Mobility estimation incorporating the effects of contact resistance and gate voltage dependent mobility in top contact organic thin film transistors

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Abstract: *In this paper we have discussed the methods to estimate the mobility incorporating the effects of contact resistance and gate voltage dependence of mobility in top contact organic thin film transistors. The ideal MOSFET equations for the linear region are modified for contact resistance and mobility is estimated which is gate voltage dependent and higher than the value obtained from standard MOSFET equations in all gate voltage ranges.*

Keywords: Gate voltage dependent mobility; MOSFET equation; parasitic resistance; Transmission Line Method (TLM)

Introduction

The research in the area of organic thin film transistors has seen many improvements in the recent years. The OTFTs' performance is now at par with the amorphous silicon (a:Si H) TFTs, which makes them strong candidates for applications where a-Si:H is used as semiconductor. However more indepth studies are required in order to fully understand the OTFT device behaviour, which at present is in a nascent stage. One of the important parameter for TFT devices is field effect mobility, the extraction of which is very much affected by its gate voltage dependence and the contact effects.

In this paper, we would present various methods to extract the mobility taking into account the affects of contact resistance and gate voltage dependence of mobility.

Methods for Extraction of Mobility

The prevalent method to extract the field-effect mobility is by using the expressions that describe the drain current (I_D) for crystalline MOSFETs [1]. From simple FET theory, in the linear regime the device behaves like a resistor, which is described by the following equation,

$$I_D = \frac{W\mu C_i}{L}[(V_G - V_T)V_D - V_D^2/2] \tag{1}$$

where, for a grounded source, V_D is drain-source voltage, V_G is gate-source voltage, W is the transistor channel width, L is the transistor channel length, μ is the field-effect mobility, V_T is the threshold voltage, $V_{D,sat}$ is saturation voltage and C_i is the capacitance per unit area of the gate insulator. Equation (1) can be simplified for $V_D \ll (V_G - V_T)$ to

$$I_D = \frac{W\mu C_i}{L}(V_G - V_T)V_D \qquad \begin{matrix} 0 \le V_D \le V_{D,sat} \\ V_G > V_T \end{matrix} \tag{2}$$

The field-effect mobility in the linear regime is extracted from the transconductance, which is defined as

$$g_m = \frac{\partial I_D}{\partial V_G} \tag{3}$$

For small V_D, the mobility in the linear regime is calculated from the relationship

$$\mu_{lin} = \frac{L.g_m}{W.C_i.V_D} \tag{4}$$

In the saturation regime, $V_D > (V_G - V_T)$, I_D is given by

$$I_D = \frac{W\mu C_i}{2L}(V_G - V_T)^2 \tag{5}$$

In the saturation regime, mobility was extracted from the transfer characteristics (plotted as ($\sqrt{I_D}$ *vs.* V_G). The mobility is calculated using Eq. 3 by solving for,

$$\mu_{sat} = \frac{2L}{WC_i}\left(\frac{\partial\sqrt{I_D}}{\partial V_G}\right)^2 \tag{6}$$

The threshold voltage was determined from the intercept of the fitting line used to extract the mobility in the linear regime ($I_D - V_G$) characteristics or the intercept of the fitting line used to extract the mobility in the saturation regime ($\sqrt{I_D} - V_G$) characteristics.

However, these equations assume a constant mobility and ignore the gate voltage dependence of mobility, which is often the case with organic transistors, alike the amorphous Si transistors. This can at once be seen from Figure 1, where the mobility is estimated from the transconductance and saturation region method as described in equation 4 and 6, respectively. It shows that the estimated mobility is not constant, but is gate voltage dependent. The mobility thus obtained from the prevalent MOSFET method is erroneous, though for the first approximation, it gives a general estimate of the mobility value.

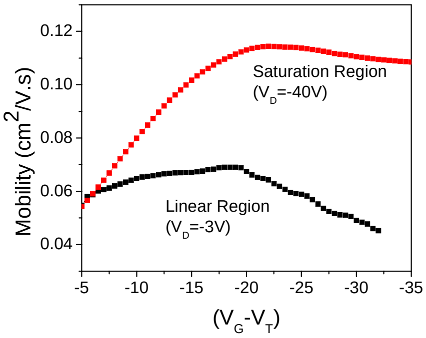

Figure 1. Mobility vs. (V_G-V_T) in linear (V_D=-3V) and saturation (V_D=-40V) region

It should be noticed that one has to take the derivative of mobility also in the equation (2), to account for the gate voltage dependence of mobility, which can be observed in the equation,

$$\frac{\partial I_D}{\partial V_G} = \frac{W C_i V_D}{L}\left[\mu + (V_G - V_T)\frac{\partial \mu}{\partial V_G}\right]$$

(7)

Therefore, this method for estimating mobility is only valid when the mobility is slowly varying with gate voltage, where we can neglect the second term in the equation (7). If this condition is not fulfilled, then the resulting mobility could be over or underestimated when mobility increases or decreases, respectively, with gate voltage.

Extraction of Parasitic contact resistance and contact resistance corrected mobility as a function of gate voltage

The parasitic source and drain contact resistances (R_s and R_D, respectively) can be extracted from the linear regime MOSFET equations, where they can be viewed as series resistors in combination with the intrinsic channel resistance. Thus the equation (2) can be modified as,

$$I_D = \frac{W \mu_{lin} C_i}{L}(V_G - V_T)(V_D - I_D R_P)$$

(8)

where R_P is the parasitic resistance and is equal to the sum of R_s and R_D.

The equation (8) can be rearranged as,

$$R_{ON} \approx \frac{V_D}{I_D} = \frac{L}{\mu W C_i (V_G - V_T)} + R_P$$

(9)

or, $R_{ON} W = \frac{L}{\mu C_i (V_G - V_T)} + R_P W$

or, $R_{ON} W = R_{ch} L + R_P W$

where R_{ch} is the channel resistance.

To estimate the R_P, the method of transmission line (TLM) is used, where R_{ON} at different V_G is estimated for different channel lengths. The intercept of the straight line fit of R_{ON}W vs. L curve at L=0 gives the value of R_PW[2].

The contact corrected field-effect mobility for the charge in the channel of the OTFT was extracted for different V_G from the slope of the fitting lines used to determine width normalized R_P, where the slope corresponds to R_{ch} and is given by

$$R_{ch} = \frac{\partial (W R_{ON})}{\partial L} = \left[\frac{1}{\mu C_i (V_G - V_T)}\right]$$

(10)

The other method as proposed by Horowitz et al [3] assumed mobility as a function of gate voltage, which is expressed in the following equation.

$$\mu = \mu_o (V_G - V_T)^{\alpha}$$

(12)

The equation (12) is fitted to the equation (9) by least square method, from where an estimate of threshold voltage, parasitic resistance and mobility is obtained.

All these methods require the value of threshold voltage, which if estimated from the equations 4 and 6 would again be erroneous. To correctly estimate the threshold voltage, we have adopted the method of Wong et al, in which threshold voltage is obtained by by taking the peak value of double derivative of (I_D vs V_G curve) at low drain voltage [4]. This method is preferred because it is claimed to be insensitive to both mobility degradation and contact resistance.

Experiment

We made top contact OTFT structures in which n+ silicon is used as a substrate as well as gate electrode. The 200 nm thermally grown SiO_2 is used as an insulator and then 50 nm pentacene is deposited by thermal evaporation at a rate of 0.3-0.4 Å/sec. Gold is then evaporated on pentacene by shadow mask to create source and drain contacts. The channel lengths that are used for TLM method are 25, 30, 75 and 160 µm.

Results and Discussion

We employed the above described methods in order to get an estimate of mobility, threshold voltage and parasitic resistance in our devices. The values of mobilities for a device with channel length of 30 μm as estimated in the linear and saturation region, by using the equations 4 and 6 are 0.065 and 0.11 cm^2/V.sec, respectively. The threshold voltage is ~-8V.

Next we calculated the parasitic resistance by the TLM method. The R_{ON}.W vs L curve for different gate voltages are shown in Figure 2. A straight line is fitted for each gate voltage by least square method and its intercept on L=0 and slope is calculated. The resulting Rp vs Vg is shown in Figure 3. The threshold voltage is determined by the method suggested by Wong et al [4]. The plot of second derivative of I_D with respect to V_{GS} in the linear regime in the Figure 4 shows the first peak at -6.5 V, which is the value of threshold voltage. The effective mobility is estimated from the slope and its variation with gate voltage is shown in Figure 5.

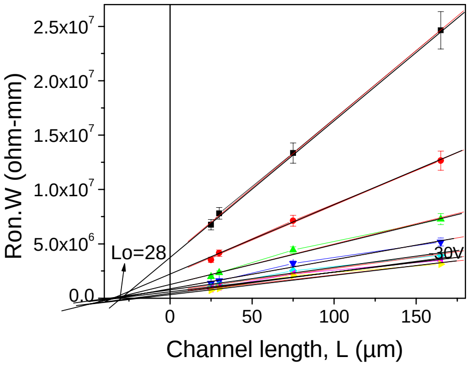

Figure 2. Plot of R_{ON}.W vs Channel length. The value of gate voltages varies from -10 to -40V in steps of -5V.

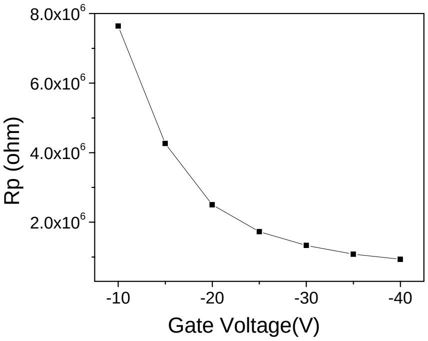

Figure 3. Plot of Rp vs. Gate Voltage

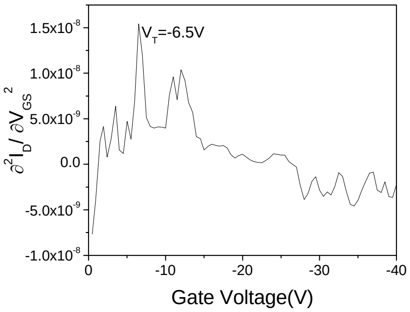

Figure 4. Second Derivative of I_D vs. Gate Voltage

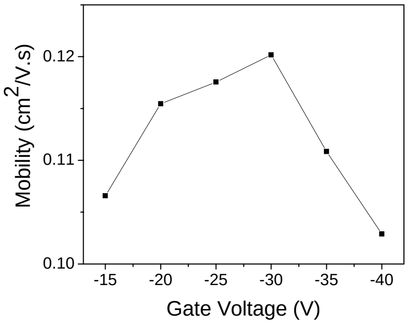

Figure 5. Plot of Mobility vs. Gate Voltage

We can see from the Figure 2 that all lines at different gate voltages merge at around 28 µm, which is an additional length that is adding up with the channel length. It means that a length of approximately 14 µm is adding up beneath each of the source and drain contacts. From Figure 3, Rp has clearly come out to be a function of gate voltage with a dependence of $\sim V_G^{-1.55}$. The effective mobility, corrected for the contact resistance, is also gate voltage dependent and its values are almost two times higher than estimated from transconductance method for each of the gate voltages.

Next we tried to fit the equation (9) in the transfer characteristics of a device with 30 micron channel length and tried to evaluate the mobility and contact resistance as a function of gate voltage by the method proposed by Horowitz et al. This gives contact corrected mobility and parasitic resistance as a function of gate voltage, which are shown in Figure 6 and 7, respectively. The parameters μ_o and α as extracted from this fit are 0.0218 $cm^2V^{-1.416}s^{-1}$ and 0.416, respectively.

The parasitic resistance and mobility obtained from this method are nearly two times lower than that obtained from TLM method at high gate voltages in the range of -30 to -40V. However, they do not show resemblance in other voltage ranges. This could be due to the fact that in the method proposed by Horowitz assumes a power law dependence of mobility on gate voltage, which could be erroneous. We also found contact resistance to be gate voltage dependent from both methods which is indicative of the change in carrier injection with induced density of the charges in the channel as a function of gate voltage.

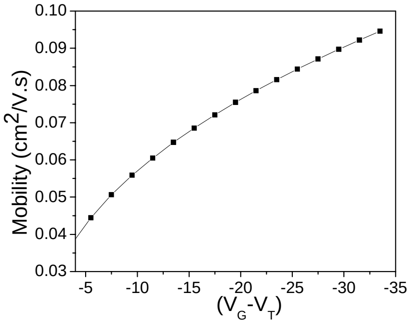

Figure 6. Plot of Mobility vs. Gate Voltage

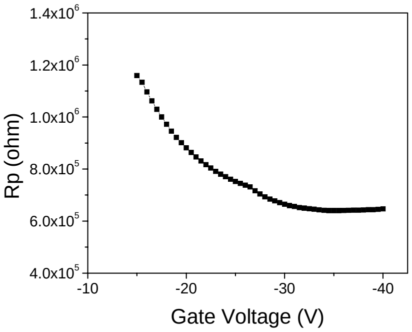

Figure 7. Plot of Rp vs. Gate Voltage

Conclusions:

The parasitic resistance obtained from TLM method and then fitted into the linear regime MOSFET equation corrected for parasitic resistance gives mobility, which are higher than those obtained from transconductance or saturation region mobilities. This states the fact that one should account for contact resistance while estimating the mobility, otherwise an under estimation of mobility is likely. We also found mobility and contact resistance to be gate voltage dependent.

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