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PAPER

Theoretical frequency limit of organic field-effect transistors

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Abstract

In this paper, a new theoretical model for the ac transit frequency of organic field-effect transistors is proposed. The model is built upon an advanced physical description of the contact resistance as a key mathematical component. Such a treatment self-consistently and predictively correlates the transit frequency to a number of materials, geometrical, and operational parameters. By navigating a broad parametric space, it is found that the ambitious gigahertz operation is observable only in highly downscaled devices, and the intrinsic carrier mobilities and charge-injection barriers required to reach that regime are specified.

1. Introduction

Organic field-effect transistors (OFETs) are entering into certain technological maturity, considering the progress made over the past three decades [1–4]. Another timely evidence is a rise in transparent research practices and directions affecting the community as a whole [5–9], which is essential to a sustainable road map that reflects the true technological status. The first relevant topic is the mobility overestimation issue, which is well enlightened by Bittle et al in 2016 [10]. More recently in 2018, Paterson et al stated in their review that 55% of the reported high mobilities are not fully data-supported or may have been affected by device non-idealities [11]. Secondly, scientific efforts are being re-oriented towards enabling real-world applications, thus making the often overlooked dynamic (or ac) behaviors of an OFET a key device criterion. In 2016, Perinot et al reported on the direct-written polymer transistors operating at 20 MHz [12], but still the maximum frequency of OFETs stays far below that of their industrial counterparts.

Interestingly, contact resistance ($R_c$) is central to both of these issues; when a given OFET is strongly contact-limited, it will feature parametric ambiguities by non-trivial gate responses, and this OFET will also have a low cut-off frequency. Over the years, our group has accumulated experimental and theoretical insights into this important $R_c$ problem, clarifying its origin and manifestation [8, 13–17]. In this article, we build upon these previous efforts and propose a new fully analytical model for the transit frequency ($f_T$) of OFETs. To some extent, the present work can be viewed as an extension of the theoretical projection of Klauk for GHz OFETs published in 2018 [18]. The major difference in our approach is not to treat $R_c$ and carrier mobility as individual variables, but to see them as an mathematically inseparable pair. This is made possible by breaking down various other parameters including mobility, and consequently, the prediction of $f_T$ does not require $R_c$ as an input. In other words, while $R_c$ does play a pivotal role in the entire process, it will only serve as a key intermediate and effectively vanishes in the final step, so that the $f_T$ is directly linked to materials-level parameters (figure 1(a)).

2. Contact resistance as a ‘macro’ parameter

Let's start by re-iterating our latest $R_c$ model [17]. It can be written for an n-type OFET as

$$
R_c = \frac{1}{q\mu W} \sqrt{N_c} \exp\left(-\frac{E_i}{2kT}\right) C_e(V_g - V_f) f_T^2 + \frac{E_i}{kT},
$$

(1)

Here, $q$ is the elementary charge, $\mu$ is the electron mobility, $W$ is the channel width, $N_c$ is the lowest-unoccupied molecular orbital (LUMO) effective density of states (DOS), $E_i$ is the electron injection barrier as the energetic distance between the source/drain Fermi level and the semiconductor LUMO level, $k$ is...
the Boltzmann constant, $T$ is the absolute temperature, $\varepsilon_s$ is the semiconductor permittivity, $C_i$ is the insulator capacitance per unit area, $V_G$ is the gate-to-source voltage, and $V_T$ is the threshold voltage.

Figure 1(b) shows $R_cW$ predicted by equation (1) with varying $\mu$ and $E_b$. All parameters other than $\mu$ and $E_b$ were taken from the base parameter list that we provide in Table 1. Note that the simulated range of $R_cW$ here is in good agreement with what is measured from high-performance OFETs [19, 20], broadly ascertaining the validity of the model. More importantly, the fact that we know the ‘origin’ of $R_c$ and have equation (1) in our hands means that $R_c$ turns into a macroscopic parameter; while $R_c$ conveniently appears as a stand-alone parameter in many device models [21], we can replace it by materials parameters when necessary and construct its value in a completely bottom-up way. As will be seen below, the ability to replace $R_c$ by other parameters is beneficial to optimizing $f_T$, as it interrelates the two critical contributors (i.e. $R_c$ and $\mu$) [18] and clarifies how to tune the value of $R_c$ by materials engineering.

There are two additional notes to make. Firstly, the precise meaning of $\mu$ should be kept in mind. In all equations of this paper, it is the intrinsic charge-carrier mobility of a given semiconductor material, not affected by any external factors. Imagine that we have two perfectly identical organic semiconductor films (i.e. same molecules arranged in the same solid-state order) but select two different source/drain metals to build two OFETs. In this case, we should have the same $\mu$ in both OFETs, but may extract different ‘effective’ mobilities (also called apparent mobilities) [13] out of measurements due to contact-related phenomena. For instance, one can extract the mobility lower than $\mu$, in the case where the current is reduced entirely due to $E_b$, but one simply interprets it as an outcome of low mobility. Then a simple reason why $R_c$ is a function of $\mu$ in equation (1) is that it is, just like any usual resistance, made of both carrier density and mobility [22]. The number of injected carriers is determined by $E_b$, but these carriers should transport through the semiconductor to reach the channel.

![Figure 1](image-url)

**Table 1.** List of the base parameters.

| Category                                | Symbol | Value           |
|-----------------------------------------|--------|-----------------|
| Parameters required for $R_cW$ prediction | $\mu$  | $1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ |
|                                        | $N_c$  | $10^{20} \text{ cm}^{-3}$ |
|                                        | $E_b$  | 0.2 eV          |
|                                        | $T$    | 300 K           |
|                                        | $\varepsilon_s$ | 3.5 $\varepsilon_0^2$ |
|                                        | $C_i$  | 100 nF cm$^{-2}$ |
|                                        | $V_G$  | 10 V            |
|                                        | $V_T$  | 0 V             |
| Additional parameters for $f_T$ prediction | $L$    | 1 $\mu$m       |
|                                        | $L_{ov}$ | 1 $\mu$m      |
|                                        | $V_D$  | 1 V             |

* $\varepsilon_0$ is the vacuum permittivity.
feeling $\mu$. Second one is a side note. When using equation (1) in practice, a care has to be taken to use consistent physical units. For instance, when $kT$ is inserted in J, the value of $E_b$, which is generally cited in eV, should also be converted to the J scale.

3. Mobility matters, but length dominates

Now, we proceed to the $f_T$ model. Assume a sinusoidal gate input voltage ($v_G$) and a resulting ac drain current ($i_D$). The corresponding gate current ($i_G$) is basically a charging current and written in phasor representation as

$$i_G = j2\pi f C_G v_G,$$  \hspace{1cm} (2)

where $j$ is the imaginary unit accounting for the phase difference between $v_G$ and $i_G$, $f$ is the frequency of $v_G$, and $C_G$ is the total capacitance bound to the gate electrode. The produced $i_D$ signal reflects the device transconductance ($g_m$) as

$$i_D = g_m \cdot v_G,$$  \hspace{1cm} (3)

so the gain as a current magnitude ratio is

$$\frac{|i_D|}{|i_G|} = \frac{g_m}{2\pi f C_G}.$$  \hspace{1cm} (4)

Upon increasing $f$, this gain falls below unity, meaning no amplification. Thus, $f_T$ captures this moment when the gain is 1, and represents the maximum operation speed of a given OFET [12, 18]. From equation (4),

$$f_T = \frac{g_m}{2\pi C_G}. \hspace{1cm} (5)$$

In the linear regime of OFET, the source-to-drain conduction path is simplified as a series connection of a channel resistance and $R_c$, expressing the static drain current ($I_D$) as [14, 16]

$$I_D = \frac{V_D}{R_c + \frac{W}{L \mu C_G (V_G - V_T)}}, \hspace{1cm} (6)$$

where $V_D$ is the drain-to-source voltage and $L$ is the channel length. Then $g_m$ is calculated to be

$$g_m = \frac{dI_D}{dV_G} = \frac{W \mu C_G L V_D}{R_c W \mu C_G (V_G - V_T) + L^2}. \hspace{1cm} (7)$$

The $C_G$ is comprised of three parallel capacitances, which are gate-to-channel capacitance, gate-to-source overlap capacitance, and gate-to-drain overlap capacitance. From figure 1(a), we notice that

$$C_G = C_i W (L + 2L_{ov}). \hspace{1cm} (8)$$

Putting equations (7) and (8) into equation (5) gives

$$f_T = \frac{\mu L V_D}{2\pi (L + 2L_{ov}) [R_c W \mu C_G (V_G - V_T) + L^2]},$$  \hspace{1cm} (9)

and replacing $R_c$ by equation (1) here, the final form becomes

Figure 2. Projection for GHz OFETs. The model-predicted $f_T$ is plotted against $\mu$ at different $E_b$, assuming (a) $L = L_{ov} = 1 \mu m$, (b) $L = 1 \mu m, L_{ov} = 0 \mu m$, (c) $L = L_{ov} = 0.1 \mu m$, and (d) $L = 0.1 \mu m, L_{ov} = 0 \mu m$. 

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required for calculating operational conditions are input parameters covering materials, geometrical, and physical model that predicts $f_T$ when a total of eleven parameters covering materials, geometrical, and operational conditions are input (figure 1(a)). Among them, there are eight parameters necessary for estimating $R, W$, and three others that are additionally required for calculating $f_T$ (table 1).

In figure 2, we evaluate how large $\mu$ has to be for GHz operation, which leads to a conclusion that, within a currently realistic range of $\mu$ [11], only extreme scaling down of $L$ and $L_{ov}$ can realize the goal. Although this is basically the same message as the previous one [18], we will prove here that reducing $E_b$ is an effective approach to reaching GHz from less challenging $\mu$ and device lengths. Remember that figure 2 involves $\mu, E_b, L$, and $L_{ov}$ as variables, and all the other parameters have their base values of table 1. When $L = L_{ov} = 1 \mu m$, which already represents quite tight process constraints for OFETs, $f_T$ never reaches 1 GHz by any combinations of $\mu$ and $E_b$ considered (figure 2(a)). At the same $L$ with ideal non-overlapping (zero $L_{ov}$), $f_T$ touches the bar only if the injection is very efficient and $\mu$ is close to $70 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ (figure 2(b)). Fabricating sub-micron channels is still a formidable challenge, while promising results have been reported [23–26]. Figure 2(c) shows that, if $L = L_{ov} = 0.1 \mu m$, $f_T = 1 \text{ GHz}$ when $E_b = 0 \text{ eV}$ (perfectly injecting contact) with $\mu = 1.9 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ or $E_b = 0.1 \text{ eV}$ with $\mu = 3.8 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. The most challenging geometry that we consider is in figure 2(d), where $L = 0.1 \mu m$ and $L_{ov} = 0 \mu m$. In this case, $f_T = 1 \text{ GHz}$ for three possibilities; $E_b = 0 \text{ eV}$ with $\mu = 0.63 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $E_b = 0.1 \text{ eV}$ with $\mu = 1.3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, or $E_b = 0.2 \text{ eV}$ with $\mu = 60 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$.

Above we have identified the parameters for GHz OFETs, in a holistic modeling approach, to answer such an emerging question of the community [18]. Now we want to take one step back and provide the maximum frequencies achievable by various parametric combinations as they are. Using the same equation (10), the value of $f_T$ is calculated and plotted as a function of $E_b$, to visualize the importance of molecular energy level tuning and contact engineering [19, 27–29]. In figure 3(a), $L = L_{ov} = 1 \mu m$, and for two fixed $\mu$, the exact calculated $f_T$ values are written.

\[
f_T = \frac{\mu L V_D}{2\pi (L + 2L_{ov}) \left[ \frac{\ln \frac{c_1 \gamma_\mu - \gamma_\nu^2}{2qN} + \frac{c_2}{\gamma_\nu} }{q\sqrt{\frac{c_1}{c_2}}} \right] + L},\]

Equation (10) is a fully analytical, closed-form physical model that predicts $f_T$ when a total of eleven parameters covering materials, geometrical, and operational conditions are input (figure 1(a)). Among them, there are eight parameters necessary for estimating $R, W$, and three others that are additionally required for calculating $f_T$ (table 1).

Figure 3. Summary of the $f_T$ values that are achievable by a number of different parametric combinations.
along with the graph symbols. Figure 3(b) is a similar summary plot, for \( L = L_{ov} = 0.1 \mu m \). Again note that, for the calculations for figure 3, the base parameters (table 1) are used except for \( \mu, E_b, L, \) and \( L_{ov} \). These two plots may serve as a benchmark for creating OFETs with a specific target frequency, not necessarily in the GHz regime.

4. Other considerations

Up to this point, we focused on and clarified the effects of \( \mu, E_b, \) and the two length parameters \( (L \) and \( L_{ov} \)) on \( f_T \), in the belief that these are the critical ones. Here, we subtly change other parameters, to verify how robust the base parameters are and to see if these less considered parameters may bring any meaningful contribution.

Now \( \mu, L, L_{ov} \) are fixed as their base values, and we systematically change four parameters one at a time, leaving \( E_b \) as the graphical variable. The DOS of organic semiconductors is by itself a complex topic, and we took \( N_c = 10^{20} \text{ cm}^{-3} \) as a rough average, considering the common molecular density of the order of \( 10^{21} \text{ cm}^{-3} \) (equivalent to the typical lattice constant of 1 nm) [30]. Figure 4(a) indicates that, within the \( 10^{19} \)–\( 10^{21} \text{ cm}^{-3} \) range, \( N_c \) is not so critical to \( f_T \) unless the charge injection is poor. The dielectric constant of an organic semiconductor is often assumed to be three, while some higher values also appear [31, 32]. Figure 4(b) shows that \( \epsilon_s \) has no significant effect within this small window. The base value of \( C_i = 100 \text{ nF cm}^{-2} \) might sound already quite high for an average OFET, while an electrolytic capacitance can certainly provide an additional boost. Figure 4(c) shows that, within one order variation, smaller \( C_i \) led to higher \( f_T \). The decrease in \( C_i \) by decreasing \( C_i \) was the major reason for this increase in \( f_T \), while a high \( C_i \) is beneficial for simply reducing \( R_c \). Finally, we change the applied bias. Equation (10) makes it clear that \( f_T \) linearly scales with \( V_D \), so increasing \( V_D \) seems to be a simple way to increase \( f_T \) with no change in the device. While this is basically true, we should remember that the entire modeling was built on the assumption of linear-regime operation. This means that when the magnitude of increased \( V_D \) becomes comparable to or exceeds that of \( V_G - V_T \), this basic assumption collapses and the model is not strictly applicable. Therefore, we changed not only \( V_D \) but both \( V_D \) and \( V_G \) simultaneously, while maintaining their one order difference. Figure 4(d) shows that, as expected, applying higher biases will get higher \( f_T \), especially when charge injection is efficient.

5. Conclusion

This article introduced a new theoretical model for \( f_T \) in OFETs. Its major feature was an extensive physical correlation of all hierarchical features, so that \( f_T \) is fully predictable by base-level parameters. This method allowed to explore the dependence of \( f_T \) on a number of parameters.
of materials parameters (including \(E_p, N_o, \) and \(\epsilon_s\)), which was not possible by the previous model. Our model seems to have two practical usages. Firstly, one can simulate \(f_L\) at design stages, then fabricate OFETs operating at a specific target frequency. Secondly, one can take a measured \(f_L\) value and put it into the model to explore hidden parameters (e.g. \(E_p\)) influencing the device. Like many other early-day issues, the limited frequency response of OFETs will be possibly overcome by leveraging both experimental and theoretical endeavors. We therefore believe that advanced theoretical models (such as one presented in this paper) will serve to guide the entire optimization process, so that experiments get the maximum results and resources are invested in the right directions.

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**References**

[1] Klauk H 2010 *Chem. Soc. Rev.* 39 2643–66
[2] Sirringhaus H 2014 *Adv. Mater.* 26 1319–35
[3] Guo X et al 2017 *IEEE Trans. Electron Devices* 64 1906–21
[4] Lampert Z A, Hancef H F, Anand S, Waldrip M and Jurchescu O D 2018 *J. Appl. Phys.* 124 071101
[5] Choi D, Chu P H, McBride M and Reichmanis E 2015 *Chem. Mater.* 27 4167–8
[6] Liu C, Li G, Di Pietro R, Huang J, Noh Y Y, Liu X and Minari T 2017 *Phys. Rev. Appl.* 8 034020
[7] Choi H H, Cho K, Frisbie C D, Sirringhaus H and Podzorov V 2018 *Nat. Mater.* 17 2–7
[8] Kim C H, Thomas S, Kim H J, Elliot M, Macdonald J E and Yoon M H 2018 *Adv. Electron. Mater.* 4 1700514
[9] Xu Y, Sun H, Liu A, Zhu H, Li B, Minari T, Balestra F, Glubaudo G and Noh Y Y 2018 *Adv. Funct. Mater.* 28 1803907
[10] Bittle E G, Basham J L, Jackson T N, Jurchescu O D and Gundlach D J 2016 *Nat. Commun.* 7 10908
[11] Paterson A F, Singh S, Fallon K J, Hodsdon T, Han Y, Schroeder B C, Bronstein H, Heeney M, McCulloch I and Anthopoulos T D 2018 *Adv. Mater.* 30 1801079
[12] Perinot A, Khirsagar P, Malvindi M A, Pompa P P, Fiammengo R and Caironi M 2016 *Sci. Rep.* 6 38941
[13] Kim C H, Bonnassieux Y and Horowitz G 2011 *IEEE Electron Device Lett.* 32 1302–4
[14] Kim C H, Bonnassieux Y and Horowitz G 2013 *IEEE Trans. Electron Devices* 60 280–7
[15] Kim C H, Hlaing H, Payne M M, Yager K G, Horowitz G, Anthony J E and Kymissis I 2014 *ChemPhysChem* 15 2913–6
[16] Kim C H, Hlaing H, Hong J A, Kim J H, Park Y, Payne M M, Anthony J E, Bonnassieux Y, Horowitz G and Kymissis I 2015 *Adv. Mater. Interfaces* 2 1400384
[17] Kim C H and Horowitz G 2019 *Materials* 12 11169
[18] Klauk H 2018 *Adv. Electron. Mater.* 4 1700474
[19] Natali D and Caironi M 2012 *Adv. Mater.* 24 1353–87
[20] Borchert J W, Peng B, Letzkus F, Burghartz J N, Chan P K L, Zoiher K, Ludwigs S and Klauck H 2019 *Nat. Commun.* 10 11119
[21] Kim C H, Bonnassieux Y and Horowitz G 2014 *IEEE Trans. Electron Devices* 61 278–87
[22] See S M and Ng K K 2007 *Physics of Semiconductor Devices* (Hoboken, NJ: Wiley)
[23] Noh Y Y, Zhao N, Caironi M and Sirringhaus H 2007 *Nat. Nanotechnol.* 2 784–9
[24] Higgins S G, Muir B V O, Dell’Erba G, Perinot A, Caironi M and Campbell A J 2016 *Appl. Phys. Lett.* 108 023302
[25] Zachieschang U, Borchert J W, Geiger M, Letzkus F, Burghartz J N and Klauk H 2018 *Org. Electron.* 61 65–9
[26] Thilburge Q, Giovanniatti A, McCulloch I and Campbell A J 2019 *Nano Lett.* 19 1712–8
[27] Hwang I, Wan A and Kahn A 2009 *Mater. Sci. Eng. R* 64 1–31
[28] Liu C, Xu Y and Noh Y Y 2015 *Mater. Today* 18 79–96
[29] Kim C H and Kymissis I 2017 *J. Mater. Chem. C* 5 4598–613
[30] Craciun N I, Wildeman J and Blom P W M 2008 *Phys. Rev. Lett.* 100 056601
[31] Kim C H, Yaghmazadeh O, Tondelier D, Jeong Y B, Bonnassieux Y and Horowitz G 2011 *J. Appl. Phys.* 109 083710
[32] Chen S, Tsang S W, Lai T H, Reynolds J R and So F 2014 *Adv. Mater.* 26 6125–31