Organic Transistors: Two-Dimensional Transport and Improved Electrical Characteristics

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The thiophene oligomer α-hexathienylene (α-6T) has been successfully used as the active semiconducting material in thin-film transistors. Field-induced conductivity in thin-film transistors with α-6T active layers occurs only near the interfacial plane, whereas the residual conductivity caused by unintentional doping scales with the thickness of the layer. The two-dimensional nature of the field-induced conductivity is due not to any anisotropy in transport with respect to any molecular axis but to interface effects. Optimized methods of device fabrication have resulted in high field-effect mobilities and on/off current ratios of $>10^6$. The current densities and switching speeds are good enough to allow consideration of these devices in practical large-area electronic circuits.

The potential for using organic and polymeric active devices such as light-emitting diodes and thin-film transistors (TFTs) in large-area electronics has recently stimulated significant research interest. Different types of organic materials have been used to make functioning field-effect transistors (FETs) including conjugated polymers and oligomers (*1*, *2*). The most successful of these materials contain thiophene groups and include poly(thienylene vinylene) and α-6T. TFTs made with α-6T and related materials, as pioneered by Garnier *et al.* (*2*), have demonstrated field-effect mobilities that are higher than the mobilities of most noncrystalline organic solids. For many practical applications, a large ratio between the on current [drain-source current (I_{DS}) when the transistor is on] and the off current (I_{DS} when the transistor is off) is needed. Organic TFTs have thus far shown very poor on/off ratios for reasons such as residual doping in the active materials (*2*) and traps due to interface states (*1*). The highest on/off ratio reported thus far is 10^5 in polythiophene transistors in which the source and drain metal contacts were coated with a conducting polymer; however, the field-effect mobility in polythiophene is only 10^{-4} cm^2 V^{-1} s^{-1}, too low for most applications (*3*).

We show here that the field-induced conductivity of FETs made with α-6T is confined to the interfacial region of the α-6T near the gate dielectric (that is, it is two-dimensional). This lower dimensionality is unlike the low-dimensional effects observed in some polymers, which are related to constraints imposed on transport owing to properties of the chain structure (*4*); instead, it is due to the alteration of the potential profile at the semiconductor-insulator interface, probably similar to the case in Si MOSFETs (metal-oxide-semiconductor FETs) (*5*) or modulation-doped quantum wells. We describe the leakage current mechanisms in α-6T TFTs and propose means to minimize this leakage. By such procedures, devices have been fabricated that have on/off ratios of $>10^6$, which is over two orders of magnitude greater than previously reported values for any organic-polymeric TFT. With careful material purification and device fabrication, we were able to achieve field-effect mobilities as high as 0.03 cm^2 V^{-1} s^{-1}, which is an order of magnitude greater than previously reported mobilities for the same device configuration (*6*) and, surprisingly, is field-dependent at high electric fields.

The transistor structure that we used for this study is shown in Fig. 1. The Si substrate, with a gold contact, functions as the gate, and the oxide is the gate dielectric. We first evaluated the nature of the channel conductivity with zero gate bias and found that the current and conductivity scale with the thickness of the active layer. This result indicates that the α-6T is doped (*p*-type) in the as-deposited condition, similar to the findings of Horowitz *et al.* (*7*).

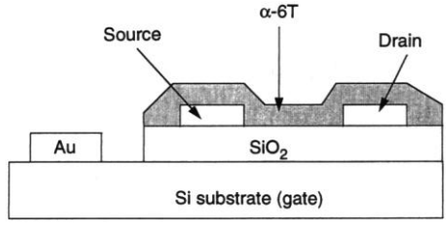

Fig. 1. Schematic of the transistors used in this study. Gold source and drain pads of thickness 30 nm are defined photolithographically on the SiO_2. The spacing between the pads, which corresponds to the gate length of the TFT, is between 1.5 to 25 μm, and the width of the pads is 250 μm. Finally, α-6T films of thickness 2.5 to 150 nm are sublimed over the contacts to complete the device.

The field-induced conductivity, however, does not scale with thickness; in fact, it is practically constant. We varied the thickness of the α-6T from 2.5 nm [approximately the length of one segment (*8*)] to 150 nm. Functioning TFTs resulted in every case, although the conductivity and effective mobility were low in those cases in which the α-6T was very thin (<5 nm) because of nonuniformities in the coverage (atomic force microscopy of as-deposited films indicated that the magnitude of the roughness is thickness-dependent).

To demonstrate the two-dimensional nature of the device, we show the field-induced conductance (Fig. 2) plotted as a function of gate voltage for different α-6T thicknesses. The slight variations (by about a factor of 2) are a consequence of a scatter in the values of the mobility and are much less than the range of α-6T thicknesses (a factor of 30). Thus, the conductance is practically independent of α-6T film thickness, which means that all of the induced charge (up to 10^{13} cm^{-2}) resides in the first one or two monolayers.

Lower dimensionality effects in organic materials are normally ascribed to the constraints imposed on transport by the nature of the chain structure (molecular ordering). This formed the basis of a description of transport in conjugated polymers proposed by Heeger *et al.* (*4*). Sublimed films of α-6T are polycrystalline with a grain size of ~100 nm (*9*). Within each crystallite, the oligomer segments are aligned approximately perpendicular to the plane of the substrate (*10*). However, the lower dimensionality in α-6T–based FETs, evident from Fig. 2, is

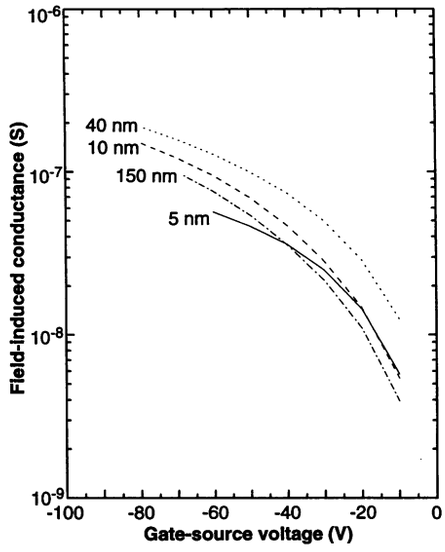

Fig. 2. Field-induced conductance as a function of gate-source voltage for TFTs with different thicknesses of α-6T. The channel length of the TFTs was 12 μm, and the drain-source voltage was −100 V.

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not a consequence of any anisotropy in transport with respect to a molecular axis; instead, it is an effect of the interface potential profile. In many inorganic FETs, the field-induced charges create a triangular potential well that effectively confines the wave function of the electron (or hole) to two dimensions. It is very likely that such a bending of bands, which is an electrostatic effect (*11*), also occurs in α-6T FETs. This would lead to the confinement of the field-induced positive charge in a very narrow region close to the interface with SiO_2. The data in Fig. 2 support such a picture.

The lower dimensionality can be used to improve the on/off ratio in TFTs. Because the field-induced conductance is thickness-independent and the residual conductance (ideally zero) scales with thickness, thinner active layers result in higher on/off ratios. The minimum α-6T thickness required depends mainly on the nonuniformity of the as-deposited film. The optimal α-6T thickness for material with a doping level of $\sim 10^{17}$ cm^{-3} was 15 nm. With such TFTs, the on/off ratio is 3×10^4 to 5×10^4, when the devices are operated both in the enhancement and in the depletion modes (between gate fields of -2×10^6 and 2×10^6 V cm^{-1}). This on/off ratio still is not adequate for many applications. The off current is dominated by leakage through the regions of the unpatterned active material, which are far from the source and drain contacts. To lower the off current further, it is necessary either to pattern the α-6T so as to eliminate most of the unmodulated material or to lower the residual doping to a level at which the contribution of the unmodulated regions of the film to the total channel conductance is insignificant. We have tried both approaches and prefer the latter because it avoids the extra step of having to pattern the α-6T, which may degrade its electrical properties.

In Fig. 3 are shown the common-source current-voltage characteristics of a TFT with a channel length of 12 μm at different gate fields. The field-effect mobility of carriers extracted from these characteristics is 0.01 to 0.02 cm^2 V^{-1} s^{-1} (*12*). In this TFT, the α-6T (thickness, 50 nm) was recrystallized under nitrogen and sublimed at a high vacuum (*13*). The on/off ratio is $>10^6$ between points A and B in Fig. 3, after correcting for probe leakage (~30 pA). The active material does not need to be patterned, a major advantage in manufacturing large-area electronic systems.

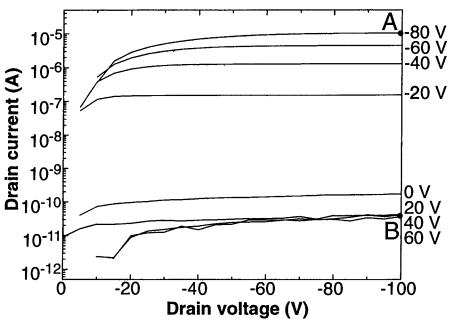

Fig. 3. Common-source current-voltage characteristics of a TFT with a channel length of 12 μm. Gate voltages for each curve are given on the right. The on/off ratio (measured between points A and B) for only enhancement mode operation is 7×10^4 and for enhancement-depletion mode operation is $>10^6$.

The field-effect mobilities extracted from the transistor characteristics are in the range 0.01 to 0.03 cm^2 V^{-1} s^{-1}, higher than previously published values for the same device configuration (6). The extracted mobility exhibits a longitudinal (source to drain) field dependence at fields higher than 10^5 V cm^{-1} (Fig. 4). In short channel devices at high voltages, the apparent (or field-effect) mobility is lower than the intrinsic mobility because of the effects of the parasitic series resistance on the shape of the current-voltage characteristics. This distinction between the intrinsic and field-effect mobilities is well known (*14*). The maximum intrinsic mobility in α-6T is at least 0.08 cm^2 V^{-1} s^{-1}. On the basis of our understanding of transport in α-6T transistors, we have developed a theoretical model (Fig. 5) that accurately describes the electrical characteristics. The model includes transport effects such as field-dependent mobility, short channel effects such as channel shortening, and parasitic resistance (*15*).

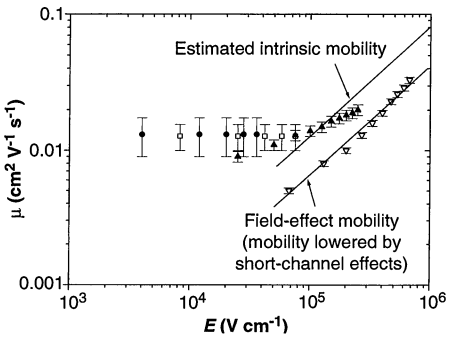

Fig. 4. Extracted field-effect mobilities μ as a function of the longitudinal electric field E for TFTs with channel length L = 25 μm (filled circles), L = 12 μm (open squares), L = 4 μm (filled triangles), and L = 1.5 μm (inverted open triangles). The estimated intrinsic mobility, which is the field-effect mobility corrected for apparent lowering caused by parasitics, is also indicated.

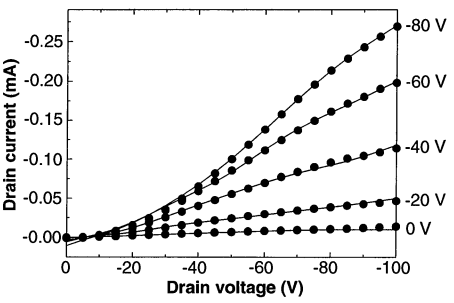

Fig. 5. Experimental current-voltage characteristics (circles) of a TFT with a channel length of 1.5 μm operated in the accumulation mode at different gate fields (the gate voltage for each curve is given to the right). Also shown are the theoretically derived characteristics (solid lines).

The on current densities (10^{-7} to 10^{-6} A per micrometer of gate width) and on/off ratios (10^6 to 10^7) reported above are adequate to allow the use of such α-6T TFTs as switching transistors in active-matrix liquid-crystal displays. The source-drain voltages required to achieve such on current densities are high and can be lowered if the field-effect mobility can be further increased as envisioned by the projection in Fig. 4. One way to increase the field-effect mobility is to increase the crystallite size (normally 100 nm) so that it is larger than the channel length, at which point we might expect single-crystal–like transport. By subjecting films of α-6T to short-time annealing near the melting point of the material, we found that the crystallite size could be increased to >5 μm. Finally, the measured switching times (~10 μs) are currently limited by the RC (resistance-capacitance) time constant but are fast enough for display applications.

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References and Notes

[2] **All-Polymer Field-Effect Transistor Realized by Printing Techniques**
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