Impact Of Organic Film Thickness On Unity Current Gain Frequency Of Top Contact Organic Thin Film Transistors

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Abstract: *The impact of organic semiconductor film thickness on frequency response of Organic thin film transistors (OTFT) is studied using 2D numerical simulations. It is shown that although transconductance increases significantly with reduction in film thickness, the improvement in unity current gain frequency is considerably less because of the accompanying increase in gate-drain capacitance except when gate-drain overlap area is sufficiently small. It is further shown that there is an optimum film thickness at which unity gain frequency is maximized.*

Keywords: unity gain frequency; transconductance; capacitances; top contact OTFT.

Introduction

Organic thin film transistors (OTFTs) are being actively pursued because of its potential for low cost fabrication of large area circuits for applications such as active-matrix flat panel displays, smart cards, radio frequency identification tags etc on substrates such as glass, plastic, fiber and paper [1-5]. One of the serious problems with OTFT is the poor frequency response or speed of operation which limits the scope of applications. In the past, most of the research effort has been devoted to increasing the frequency response through increase in mobility of organic materials by improving deposition conditions [6]. Although considerable improvement in the performance of OTFTs has been achieved with mobilities exceeding 1 cm^{-2} $V^{-1}s^{-1}$ for Pentacene [7] and 0.1 cm^{-2} $V^{-1}s^{-1}$ for P3HT [8] based TFTs, the performance of these devices is still inadequate for may applications. In recent years, besides mobility, other ways of improving frequency response of OTFTs such as channel length scaling has also attracted considerable attention [9-11].

In the present work we use 2D numerical simulations to describe the potential benefits that can be obtained through scaling of semiconductor film thickness and highlight the conditions necessary for achieving this. Since unity gain frequency results from interplay of transconductance and device capacitances, these are individually described in Sections II and III respectively. Section IV describes the resulting impact on unity gain frequency while the important conclusions from the work are summarized in section V.

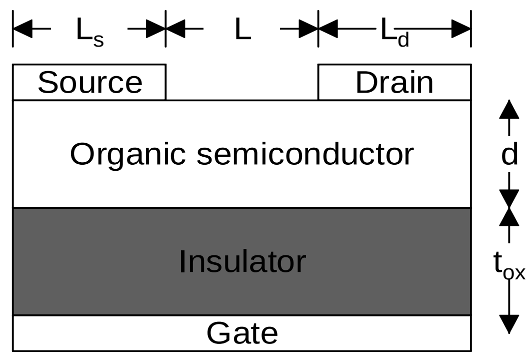

Figure 1. Schematic of top contact organic thin film transistor

Transconductance

Fig. 1 shows a cross-section of the top contact p-type organic TFT studied in this work. The typical dimensions of the device include channel length of 1 μm, insulator thickness of 20nm, semiconductor film thickness of 50nm and the source (L_s)and drain (L_d) contact length of 1 μm. ATLAS, a 2D device simulation tool from Silvaco [12] was used to carry out numerical simulations. The properties of organic semiconductor used in simulations include ionization potential (IP) of 5.1 eV, band gap (E_g) of 2.5 eV, density of state (N_V) of 5.8×10^{21} cm^{-3} and permittivity of 4.0. A field dependent mobility model with $\mu = \mu_0 e^{\sqrt{E/E_0}}$, where low field mobility μ_0 is 0.1 $cm^2v^{-1}s^{-1}$, and a critical electric field E_0 is 10^5 V/cm, was used in simulations. The source and drain contact barrier height was chosen to be small enough so that current is determined primarily by transport in the bulk of organic semiconductor rather than injection at the contact. This was done to ensure that performance trends indicated by simulations were representative of intrinsic properties of top contact TFT structure. All the data were taken at a constant current of $I_{ds}=2.0 \times 10^{-6}$ A/μm.

Fig. 2 shows the variation of transconductance at constant current in saturation with film thickness. The transconductance enhances by almost 75% as film thickness is reduced from 250nm to 20nm. The reason for this is reduction in source resistance.

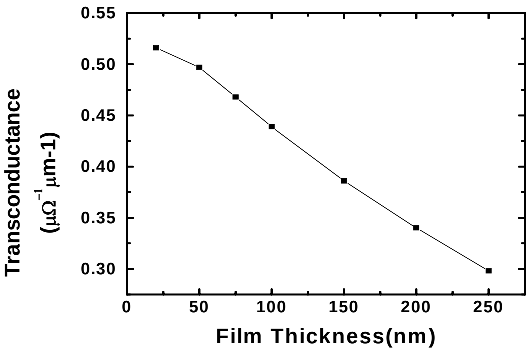

Figure 2. Variation of Transconductance at constant current in saturation with film thickness.

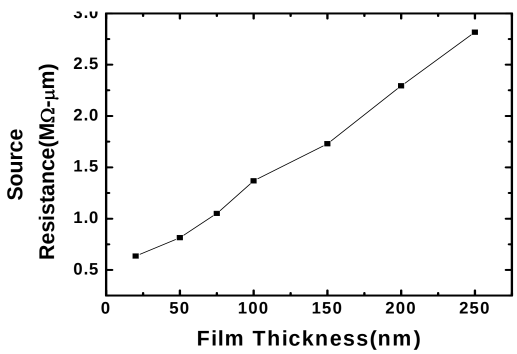

Figure 3. Variation of source resistance with semiconductor film thickness.

The transconductance at saturation in presence of source resistance (R_{source}) can be expressed as

$$g_m = \frac{g_{mo}}{1 + g_{mo} \times R_{source}} \qquad (1)$$

The variation of source resistance extracted from simulations with film thickness is shown in Fig. 3. It can be seen that source resistance increases almost linearly with film thickness. Fig. 4 shows that a plot of inverse of device transconductance with source resistance can be very well fitted with a linear curve. This confirms that improvement in transconductance occurs primarily due to reduction in source resistance when film thickness is scaled.

Device Capacitances

As discussed earlier, unity gain frequency is inversely proportional to gate-source and gate-drain capacitances. Fig. 5 and 6 show the variation of gate-source and gate-

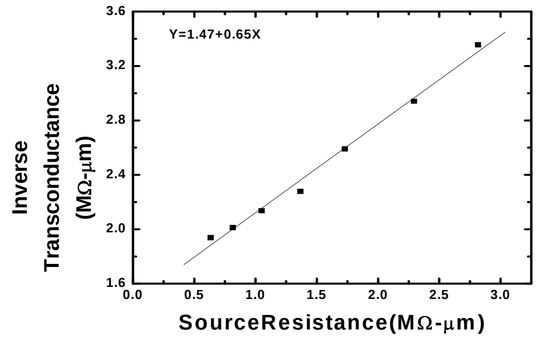

Figure 4. Variation of inverse of transconductance with respect to extracted values of source resistance as semiconductor film thickness was scaled from 20nm to 250nm.

drain capacitances with film thickness respectively. It can be seen that gate-source capacitance is weakly dependent on film thickness. Ideally, this capacitance in strong inversion should be independent of film thickness and depend only on insulator thickness. The small dependence arises likely due to increasingly poor saturation of drain current observed with increase in film thickness. This causes decrease in source control over channel inversion charge leading to reduced capacitance.

A major contribution to drain capacitance in saturation comes from the overlap between drain and gate. Fig. 7 shows a typical hole profile at the insulator/semiconductor interface in saturation mode of operation. It can be seen that there is negligible hole accumulation charge under the drain contact as a result of which the gate-drain capacitance is a series combination of insulator and semiconductor film capacitances

$$C_{ovd} \approx \frac{\varepsilon_s}{d + \left(\frac{\varepsilon_s}{\varepsilon_{ox}}\right) t_{ox}} \qquad (2)$$

The gate-drain overlap capacitance is thus different from gate-source overlap capacitance and is a relatively stronger function of film thickness as observed in Fig. 6.

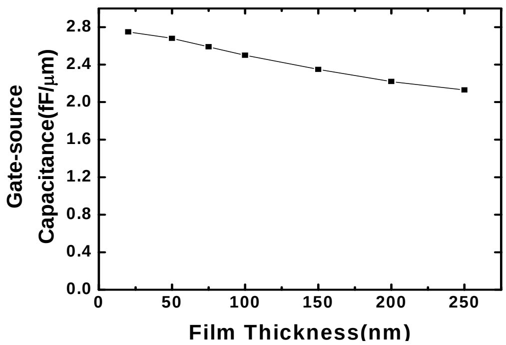

Figure 5. Variation of Gate-source capacitance (Cgs) in saturation with film thickness.

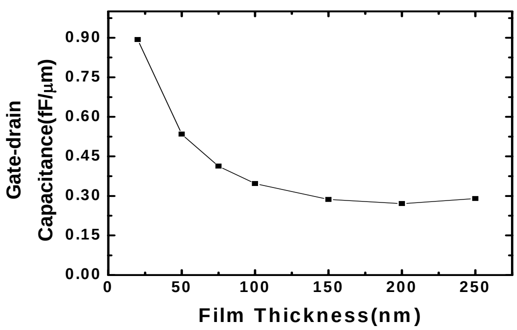

Figure 6. Variation of Gate-drain capacitance (C_{gd}) in saturation mode of operation with semiconductor film thickness.

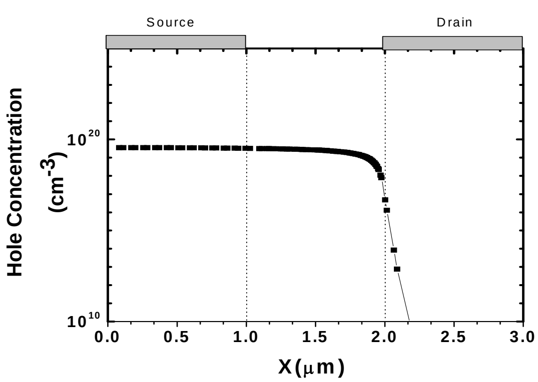

Figure 7. A typical hole concentration profile at organic semiconductor/insulator interface in saturation mode of operation.

Unity Current Gain Frequency

The unity current gain frequency for a field effect transistor can be expressed as [13]

$$f_T = \frac{g_m}{2\pi C_{gg}} \quad (3)$$

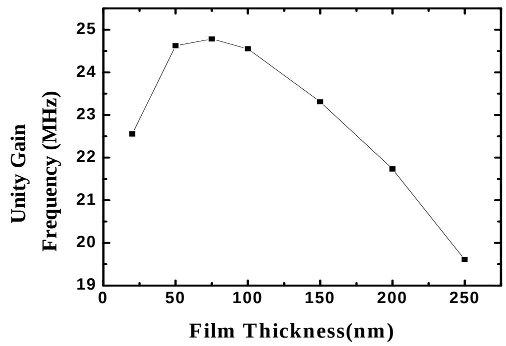

Figure 8. Unity gain frequency (f_t) versus semiconductor film thickness at constant current at saturation.

Where C_{gg} is total gate capacitance and is equal to the sum of C_{gs} and C_{gd}. It was seen earlier that with decrease in film thickness, the transconductance increases but the gate-drain capacitance also increases thereby offsetting the potential improvement that could have been obtained in unity gain frequency. Fig. 8 shows the extracted value of unity current gain frequency and its dependence on film thickness. With the reduction of film thickness, unity gain frequency first improves due to increase in transconductance but begin to decrease for very small thickness due to increase in gate-drain capacitance. Thus there exists an optimum film thickness for which unity gain frequency is maximized. The peak value of f_T can be increased by reducing the gate-source and gate-drain overlap lengths. Figure 9 shows a typical view of current flow lines in saturation mode of operation. It can be seen that current is localized in a narrow region at the edge of drain contact and a large fraction of it plays almost negligible role in current conduction. Hence, if gate-drain overlap area could be reduced and the resulting capacitance made insignificant with respect to gate-source capacitance, the unity gain frequency would scale proportionately with increase in transconductance as semiconductor film thickness is reduced and attain significantly higher values.

Conclusion

To summarize, reduction in organic film thickness significantly improves transconductance of top contact OTFT as a result of reduction in source resistance. However, this improvement does not translate into a proportionate improvement in unity gain frequency because of the accompanying increase in gate-drain overlap capacitance. Due to these two opposing effects, an optimum film thickness exists for achieving maximum unity gain frequency. The improvement in unity gain frequency through scaling of semiconductor film thickness can be significantly enhanced if drain contact length could be reduced through innovations in fabrication process.

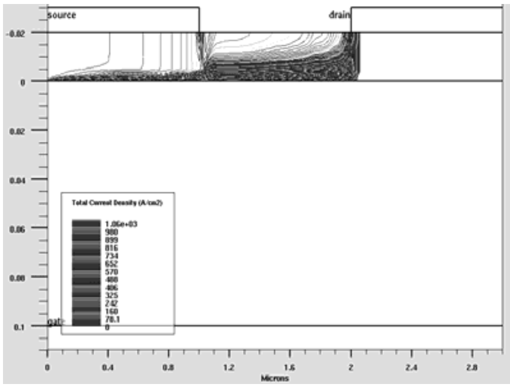

Figure 9. A typical view of current flow lines in saturation mode of operation. Source and drain contacts are on left and right.

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