Channel Length Dependent Performance of Organic Field Effect Transistor: MATLAB Based Simulation and Analytical Modelling

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***Abstract*- Organic transistor plays an important in electronic applications as it provides additional benefit of flexibility and low cost compared to silicon electronic devices. Simulation and analytical model of such organic devices helps in improving and optimizing the performance of the device. There are various parameters that effect the performance of the device. In this paper, analytical modelling of the organic device is done based on the device physics to simulate the output characteristics using MATLAB for various channel length (L). Here, the variation is observed on varying the device length and its impact is observed on the drain current. Different channel length taken into consideration are 5µm, 15 µm, 30 µm and 60 µm and the simulation result states that the drain current increases on decreasing the channel length. Thus, simulation of such analytical models helps in extracting the useful information about the performance of the organic transistors.**

Keywords*- *Organic field effect transistor (OFET); analytical model; MATLAB simulation; Channel length modulation; OFET modelling; mobility; drain current.

I. INTRODUCTION

Organic field effect transistor (OFET) is a voltage controlled current source device consisting of three terminals - source, drain and gate. Unlike silicon field effect transistor (FET) Organic FET usually operate in the accumulation mode and not in the inversion mode. Depending on organic semiconductor material used and material of contacts charge flow of one carrier type (electrons or holes) is more than other, this defines whether the device works like p-channel FET or n-channel FET [1],[2]. Just like the silicon FET, device performance of OFET also depends on the various parameters of the device such as oxide layer thickness, material used in the electrodes, oxide material, etc. Designing of organic electronic circuit depends on the exact modelling and accurate parameter extraction of device [3]. In order to better understand the various performance parameters of the device such as output characteristics, transfer characteristics, on/off ratio, mobility, etc., modelling of the device is done. There are usually two methods of simulation – finite element-based simulation and analytical model-based simulation [4]. This paper deals with the analytical model of pentacene based OFET showing the drain current variation as per the channel length modulation ranging from 5µm to 60µm.

II. DEVICE STRUCTURE

In the case of OFET there are usually 4 types of the device structures based on the location of the electrodes – source, drain and gate [5]– 1. Bottom gate top contact, 2. Bottom gate bottom contact, 3. Top gate top contact, 4. Top gate bottom contact [6],[7].Figure 1 shows various types of OFET devices.

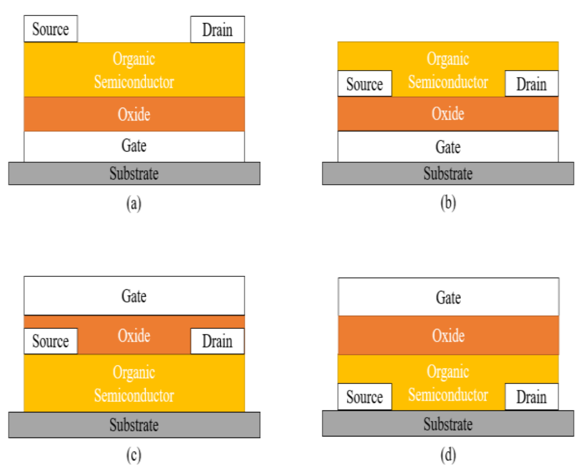

Figure 1. Various types of OFET device structures – (a) Bottom gate top contact, (b) Bottom gate bottom contact, (c) Top gate top contact, (d) Top gate bottom contact.

Without changing organic semiconductor material and dielectric material, top contact bottom gate device offers better mobility due to less contact resistance compared to top gate devices [8]. Another reason for this difference is large semiconductor and metal contact resistance due to interface contact barrier of semiconductor film around source and drain contacts [9]. Due to better mobility and better drain current result observed in bottom gate devices as compared to top gate devices, bottom gate top contact device structure as shown in figure 2 is taken into consideration for the analytical model. Pentacene is used as the organic semiconductor. Channel length and width and length L and Z respectively [10]. Dielectric thickness is t_{ox} having permittivity of $\in_{ox}$ resulting in the capacitance of C_{ox} given by $C_{ox} = \in_{ox}/t_{ox}$. Semiconductor thickness is t_s having permittivity of $\in_s$ resulting in the capacitance of $C_{ox} = \in_s/t_s$. For the simplicity of the model threshold voltage is set to be 0V. Its value is included in model by replacing V_{gs} with $V_{gs} - V_{th}$ [11].

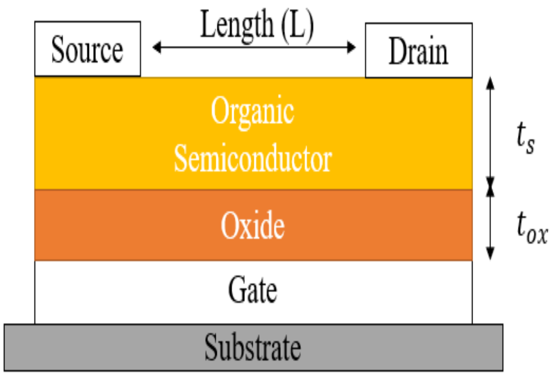

Figure 2. Pentacene based OFET device structure.

III. ANALYTICAL MODEL

It is usually the modelling of the device characteristics based on the equations that best describes the behaviour of the device. Drain to source current both in linear and saturation region of OFET having 50µm channel length shows good agreement with the drain to source current equations for the silicon FET. When this channel length is decreased up to 1µm it shows variations similar to the one observed in silicon FET [12]. Transistor model parameter extraction is one of the benefits from the modelling ad circuit simulation and it's also a time saving task. Material used in the thin film is Pentacene [13]. Thus, the modelling of such OFET is done using MATLAB [14] to obtain the output characteristics and see the variations in the current as per the channel length modulation in – 1. Linear region, 2. Saturation region.

a. *Linear region*

Linear region mode of operation is observed when the drain to source voltage is less than the gate voltage of the device, i.e.$(V_{ds} < V_g)$. Drain current I_{ds} in the linear mode of operation of transistor is denoted as the combination of accumulation layer current and bulk current due to free carriers in semiconductor [11]. Here, Q_0 representsfree carriers surface density and its numerically given as -

$$Q_0 = \pm q n_0 d_s \tag{1}$$

$Q_g(x)$ represents carriers surface density in accumulation layer, which causes capacitive effect,

$$Q_g(x) = C_i[V_{gs} - Vs(x) - V(x)] \tag{2}$$

Thus, giving total drain current as,

$$\frac{I_{ds}}{Z\mu} = -[Q_g(x) + Q_0]\frac{dV}{dx} \tag{3}$$

On combining equations 1, 2 and 3 we get,

$$\frac{I_{ds}}{Z\mu} = C_i\left[V_{gs} - V_{th} - V(x)\frac{dV}{dx}\right] \tag{4}$$

Above equation is integrated over the length from (x = 0) to (x = L) and the voltage range from V=0V to V=V_{ds} given by,

$$I_{ds}\int_0^L dx = I_{ds}L = Z\int_0^{V_{ds}} \mu\, C_i(V_{gs} - V + V_{th})dV \tag{5}$$

Resulting in the final equation representing the drain to source current in the linear region.

$$I_{ds} = \frac{Z}{L}\mu C_i\left[(V_{gs} + V_{th})V_{ds} - \frac{V_{ds}^2}{2}\right] \tag{6}$$

b. *Saturation region*

When drain to source voltage exceeds the gate voltage $(V_{ds} > V_g)$ depletion layer is formed and the device now operates in the saturation region. This depletion layer extends form the point x_0 to the point of drain contact [15]. Now the drain current is given by,

$$I_{ds}dx = Zq\mu n_0[d_s - W(x)]dV \tag{7}$$

Where width of the depletion region W(x) is obtained from the following Poisson equation [15],[16],

$$\frac{d^2V}{dy^2} = -\frac{qN}{\in_s} \tag{8}$$

having the boundary conditions

$$V(W) = 0 \tag{9}$$

$$\left.\frac{dV}{dy}\right|_{y=W} = 0 \tag{10}$$

giving the solution as,

$$V(x) = \frac{qN}{2\in_s}(x - W)^2 \tag{11}$$

Potential at insulator/semiconductor interface is,

$$V_s = \frac{qN}{2\in_s}W^2 \tag{12}$$

and the voltage drop at insulator is,

$$V_i = \frac{qNW}{C_i} \tag{13}$$

The following Kirchhoff's equation holds,

$$V_g + V(x) = V_i + V_s \quad (14)$$

Hence, width of the depletion layer is,

$$W(x) = \frac{\epsilon_s}{C_i}\left\{\sqrt{1+\frac{2C_i^2[V(x)-V_{gs}]}{qN\epsilon_s}}\right\} - 1 \quad (15)$$

Here we have assumed that till $V(x_0) = V_{gs}$ accumulation layer extends and after x_0 depletion layer extends. Thus,drain current in the saturation mode of operation is due to the combination of both and can be stated as –

$$I_{ds} = \frac{Z}{L}\mu C_i \int_0^{V_{gs}}(V_{gs} + V_{th} - V)dV + \frac{Z}{L}\mu q n_0 \int_{V_{gs}}^{V_{ds}}(d_s - W)dV \quad (16)$$

Gate voltage at which the depletion layer is equal to t_s is the pinch-off voltage V_p, which is obtained after substituting $V_p = V_g - V(x)$ in equation 15. Thus,

$$V_p = \pm\frac{qNd_s^2}{2\epsilon_s}\left(1 + 2\frac{C_s}{C_i}\right) \approx \frac{qNd_s}{C_i} \quad (17)$$

where flat band voltage is neglected and $t_s \ll t_{ox}$ in the approximated value above. Assuming $n_0 = N$, then $V_p = V_0$ andfinally, current in the saturation region is given by –

$$I_{ds} = \frac{Z}{2L}\mu C_i (V_{gs} - V_{th})^2 \quad (18)$$

IV. RESULT

4.1 Mobility

It is the ease with which charge carrier can flow in device and can result in the current flow. It depends on impurity, defects and organic semiconductor material [17]. Channel conduction in thin film organic transistor is demonstrated by Poole-Frenkel mobility model which states the mobility as [18]–

$$\mu(E) = \mu_0 \exp\left[-\frac{\Delta}{KT} + \left(\frac{\beta}{KT} - \gamma\right)\sqrt{E}\right] \quad (19)$$

Where effective mobility is represented by$\mu(E)$,electric field is represented by E, fitting parameter is represented by γhaving value 10^{-5} $(cm/V)^{1/2}$, Pool-Frenkel factor is represented byβhaving value $4.35x10^{-5}$ $eV(cm/V)^{1/2}$, Boltzmann constant is represented by K, temperature is represented by T, zero field activation energy is represented by Δhaving value 0.1 eV and zero field mobility is represented byμ_0[4],[15].

Following table 1 shows the parameters taken into consideration for the analytical model –

Table 1. Parameters and values taken for modelling [18]

Parameters	**Values**
Channel Length (µm) (variable)	5-60
Channel Width (µm)	100
Thickness of dielectric Al_2O_3 (nm)	5.7
Effective mobility (cm^2/Vs)	0.395
Capacitance of gate $\mu F/cm^2$	0.7

In the analytical model mobility is taken as a fixed value but based on the several experiments it is stated that it depends on the voltage variation between drain-source and gate-source [13]. Mobility is found lower in the bottom contact device than top contact device due to the structural differences, poor morphology [8].

4.2 Output characteristics

Output characteristics obtained for the different channel lengths - 5µm, 15µm, 30µm and 60µm is shown below in the figure 3.

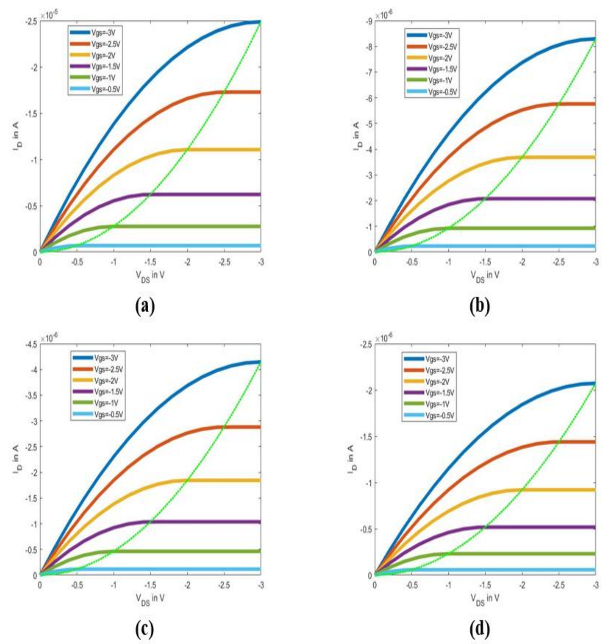

Figure 3. Output characteristics of OFET – (a) 5µm, (b) 15µm, (c) 30µm and (d) 60µm as channel length.

From the above figure it is observed that the output characteristics looks similar to that of the conventional transistor [19].2.489x10^{-05}A is the maximum drain current for 5µm channel length, 8.29x10^{-06} A is for 15µm, 4.148x10^{-06} A isfor 30µm and2.074x10^{-06} A for 60µm. All these values are plotted by taking the range of V_{ds} from -3V to 0V and varying the value of V_{gs} from -0.5V to -3V in the intervals of 0.5V. This shows that topcontact bottom gate OFET device shows inverse relation between drain current and channel length.

4.3 Transfer characteristics

It's usually the curve between V_{gs} and $\sqrt{I_D}$ as shown in the figure 4. It is plotted by varying the drain voltage and plotting the corresponding values of square root of drain current. From the intercept of this curve we determine the value of the threshold voltage [4],[20].

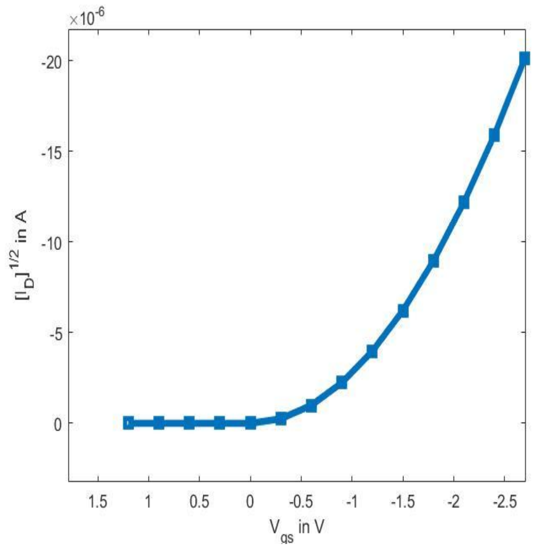

Figure 4. Transfer characteristics curve

Here in the case of analytical modelling we have stated that the threshold voltage is assumed to be zero and MATLAB simulated result clearly support this assumption. On/off ratio is numerically coming out to be 10^6 which states that the switching is better in this device.

V. CONCLUSION

In this paper analytical modelling of organic transistor was done using MATLAB for different channel length and keeping rest of the device parameters constant. It was observed that the drain current in the linear and saturation region follows the square law equations of the current. Similar types of modelling can be done in MATLAB to understand the behaviour of the device in the better way and optimize the device performance easily.

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