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Modelling of saturation current of an organic field-effect transistor with accounting for contact resistances

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Abstract. The saturation current of an organic field-effect transistor was calculated numerically by bisection method taking into account the source and drain resistances. Dependences of the saturation current as a function of the gate voltage, centred on the threshold voltage, and as a function of the "extrinsic" (taking into account the source and drain resistances) saturation voltage are presented. The calculations were carried out using an iterative scheme assuming the saturation current to be zero for iteration zero and using different numbers of iterations. In addition, we carried out a compact modelling of the saturation current in the framework of the approach we proposed earlier. It is shown that when in the equation for the compact modelling initial value of saturation current of zero value (corresponding to zero iteration) is used, a good agreement with the bisection method of over a wide range of gate voltages is obtained.

1. Introduction

The approach to organic field-effect transistor (OFET) above-threshold drains current compact modeling (CM) that provides monotonic decrease of the output conductance with drain bias increasing [2-4] and with an analytical account of the source and drain resistances was proposed in [1]. An equation determining the dependence of the saturation current on "extrinsic" centered gate voltage was obtained in an implicit manner. Based on that equation, an iterative procedure was proposed for modeling the OFET saturation current. Linearization yielded an equation for the compact modeling of the OFET saturation current using the initial value of the saturation current obtained after several iterations.

In our paper, we simulate the saturation current of the OFET taking into account the source and drain resistances by the bisection method.

We also investigate the simulation of the saturation current of the OFET by the iterative method performing calculations for a different number of iterations. The value of the saturation current at zero iteration is assumed to be zero.

In addition, we carried out a compact modeling of the saturation current in the framework of the proposed in [1] approach. We investigate solutions of the equation for the saturation current of the OFET compact modeling when using the initial saturation current value obtained by iterative method with different number of iterations.

As a basis, in our work we use a compact model of OFET, proposed in the [5] and developed on the basis of a compact model MOSFET Level 1 for a long-channel MOSFET.

The saturation voltage for an OFET is given by

$$V_{SAT} = \alpha_S V_{GT} \,, \tag{1}$$

where α_S is a dimensionless parameter related to the influence of the substrate, $V_{GT} = V_{GS} - V_T$ is the gate-to-source voltage V_{GS} centered on threshold voltage with threshold voltage V_T.

The saturation current of the OFET is assumed to be equal to:

$$I_{SAT} = g_{CH} V_{SAT} = \alpha_S K \frac{\mu_0}{V_{aa}^{\gamma}} V_{GT}^{\gamma+2}, \tag{2}$$

where g_{CH} is the OFET channel differential conductance in linear regime:

$$g_{CH} = K \mu_{FET} V_{GT}, \tag{3}$$

where $K = W / L\ C_i$, W is the channel width, L is the channel length, $C_i = \epsilon_0 \epsilon_{ox} / d_{ox}$ is the insulator capacitance per unit area, $\mu_{FET} = \mu_0 (V_{GT}/V_{aa})^{\gamma}$ field-effect mobility, μ_0 is the conversion mobility set to 1 cm^2/V·s. In our work, we mainly use the parameters of the OFET model with a channel length L = 40 um and the gate width W = 1000 um from [6]: $\gamma = 0.91$, $V_{th} = -12$ V, $\mu_{FET} = 0.13$ cm^2/Vs at the gate-to-source bias $V_{GS} = -50$ V, $\alpha_S = 0.46$, $C_i = 3.3$ nF/cm^2 and $V_{aa} = 358$ V. The value of the total resistance of the contacts $R_T = 2.4$ MΩ ($R_S = R_D = 1.2$ MΩ) were chosen sufficiently large to more clearly demonstrate the influence of these parameters on the results of calculations.

The OFET transconductance in the saturation regime, is determined by the following equation:

$$g_{mSAT} = \frac{\partial I_{SAT}}{\partial V_{GS}} = \alpha_S K \frac{\mu_0}{V_{aa}^{\gamma}} (\gamma + 2) V_{GT}^{\gamma+1} \tag{4}$$

when neglecting differential conductivity in the saturation regime. "Extrinsic" and "intrinsic" voltages on the drain, source, and gate are related as:

$$V_{ds} = V_{DS} + I R_T, \tag{5}$$

$$V_{gt} = V_{GT} + I R_S. \tag{6}$$

2. Implicit equation for saturation current in "extrinsic" case and its solutions by bisection method and by iterations

For An equation obtained in [1] determined the dependence of the saturation current on the "extrinsic" centered voltage on the gate V_{gt} implicitly:

$$I_{sat} = I_{SAT}\big(V_{gt} - I_{sat} R_S\big) = \alpha_S\, K\, \frac{\mu_0}{V_{aa}^{\gamma}} \big(V_{gt} - I_{sat} R_S\big)^{\gamma+2}, \tag{7}$$

where function I_{SAT} is given by equation (2) with argument V_{GT} given by equation (6) in case when current I is equal to saturation current I_{sat}.

We solve equation (7) by the method of bisection. But this equation is also suitable for calculating the saturation current I_{sat} by the iterative method:

$$I_{sat\ i+1} = I_{SAT}\big(V_{gt} - I_{sat\ i}\, R_S\big) = \alpha_S\, K\, \frac{\mu_0}{V_{aa}^{\gamma}} \big(V_{gt} - I_{sat\ i}\, R_S\big)^{\gamma+2}. \tag{8}$$

Here i is the iteration number. In this case, for the value of the saturation current at zero iteration $i = 0$ we take the zero value of the saturation current:

$$I_{sat\ 0} = 0. \tag{9}$$

For the first iteration $i = 1$, we have:

$$I_{sat\ 1} = I_{SAT}\big(V_{gt}\big) = \alpha_S\, K\, \frac{\mu_0}{V_{aa}^{\gamma}} \big(V_{gt}\big)^{\gamma+2}. \tag{10}$$

Note, that on this iteration we calculate saturation current considering V_{gt} as "intrinsic" voltage (without taking into account the source and drain resistances).

For the second iteration $i = 2$, we have:

$$I_{sat\ 2} = I_{SAT}\big(V_{gt} - I_{SAT}(V_{gt})\, R_S\big). \tag{11}$$

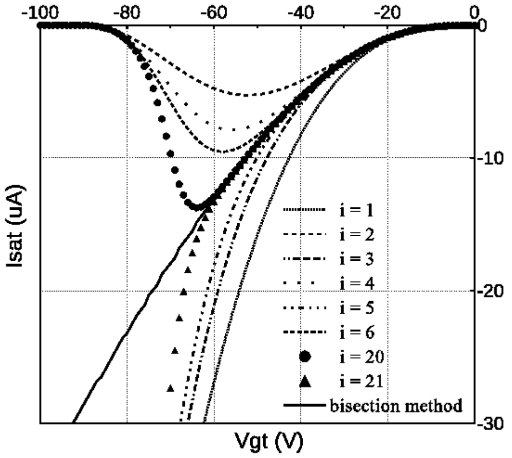

Figure 1. The saturation current as a function of the "extrinsic" centered gate voltage V_{gt}, obtained by the modelling with iterative method for a different number of iterations i = 1 .. 6, 20, 21 in comparison with the modelling with the method of bisection (solid line).

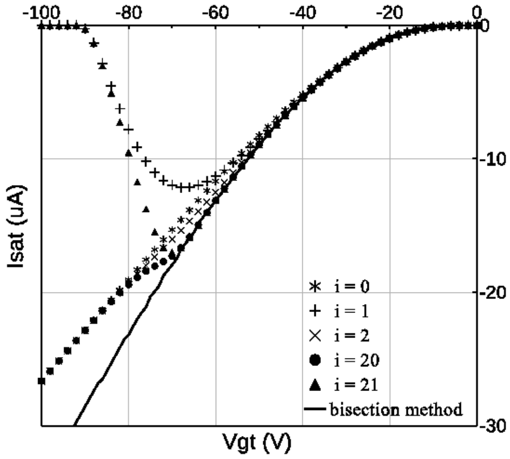

Figure 2. The saturation current as a function of the "extrinsic" centered gate voltage V_{gt}, obtained by compact modelling with the initial saturation current obtained from iterations with different i in comparison with the method of bisection (solid line).

3. Compact modelling of saturation current in "extrinsic" case

But for compact modeling, equations are needed that can be solved by quadrature. To obtain such an equation (7) has to be linearized [1]. In this case, the value of the current $I_{sat\ i}$, that is obtained after i iterations, is taken as the initial value of the saturation current for the linearization. The equation (7) for the saturation current is transformed as follows:

$$\begin{gathered}
I_{sat} = I_{SAT}\left(V_{gt} - I_{sat}R_S\right) = I_{SAT}\left(V_{gt} - (I_{sat\ \ i} + dI_{sat})\ R_S\right) = \\
I_{SAT}\left(\left(V_{gt} - I_{sat\ \ i}\ R_S\right) - dI_{sat}\ R_S\right) = \\
I_{SAT}(V_{GT\ \ i} + dV_{GT}) \approx I_{SAT}(V_{GT\ \ i}) + \left.\frac{\partial I_{SAT}}{\partial V_{GS}}\right|_{V_{GT\ \ i}} dV_{GT} = \\
I_{SAT}(V_{GT\ i}) + g_{mSAT}(V_{GT\ \ i})dV_{GT} = I_{SAT}(V_{GT\ \ i}) - g_{mSAT}(V_{GT\ i})\ dI_{sat}\ R_S = \\
I_{SAT}(V_{GT\ \ i}) - g_{mSAT}(V_{GT\ \ i}) \cdot (I_{sat} - I_{sat\ \ i})\ R_S = \\
I_{SAT}\left(V_{gt} - I_{sat\ \ i}\ R_S\right) - g_{mSAT}\left(V_{gt} - I_{sat\ \ i}\ R_S\right) \cdot (I_{sat} - I_{sat\ \ i})\ R_S.
\end{gathered} \quad (12)$$

Leaving only the last line, replacing the approximate equality by the exact equality and replacing the notation I_{sat} with $I_{sat\ CM}$, an equation is obtained that implicitly determines the saturation current for compact modeling:

$$I_{sat\ CM} = I_{SAT}\left(V_{gt} - I_{sat\ \ i}\ R_S\right) - g_{mSAT}\left(V_{gt} - I_{sat\ \ i}\ R_S\right) \cdot (I_{sat\ CM} - I_{sat\ \ i})\ R_S\,. \quad (13)$$

From the resulting equation, the saturation current of the OFET is easily expressed in the form suitable for compact modeling:

$$I_{sat\ CM} = \frac{I_{SAT}\left(V_{gt} - I_{sat\ \ i}\ R_S\right) + g_{mSAT}\left(V_{gt} - I_{sat\ \ i}\ R_S\right) I_{sat\ \ i}\ R_S}{1 + g_{mSAT}\left(V_{gt} - I_{sat\ \ i}\ R_S\right) R_S}. \quad (14)$$

Taking as the initial value $I_{sat\ 0}$, we have:

$$I_{sat\ CM\ 0} = \frac{I_{SAT}\left(V_{gt}\right)}{1 + g_{mSAT}\left(V_{gt}\right) R_S}. \quad (15)$$

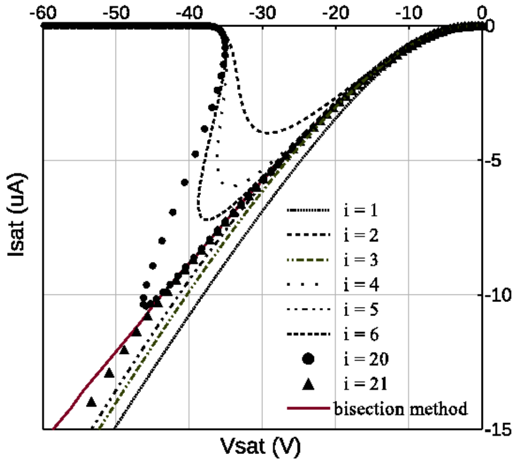

Figure 3. The saturation current as a function of the saturation voltage, obtained by the modelling with iterative method for a different number of iterations i = 1 .. 6, 20, 21 in comparison with the modelling with the method of bisection (solid line).

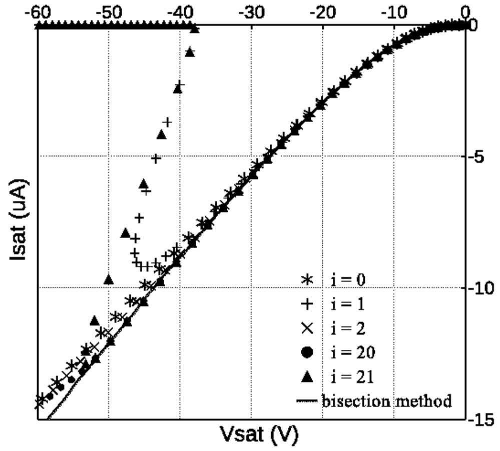

Figure 4. The saturation current as a function of the saturation voltage, obtained by compact modelling with the different initial value of the saturation current obtained from iterations with different i in comparison with the method of bisection (solid line).

If for the initial value we will take $I_{sat\,1} = I_{SAT}(V_{gt}) = \alpha_S\, K\, \frac{\mu_0}{V_{aa}^{\gamma}}\, V_{gt}^{\gamma+2}$, we will get:

$$I_{sat\,CM\,1} = \frac{I_{SAT}(V_{gt}-I_{sat\,1}\,R_S)+g_{mSAT}(V_{gt}-I_{sat\,1}\,R_S)\,I_{sat\,1}\,R_S}{1+g_{mSAT}(V_{gt}-I_{sat\,1}\,R_S)\,R_S}. \quad (16)$$

It is this equation that was used in the [1].

If we will take $I_{sat\,2} = I_{SAT}\big(V_{gt} - I_{SAT}(V_{gt})\,R_S\big)$ as the initial value, we will get:

$$I_{sat\,CM\,2} = \frac{I_{SAT}(V_{gt}-I_{sat\,2}\,R_S)+g_{mSAT}(V_{gt}-I_{sat\,2}\,R_S)\,I_{sat\,2}\,R_S}{1+g_{mSAT}(V_{gt}-I_{sat\,2}\,R_S)\,R_S}. \quad (17)$$

The "extrinsic" saturation voltage is easy to calculate by use of equation (5) with V_{sat} instead of V_{ds} and I_{sat} instead of I:

$$V_{sat} = V_{SAT}(V_{gt} - I_{sat}\,R_S) + I_{sat}\,R_T = \alpha_S\,(V_{gt} - I_{sat}\,R_S) + I_{sat}\,R_T\ , \quad (18)$$

where function V_{SAT} is given by equation (1) with argument V_{GT} given by equation (6) in case when current I is equal to saturation current I_{sat}. We can use equation (18) with the value for the "extrinsic" saturation current I_{sat}, obtained by any method previously discussed: bisection method, iterative method or using the equation for compact modeling.

4. Results and discussions

Figures 1 and 3 show that an even number of iterations, starting with a certain "extrinsic" centered voltage on the gate V_{gt} or saturation voltage V_{sat}, correspondingly, leads to a quick conversion of the calculated saturation current in comparison with the value calculated by the bisection method. With an odd number of iterations some increase of the calculated value of the saturation current is observed in comparison with that calculated by the bisection method. Note that the curve for i = 1 in Figure 1 corresponding to the first iteration, can be considered as the saturation current dependence on the "intrinsic" centered gate voltage.

The dependence in Figures 2 and 4 represented by asterisks * was obtained by the compact modeling using equation (15) (i = 0); the dependence represented by the pluses + is obtained using equation (16) (i = 1); the dependence represented by a cross-sign of multiplication × is obtained using equation (17) (i = 2); the circles correspond to the calculation using equation (14), where the initial value of the saturation current is taken as the value obtained by the iterative method for i = 20; triangles correspond to the calculation using equation (14), where the initial value of the saturation current is taken as the value obtained by the iterative method for $i = 21$.

It can be seen from the Figures 2 and 4 that taking the starting point for compact modeling of saturation current using the results of calculation of the saturation current by the iterative method for odd values of the number of iterations ($i = 1$ and $i = 21$ are presented on Figures) results in a rapid convergence of the saturation current to zero from a certain value of V_{gs} or V_{sat}, correspondingly.

But for even values of the number of iterations ($i = 0$, $i = 2$ and $i = 20$ are presented on Figures), the form of the saturation current dependence on an "extrinsic" centered voltage on the gate V_{gt} or saturation voltage V_{sat}, correspondingly, obtained from compact modeling, is not much different from the results of modeling by the method of bisection.

Comparison of the saturation current calculation results by the iterative method, for a given number of iterations i, (Figures 1 and 3) and by the compact modeling (Figures 2 and 4), using the initial value for the saturation current, obtained by the iterative method with the same number of iterations i, allows us to conclude that compact modeling gives a good accuracy in a much wider range than the calculation using the iterative method that using the same number of iterations.

Finally, we conclude that even compact modeling of the saturation current using equation (15), taking as the starting point the saturation current equal to zero gives an acceptable accuracy for a sufficiently large range of an "extrinsic" centered voltage on the gate V_{gt}.

5. References

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