, we show the compact model for the above threshold drain current of the “extrinsic” OFET with proper account of the differential conductance with one monotonic decrease from maximum value in linear regime to minimum value in saturation regime. To plot differential conductance and transconductance dependences we give priority to analytical equations. However, in some cases, until the code is debugged, we used numerical differentiation. Note, that in [12] we have studied the asymptotic behavior for the OFET drain current dependence on rising “extrinsic” drain bias in saturation regime. In further work, we have plan to continue investigation of the drain current asymptotic in case of the increasing drain-to-source bias [11, 12]. In addition, we have plan to incorporate developed improved OFET compact model into EDA software.

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References


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THANK YOU FOR YOUR ATTENTION!