An approach to organic field-effect transistor above-threshold drains current compact modeling that provides monotonic decrease of the output conductance with drain bias increasing

V O Turin¹, B A Rakhmatov¹, C H Kim² and B Iñiguez³

¹Orel State University after Ivan Turgenev, Naugorskoie shosse 29, 302040 Orel, Russian Federation
²Gwangju Institute of Science and Technology, 61005 Gwangju, South Korea
³Rovira i Virgili University, 43840 Tarragona, Spain

Corresponding author e-mail address: voturin@ostu.ru

Abstract. For compact modeling of the organic field-effect transistor above-threshold drain current, we suggest using an approach that was recently proposed for the improved compact MOSFET model with the correct accounting of the nonzero output conductance in the saturation regime. This approach ensures a monotonic decrease of transistor output conductance from its maximum value in the linear regime to the minimum value in the saturation regime.

1. Introduction
Organic electronics is a relatively young area of science and technology and is aimed at the development of electronic devices based on organic materials [1]. Organic materials have some advantages compared with conventional monocrystal, polycrystalline and amorphous materials used in electronics. Organic materials can be flexible, cheap, biodegradable and easy to apply on large areas and provide almost room temperature fabrication process of electronic devices. The disadvantages of organic materials are rapid degradation and low radiation resistance of material parameters, the low mobility of the charge carriers and relatively large geometric dimensions of devices.

A key device for organic electronics, however, as for the conventional solid-state electronics, is a field-effect transistor [2-5]. Accordingly, for the effective development of organic electronics by using modern electronic CAD, based on the SPICE simulators, the correct compact model of the organic field effect transistor (OFET) is required. At the same time, the current development of the OFET compact model repeats the same steps as the conventional compact models of MOSFET and TFT already have passed.

2. Basics of modern above-threshold OFET drain current theory
In our work, we use as starting point an OFET compact model proposed in [2] and developed on the basis of the MOSFET Level 1 compact model. At low drain bias $V_{DS}$ drain current of OFET is linearly dependent on $V_{DS}$:

$$ I_{lin} = g_{ch} \cdot V_{DS}. $$

(1)
The output conductance \( g_{ch} \) of the OFET at low drain bias \( V_{DS} \) is determined by the following equation:

\[
g_{ch} = \frac{K \mu_{FET} |V_{GS} - V_T|}{[1 + R_C K \mu_{FET} |V_{GS} - V_T|]},
\]

(2)

where \( V_{GS} \) - the gate voltage, \( V_T \) - threshold voltage, \( K = W/L \times C_i \) - parameter, related to gate capacitor geometry and the characteristics of the material, \( W \) - the width of the gate, \( L \) - gate length, \( C_i = \varepsilon \alpha / d_{ox} \) - is the gate insulator capacitance per unit area, \( \varepsilon \) - dielectric constant of the gate insulator, \( d_{ox} \) - the insulator thickness, \( R_C \) - contact resistance and \( \mu_{FET} \) - field effect mobility:

\[
\mu_{FET} = \frac{\mu_0}{V_{aa}}, \quad \gamma\]

(3)

where \( \mu_0 \) – is the conversion mobility set to 1 cm²/V·s; \( V_{aa} \) - is the mobility enhancement voltage, \( \gamma \) - is the characteristic mobility exponent.

With the increase in the drain bias, the drain current saturates. The saturation voltage for OFET is \( V_{sat} = \alpha_s |V_{GS} - V_T| \) with the saturation modulation parameter \( \alpha_s \). At the same time, the saturation current is \( I_{sat} = g_{ch} \cdot V_{sat} \), where \( g_{ch} \) – OFET channel conductance (2). However, for realistic devices there is no perfect saturation due to variety of effects with the Channel Length Modulation effect as the most relevant. This imperfect saturation is usually taken into account through a saturation coefficient \( \lambda \) that enters equation for an asymptotic value of OFET output conductance for the case of large drain bias:

\[
I_{asy} = \lambda I_{sat}
\]

(4)

This saturation coefficient \( \lambda \) has V⁻¹ dimension and is identical to the inverse of the Early voltage from the theory of bipolar transistors.

In [2] the asymptotic behavior of the drain current in the saturation regime, similar to those used in MOSFET Level 1 and RPI TFT models, is proposed:

\[
I_{asy} = I_{sat} + g_{asy} |V_{DS}|
\]

(5)

In [4] for the asymptotic behavior of the drain current in saturation regime is proposed to use the equation from MOSFET BSIM3/4 compact models, that significantly improves the characteristics of the model, but does not eliminate it from some of the shortcomings analyzed in [6,7]:

\[
I_{asy} = I_{sat} + g_{asy} (|V_{DS}| - V_{sat})
\]

(6)

For above-threshold OFET drain current in [2,4] is proposed to use equation, traditional for MOSFET Level 1 and BSIM3/4 models:

\[
I = \frac{I_{lin} I_{asy}}{|I_{lin}|^m + I_{sat}^m}, \quad\]

(7)

where \( m \) - the exponent that determines the smoothness of the transition from the linear transistor regime to the current saturation regime.

In [6, 7] the equation (7) were analyzed with \( I_{asy} \), defined by both equations (5) and (6). It has been shown that the output conductance doesn’t decrease monotonically with increasing drain bias \( V_{DS} \), which is a drawback of MOSFET Level 1, RPI TFT and BSIM3/4 models. In addition, in the case when \( I_{asy} \) is given by equation (6) the output conductance of the OFET at zero drain bias (obtained by taking the derivative of \( I \) with respect to \( V_{DS} \) and supposing \( V_{DS}=0 \)) is not equal to postulated value \( g_{ch} \), given by equation (2).

3. New set of equations for the above-threshold OFET drain current

In this work, for OFET above-threshold drain current calculation, we suggest to use approach, that was recently proposed in [6,7] for the improved compact MOSFET model. This ensures the correct accounting of the nonzero output conductance in the saturation regime with a monotonic decrease of OFET output conductance from its maximum value in the linear regime to the minimum value in the saturation regime.
Figure 1. Output conductance-voltage characteristics for OFET calculated with different equations for drain current. In all the figures the lower curve for the gate voltage $V_{GS} = -30$ V, with further increments of 5 V to -50 V; (a): the equation for the drain current (7) with the asymptotic (5); (b) the equation for the drain current (7) with the asymptotic (6); (c) the drain current equations (8) and (9) with an asymptotic (6); (a), (b) and (c): $\lambda = 0.01$ V$^{-1}$; (d): $\lambda = 0$ V$^{-1}$.

At the same time, we preserve the equation for the asymptotic behavior of the drain current (6). Hence, the modified equation for the OFET drains current is:

$$I = \frac{I_{lin} I_{asy}}{|l_{lin}\left[m + I_{asy} m\right]|^{1/m}},$$

where $I_{asy}$ is given by equation for the OFET drain current asymptotic (6) multiplied by a correction factor, which provides the correct asymptotic behavior of the equation (8):

$$I_{asy} = \frac{g_{ch}}{[g_{ch} - g_{asy} m]} I_{asy}.$$

Note, that if we impose obvious condition $g_{asy} < g_{ch}$ on scope where we will use equations (8) and (9), we will ensure positive values of $I_{asy}$ and $g_{ch} m - g_{asy} m$ that is necessary for correct use of equations (8) and (9) in numerical calculations, in respect that exponents $m$ and $1/m$ is not necessarily even integer numbers.

Table 3. Parameters of the pentacene OFET and one's compact model [4].

| $\gamma$ | $V_T$ | $\mu_{ET}(V_{GS} = -50$ V) | $\alpha_s$ | $R_C$ (kΩ) | $m$ | $\lambda$ (V$^{-1}$) | $L$ (um) | $W$ (um) | $C_i$ (nF/cm$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| 0.91 | -12 | 0.13 | 0.46 | 24 | 1.8 | $1.2 \times 10^{-3}$ | 40 | 1000 | 3.3 |
Figure 2. Current-voltage characteristics for OFET calculated with different equations for drain current. In all the figures the lower curve for the gate voltage $V_{GS} = -30$ V, with further increments of 5 V to -50 V; (a): the equation for the drain current (7) with the asymptotic (5); (b) the equation for the drain current (7) with the asymptotic (6); (c) the drain current equations (8) and (9) with an asymptotic (6); (a), (b) and (c): $\lambda = 0.01$ V$^{-1}$; (d): $\lambda = 0$ V$^{-1}$.

The numerical values of the compact model parameters are shown in Table 1 and are the same as extracted for pentacene OFET in [4]. By use of equation (3) for the field effect mobility with data for $\mu_{FET}(V_{GS} = -50$ V) from Table 1 we can calculate $V_{aa} = 358$ V, that is necessary to calculate field-effect mobility for different values of gate bias $V_{GS}$.

Calculations show that at $\lambda = 1.2 \times 10^{-3}$ V$^{-1}$ new equations (8) - (9) do not give a significant difference from equation (7), that was used in [4] to plot OFET current-voltage and output conductance-voltage characteristics. However, in [5] sufficiently large value of $\lambda = 0.01$ V$^{-1}$ was used, for which our calculations show a significant difference between the use of equations (8) - (9) instead of (7). New equations provide a monotonic decrease in the differential output conductance of OFET (Figure 1(c)). Equation (7) gives a significant deviation from the monotonic decrease of the OFET output conductance with the usage of both asymptotes of the OFET drain current (5) (see Figure 1(a)) and (6) (see Figure 1(b)). For comparison, Figure 1(d) shows the output conductance of OFET for the case of $\lambda = 0$ V$^{-1}$. On Figures 2(a), (b), (c) and (d) corresponded current-voltage characteristics are presented.

4. Conclusion

The development of the OFET compact model repeat the same steps as the conventional compact models of MOSFET and TFT already have passed. Hence, for above-threshold drain current in OFET compact model traditional equation for a smooth transition from the linear regime to saturation regime is usually used. However, in the case of accounting nonzero output conductance in saturation regime, this equation doesn’t provide a monotonic decrease of the output conductance with increasing drain
bias from its maximum value in the linear regime to the minimum value in the saturation regime. In this paper for OFET above-threshold drain current calculations, we offer to use a new approach that was proposed recently for the improved compact MOSFET model. This approach ensures monotonic decrease of the output conductance with an increase of the drain bias from the maximum value in a linear regime to a minimum value in the saturation regime. Our calculations show significant drawback in the usage of the traditional equation for parameters set extracted for typical OFET with a value of saturation coefficient $\lambda = 0.01$ V$^{-1}$ or more. On the other hand, new equations for above-threshold drain current give a perfect monotonic decrease of output conductance from the maximum value in a linear regime to a minimum value in the saturation regime for all range of saturation coefficient $\lambda$. In further work, we plan to take into account source and drain resistances separately for a correct accounting one's effect on output characteristic both in linear and in the saturation regime follow approach developed in [8].

Acknowledgments
This work was partially supported by RFBR grant No. 12-02-97534 and by the Ministry of Education and Science of the Russian Federation grant No. 16.1117.2014/K (Goszadanie).

References
[1] Kuhto A V 2013 Chemistry and Life – XXI century 2 3 (In Russian)
[2] Estrada M, Cerdeira A, Puigdollers J, Reséndiz L, Pallares J, Marsal L F, Voz C and Iñiguez B 2005 Solid State Electron. 49(6) 1009
[3] Marinov O, Deen M J, Zschieschang U, Klauk H 2009 IEEE T. Electron Devices 56(12) 2952
[4] Kim C H, Castro-Carranza A, Estrada M, Cerdeira A, Bonnassieux Y, Horowitz G and Iñiguez B 2013 IEEE T. Electron Devices 60(3) 1136
[5] Kim C H, Bonnassieux Y and Horowitz G 2014 IEEE T. Electron Devices 61(2) 278
[6] Turin V O, Zebrev G I, Makarov S V, Iñiguez B and Shur M S 2014 Int. J. Numer. Model. El. 27 863.
[7] Turin V O, Sedov A V, Zebrev G I, Iñiguez B and Shur M S 2009 Proc. SPIE 7521 75211H-1
[8] Turin V O, Zebrev G I, Makarov S V, Iñiguez B and Shur M S 2015 Proc. Int. Conf. “Energy and Resource Saving – XXI”, ed O V Pilipenko, A N Kachanov and Y S Stepanov (Orel: State University ESPC) p 150 (In Russian)