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Scaling down of organic thin film transistors: short channel effects and channel length-dependent field effect mobility

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Abstract Organic thin film transistors with P3HT (poly-3-hexylthiophene) as active semiconducting layer, channel lengths from 0.3 to 20 μm, and gate oxide thicknesses from 15 to 170 nm have been successfully fabricated on Si substrates. The measurement results show that the channel length over oxide thickness ratio should be large enough (i.e., the vertical electric field should be at least 10 times higher than the lateral electric filed) in order to suppress the short channel effects of transistors. The field effect mobility of long channel devices ($L \geq 5$ μm) is about an order of magnitude larger than small channel devices (L from 0.3 to 2.5 μm), which could be attributed to the more severe contact resistance effects between organic materials and metal contacts for devices with smaller dimensions.

Introduction

Organic thin film transistors (OTFTs) have attracted significant research interests due to their potentials for the applications of low-cost, light-weight, and flexible LPDs (Large Panel Displays). Since both the cut-off frequency and packing density are proportional to $1/L^2$ (L is channel length), transistor devices with smaller dimensions are more favorable for high-speed applications. Hence, many efforts have been made to fabricate short channel OTFTs [1–3]. In this work, we fabricated organic thin film transistors with different channel lengths (from 0.3 to 20 μm) with various gate oxide thicknesses (from 15 to 170 nm). Through I_D-V_D measurements, the relationship between channel length over gate oxide thickness ratios and short channel effects were studied. It was found that when the channel length to oxide thickness ratio is greater than 10, short channel effects can be suppressed.

Experimental

Organic thin film transistors were fabricated on *n*-type Si substrates with two different structures. In order to overcome the limit of conventional photolithography for devices with submicron channel lengths, a vertical channel transistor configuration was used for devices with $0.3\ \mu m \leq L \leq 10\ \mu m$. The transistor channel was created by a vertical step formed by Si etching (see Fig. 1a for device structure), the fabrication details have been published elsewhere [4]. By carefully controlling the etching time, the step height (the transistor channel length) can be precisely controlled down to 0.3 μm. Another structure, as shown in Fig. 1b, was used for devices with $L > 10$ μm. Here, conventional photolithography and lift-off processes were used for device fabrication. Thermally grown SiO_2 layers with different thicknesses (from 15 to 170 nm) were used for different devices in order to observe effects of oxide thickness on V_T and I_D. Vacuum evaporated Au was used for source and drain contacts. Finally, the fabrication was completed by spin-coating a layer of the organic material P3HT (poly-3-hexylthiophene) onto the substrates. About 50 samples were fabricated in the present work with a fabrication yield about 70%.

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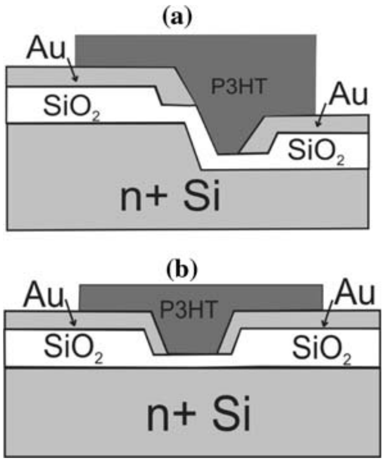

Fig. 1 Basic OTFT structure for: **a** $L \leq 10$ µm, and **b** $L \geq 10$ µm

Results and discussions

Current–voltage characteristics (I_D–V_D and I_D–V_G) of the transistors were obtained with an HP4145A Parameter Analyzer. All measurements were done in air. Measurement results were grouped into two categories: (1) 8 OTFT samples with smaller channel lengths (0.3 µm $\leq L \leq$ 2.5 µm) corresponding to different L/t_{ox} ratios (20–4) as shown in Fig. 2 from a to h. (2) Mobility values of OTFTs with different channel lengths (0.3 µm $\leq L \leq$ 20 µm) extracted form I_D to V_G curves are shown in Fig. 3. All the measurements have been repeated more than once and the results are summarized in the following section. However, it is noted that both the ON/OFF current ratios and mobility values obtained in the present work are relatively low compared with those reported in the literatures. Since the main objective of this work is to study the suppression of the short channel effects, no special efforts were made to select regioregular P3HT and to employ processes with special surface or heat treatment.

Electric field conditions for long channel and short channel behavior

The measurement results obtained for OTFTs with decreasing L/t_{ox} ratios are shown in Fig. 2 and also listed in Table 1. The values of drain current I_D were normalized to L/W ratios for comparison. It is noted from our present results that the OTFTs behave as long channel devices with current saturation as long as the L/t_{ox} ratio is greater than 10 (Fig. 2a–e). However, when the L/t_{ox} ratio is less than 10, the OTFTs show more and more severe short channel behavior with decreasing L/t_{ox} ratios (Fig. 2f–h). In other words, the vertical electric field (from V_G) should be at least 10 times larger than the lateral electric field (from V_D) in order to suppress the short channel behavior. Moreover, the normalized I_D of device with $L = 2.5$ µm (Fig. 2c) is about 10 times larger than devices with $L \leq 1$ µm (Fig. 2a, b, d, e). This mobility dependence on channel length will be discussed in detail later.

It has been reported by different groups that when the channel lengths of OTFTs were decreased to a small enough value, the devices showed severe short channel behavior. These devices cannot enter saturation operation and the drain currents increase quadratically with drain voltages. Hence, these short channel devices could not be turned off and the gate loses control of the devices [1, 5, 6]. It is generally believed that the condition for devices showing short channel behaviors is $L \leq 1$ µm. However, from our present results, we can see that even when the channel length is reduced to 0.3 µm, the present OTFTs can still maintain long channel behavior with good saturation operation (Fig. 2a). The OTFTs operate in accumulation mode with majority charge carriers (holes in this case) induced by the vertical electrical field from the applied gate voltage (V_G). The motion of these carriers is also affected by the lateral electric field from the drain voltage (V_D). The total drain current is the sum of two competing current components: surface current with charge carriers mainly induced by V_G and bulk current of the space charge limited current (SCLC) with charge carriers controlled by V_D [6]. For devices with relatively large channels ($L \geq 5$ µm), vertical electric field is much larger than the lateral electric field, so that the second current component is negligible. However, when the channel length is reduced, the lateral electric field keeps increasing until it reaches a point that the second current component is comparable to and even larger than the first component. Then the I_D–V_D relationship becomes $I_D \propto (V_D)^n$ ($n > 1$), following the I–V relationship of space charge limited current [6]. In other words, when the vertical electric field (V_G) is not large enough to take full control of the charge carriers, channel cannot be turned off by the gate voltage, leading to a severe short channel behavior. The results can be clearly seen from Fig. 2f–h: when L/t_{ox} ratio (or ratio of vertical to lateral electric field since $E_{vertical} \propto 1/t_{ox}$ and $E_{parallel} \propto 1/L$) is lower than 9, the transistor starts to show short channel behavior, with $I_D \propto (V_D)^n$, and the values of n increase with L/t_{ox} ratios. Consequently, the normalized off current I_D of devices with $L/t_{ox} < 10$ (Fig. 2f–h) are more than 100 times larger than that of devices with $L/t_{ox} > 10$ (Fig. 2a–e). This phenomenon is the so-called short channel effects: the transistor cannot be turned off no matter how big a gate voltage is applied. Short channel effects observed by other groups on different organic semiconductors, such as polythiophene ($L/t_{ox} = 4$) [7], pentacene ($L/t_{ox} = 2.7$) [8], and DH-4T ($L/t_{ox} = 0.5$) [9] also follow the above rule.

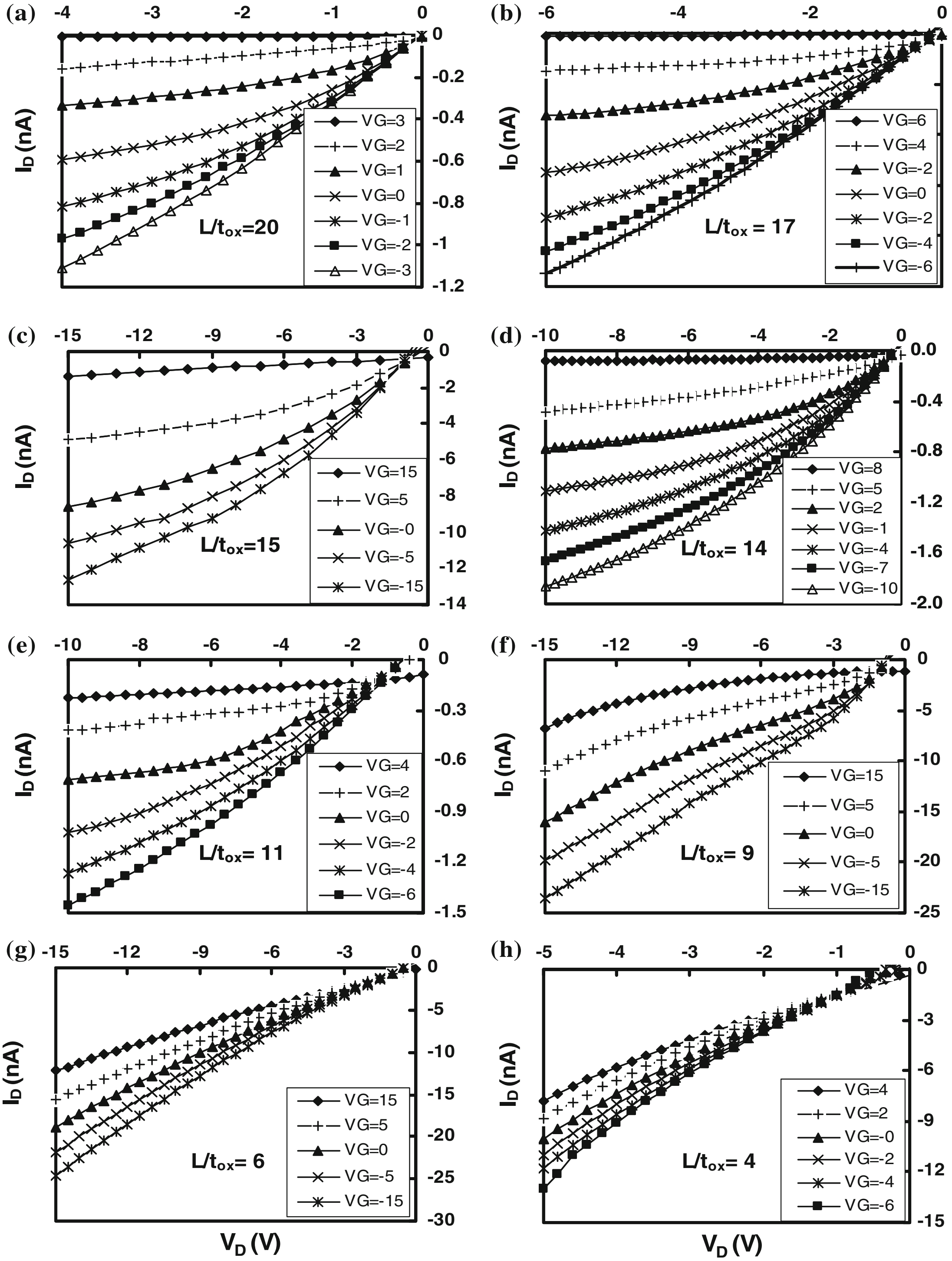

Fig. 2 Normalized I_D–V_D curves for OTFTs with different L/t_{ox} ratios: **a** $L/t_{ox} = 20$, **b** $L/t_{ox} = 17$, **c** $L/t_{ox} = 15$, **d** $L/t_{ox} = 14$, **e** $L/t_{ox} = 11$, **f** $L/t_{ox} = 9$, **g** $L/t_{ox} = 6$, and **h** $L/t_{ox} = 4$ (Gate voltage V_G in volts)

Dependence of field effect mobility on channel length

The field effect mobility and threshold voltage V_T of a TFT can be deduced from plots of $I_D^{1/2}$ versus V_G at a constant V_D with the following equation (1):

$$\sqrt{I_D} = \sqrt{\frac{W}{2L}\mu_{eff}C_{ox}} \quad (V_G - V_T) \tag{1}$$

Here, μ_{eff} is the field effect mobility and C_{ox} is the capacitance per unit area of the gate oxide. Values of μ_{eff}

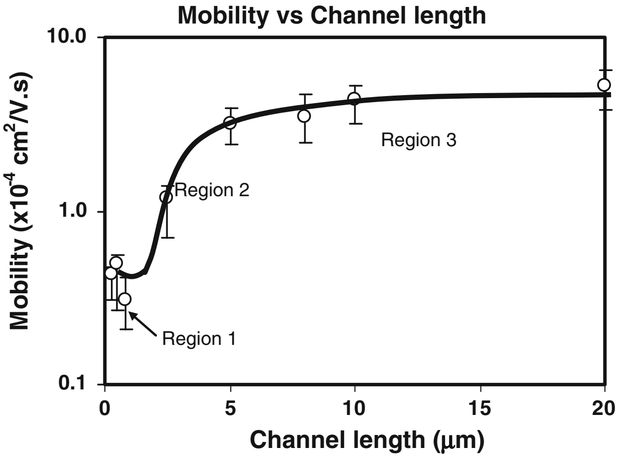

Fig. 3 Variation of the field effect mobility with the channel length

Table 1 OTFTs with different channel lengths L and SiO_2 thicknesses t_{ox} showing either short or long channel characteristics

Sample No.	L (µm)	t_{ox} (nm)	L/t_{ox}	Short or long channel behavior
S#41	0.3	15	20	Long (Fig. 2a)
S#46	0.5	30	17	Long (Fig. 2b)
S#5	2.5	170	15	Long (Fig. 2c)
S#33	0.7	50	14	Long (Fig. 2d)
S#24	0.8	70	11	Long (Fig. 2e)
S#2	1.5	170	9	Short (Fig. 2f)
S#4	0.6	100	6	Short (Fig. 2g)
S#32	0.3	70	4	Short (Fig. 2h)

were calculated according to Eq. 1 for OTFTs with long cannel behaviors. The variation of mobility μ_{eff} with the channel length is shown in Fig. 3. It is clear from Fig. 3 that μ_{eff} increases with the increase in channel length, and the variations can be divided into 3 different regions. For OTFTs with $L \geq 5$ µm (region 3), the mobility values tend to saturate at an average of 4.1×10^{-4} cm^2/V s; when the channel length is further decreased to 1 µm, the mobility decreases drastically with channel length (region 2). In region 1 for transistors with $L < 1$ µm, the mobility values tend to approach a lower limit with an average of 3.3×10^{-5} cm^2/V s. This value is one order of magnitude smaller than that in region 3. One possible reason for the dependence of mobility on the channel length is due to the contact effects between the organic material and source/drain. The total resistance (R_{on}) between the drain and source contacts consists of two components: the channel resistance (R_{ch}) and the contact resistance (R_C). For OTFTs with long channels ($L \geq 5$ µm) the contact resistance effect is not as severe and only a small portion of the total resistance R_{on}. However, for OTFTs with small channel lengths (1 µm $\leq L <$ 5 µm), value of R_C remains constant, while R_{ch} decreases with the decrease in L, increasing the proportion of R_C in the total resistance. This will lead to a large decrease in apparent mobility deduced from the I_D–V_G curves. Finally, when the channel length is reduced further ($L < 1$ µm) so that R_C is much greater than R_{ch}, the mobility reaches its minimum value and the measured I–V curves may deviate significantly from the properties of the organic materials. It should be mentioned that the increase of I_D with increasing V_D and V_G could be due to a decrease in R_C resulting from the Schottky barrier lowering effects of the contacts. Hence, without considering the contact effects, the apparent mobility value calculated from the I_D–V_G curves could be much smaller than its intrinsic value. This kind of apparent mobility increase with channel length has also been observed by other researchers [10–12]. Further investigation of contact effects is needed to explain the origin of contact resistance and to minimize the contact resistance so as to improve device performance.

Conclusions

In order to study the effect of device dimensions on device characteristics, we have fabricated organic thin film transistors with channel lengths from 0.3 to 20 µm and oxide thicknesses from 15 to 250 nm. The present measurement results show that scaling down the device dimension of OTFTs can lead to certain adverse changes in device behavior. Firstly, due to increased proportion of the lateral electric field which can lead to an increasing SCLC component leading to $I_D \propto (V_D)^n$ ($n > 1$), device cannot reach normal saturation operation. In other words, when the vertical electric field is not large enough compared to the lateral electric field, the control of channel by the gate voltage decreases and the OTFTs may not be turned off. Secondly, the observed decrease in mobility with the decrease in channel length is believed to be due to increasing influence of contact resistance. All in all, in order to optimize device performance of OTFTs with submicron device dimensions, not only the oxide thickness should be carefully selected, but also the resistance of organic materials contacting the source and drain should be under control.

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