Mater. Res. Soc. Symp. Proc. Vol. 871E © 2005 Materials Research Society **I4.5.1**

Nanoscale Measurements of Electronic Properties in Organic Thin Film Transistors

Oren Tal and Yossi Rosenwaks

Department of Physical Electronics, Faculty of Engineering, Tel Aviv University, Tel Aviv 69978, Israel.

Yohai Roichman and Nir Tessler

Department of Electrical Engineering Dept., Technion Israel institute of technology, Haifa 32000, Israel.

Calvin K. Chan and Antoine Kahn

Department of Electrical Engineering, Princeton University, Princeton NJ 08544, USA

Abstract

Kelvin probe force microscopy was used for extraction of the threshold and the pinch off voltages in organic thin film transistors. The first was determined by direct detection of the charge accumulation onset and the latter by a direct observation of the pinch off region formation. In addition, an effective threshold voltage shift can be extracted from the pinch-off voltage as a function of charge concentration. The dependence of the effective threshold voltage on the gate voltage must be considered when calculating charge carrier concentrations in organic thin film transistors.

It is well established that charge carrier mobility in disordered organic semiconductors strongly depends on the charge concentration[1]. The primary experiment used to study this phenomenon is the transfer characteristics of organic field effect transistors (OFET)[2-4]. Quantifying the dependence of mobility on charge density is important for studying the underlying physics of the devices and for optimizing materials by extracting an effective disorder parameter[5].

The first important step in the analysis of an OFET is the determination of the threshold voltage (V_t) defined as the onset of charge accumulation. Since the mobility is charge density-dependent, the classical shape of the I_S-V_G curve is altered[2] and the determination of V_t by back extrapolation may not be correct[4,5]. We have overcome the current detection problem by measuring the onset of the gate screening by charge accumulation in the channel[6]. In this case, a potential mapping of the channel region is done using Kelvin Probe Force Microscopy (KPFM)[7]. Moreover, we present a method for direct determination of the pinch-off voltage (V_{PO}) using KPFM. V_{PO} is defined as the drain-source voltage (V_D) for which there is zero charge at the drain-channel interface and it is used to extract V_t^{eff}, the effective threshold voltage, at different gate voltages (V_G). V_t^{eff} is used instead of a standard threshold voltage, since the OFET acts as if it has a different threshold voltage at each gate voltage. The conventional threshold voltage is determined by the onset of the channel charge.

Experimental Apparatus and Methods

OFET substrates were fabricated at the Technion Institute of Technology. These substrates consisted of a heavily doped p-type silicon gate electrode, a 90 nm thermally grown silicon-oxide gate insulator, and 50nm gold strips evaporated on the oxide to form the source and drain electrodes. A 50 nm thick film of N,N^{I} -diphenyl-N,N^{I} -bis(1-naphthyl)-1,10 -biphenyl-4,4^{II} -diamine (a-NPD) was deposited on the substrates by sublimation from solid source in an ultra high vacuum (UHV) growth chamber in Princeton University and transported under nitrogen atmosphere to the glove box containing the KPFM at Tel Aviv University. Contact resistance, leakage current to the periphery of the transistor active area, threshold voltage shifts during measurements, and current-voltage (IV) curve hysteresis were negligible in the measured transistors.

KPFM was used for the determination of the surface potential[8] profile across the

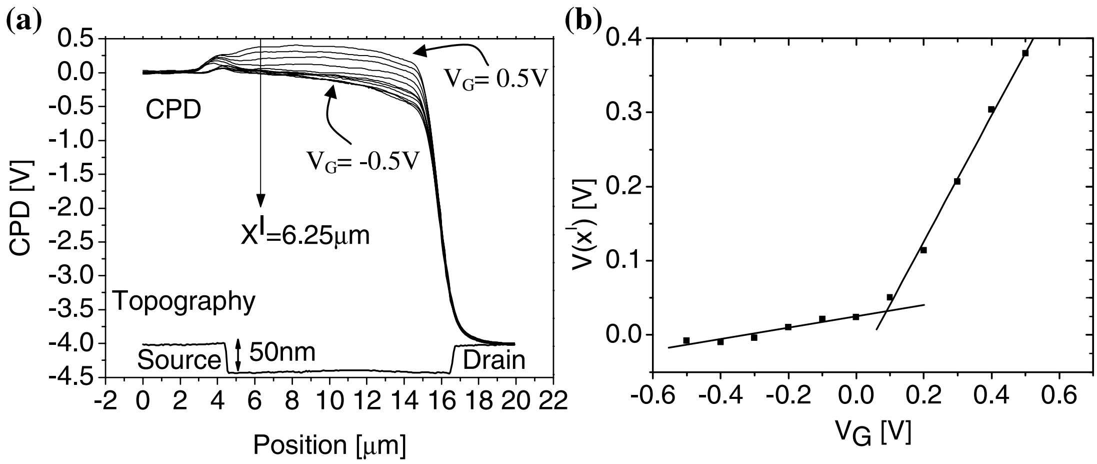

Figure 1: *(**a**) Contact potential difference curve as a function of distance from the source electrode. V_D=-4V and -0.5 ≤ V_G ≤ 0.5V. (**b**) The CPD measured at position X^I=6.25 μm (vertical arrow in (a)) as a function of gate voltage for V_D=-4V.*

OFET channel. KPFM utilizes an atomic force microscope tip as a probe electrode for measuring the contact potential difference (CPD)[9] with high spatial resolution (~30nm) and high voltage sensitivity (few meV). All the measurements were conducted inside a glove box under nitrogen atmosphere (<2ppm water) in the dark. The transistors were scanned for different applied source-drain and source-gate biases applied with a semiconductor parameter analyzer.

Results and discussion

Figure 1(a) shows a set of CPD curves measured for V_D=-4V and V_G ranging between 0.5V and -0.5V. Note that the separation between the upper five curves ($0.1 \le V_G \le 0.5V$) is larger than between the lower six curves ($-0.5 \le V_G \le 0.2V$). In order to better determine the threshold voltage, we plot in Figure 1b the potential in the channel, close to the source (at a position X^I = 6.25μm in Figure 1(a)), as a function of V_G. As long as the gate bias is smaller then the threshold voltage ($V_G < Vt$), the charge in the accumulation layer screens the gate potential and the increase of the surface potential is smaller than the increase of the gate bias ($\Delta CPD / \Delta V_G < 1$). On the other hand, when the gate bias is above the threshold voltage, ($V_G > V_t$), there are no mobile charges between the gate and the film surface (except for a negligible charge concentration corresponding due to intrinsic carriers, to unintentional doping, and to electrons that overcome the relatively large electron barrier for injection). In this case the slope of the surface potential versus gate bias curve is close to one ($\Delta CPD / \Delta V_G \approx 1$); the slope is not equal to unity because of the potential drop across the oxide. The crossover point between these two regions yields the gate voltage for which the charge accumulation onset takes place. This defines the threshold voltage at the point of the KPFM tip in the channel. Here, $Vt(X^I = 6.25um) = 0.59 \pm 0.03V$ and V_t at the source-channel interface (i.e., the onset of charge accumulation in the channel) is $Vt = Vt(X^I) - CPD(X^I) = 0.56 \pm 0.03V$.

Figure 2(a) shows the potential distribution measured across the transistor; the protruding regions appearing in the topography profile on the left and right sides are the source and drain contacts respectively. The CPD profiles were measured for $V_G = -10V$ and V_D ranging between 0 and –10V. As V_D approaches the pinch-off voltage, there is a relatively large potential drop near the drain (left side). Beyond a certain V_D value (~ -7.5V), there is almost no change in the potential between adjacent curves except for a small region near the drain where the abrupt potential drop increases (bottom 5 curves). The large voltage drop across this region can be ascribed to the abrupt voltage change that is known to occur at the pinch-off region. As long as the (absolute) drain-source bias is smaller then the pinch-off voltage ($|V_D| < |V_{PO}|$), the voltage drop across the accumulation layer increases as the source-drain potential increases. On the other hand, when the absolute drain-source bias exceeds the pinch-off voltage, ($|V_D| > |V_{PO}|$), the potential between the source and the pinch-off point

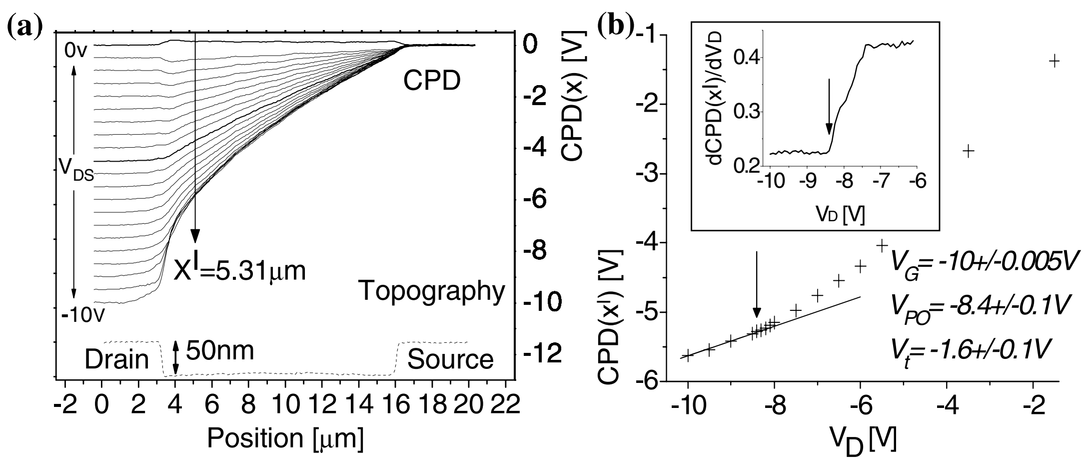

*Figure 2: (a) Contact potential difference curve as a function of distance from the drain electrode. V_G=-10V and $-10 \le V_D \le 0V$. (**b**) CPD measured at position X^I=5.31 μm (vertical arrow in (a)) as a function of drain voltage for V_G=-10V.*

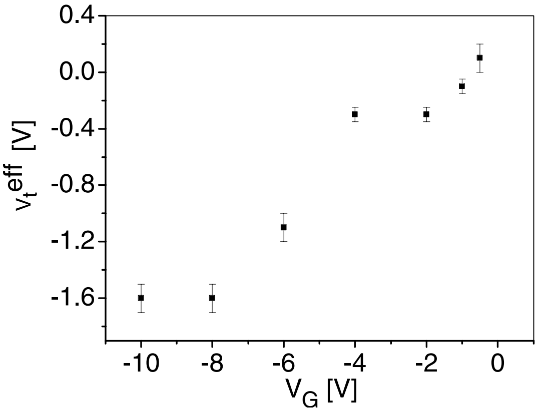

Figure 3: effective threshold voltage extracted from pinch-off voltage at different gate voltages.

does not change with increasing $|V_D|$, as all the voltage drop occurs at the vicinity of the drain. This can be clearly seen with the 5 bottom curves in Figure 2(b); however the curves do not perfectly coincide due to the small shift of the pinch-off point position towards the source as the drain-source bias increases.

The pinch-off voltage can be accurately determined by plotting the channel potential measured at 1μm to the right of the drain, as a function of increasing V_D as shown in Figure 2(b). The pinch-off voltage is the V_D for which $dCPD / dV_D = const.$ (Figure 2(b) inset), since any additional voltage beyond V_D=V_{PO} drops across the pinch-off region. The constant separation is attributed to the lateral shift of the pinch-off point toward the source as V_D increases. We determine V_{PO} at a point in the channel where the voltage difference between curves is maximal, yet far enough from the estimated pinch-off point (~maximum curvature point) in order to minimize the tip averaging effect on the measured *CPD* [10]. Based on the pinch-off voltage definition: $V_{PO} \equiv V_D = V_G - V_t$, we can now use V_{PO} extracted at different V_G for determining the threshold voltage as a function of V_G. Figure 3 shows a series of V_t^{eff} extracted in this way for different V_G values. The effective threshold voltage has a relatively large shift at lower gate voltages. This has a direct influence on the charge concentration calculation that is based on the threshold voltage.

Conclusions

We have presented an accurate method to extract the threshold voltage in an OFET, which overcomes the problem of the current detection by measuring the onset of the gate screening by charge accumulation in the channel. In addition, we have presented a new method for direct determination of the pinch-off voltage at different gate voltages in OFETs using Kelvin probe force microscopy. Based on this method, effective threshold voltages were extracted for different channel charge concentrations. The effective threshold voltage dependence on the gate voltage should be taken into consideration when calculating charge concentrations in organic thin film transistors.

Acknowledgements

Support of the work in Princeton was provided by the US-Israel Binominal Science Foundation (BSF), Grant No. 2000-092 and by the NSF (DMR-0408589)

References

[1] V. I. Arkhipov, E. V. Emelianova, and H. Bassler, Philos. Mag. B-Phys. Condens. Matter Stat. Mech. Electron. Opt. Magn. Prop. **81** (9), 985-996 (2001); Mcjm Vissenberg and M. Matters, Physical Review B 57 (20), 12964-12967 (1998).

[2] V. I. Arkhipov, E. V. Emelianova, and H. Bassler, Philos. Mag. B-Phys. Condens. Matter Stat. Mech. Electron. Opt. Magn. Prop. 81 (9), 985 (2001); Mcjm Vissenberg and M. Matters, Physical Review B **57** (20), 12964 (1998).

[3] G. Horowitz, M.E. Hajlaoui, and R. Hajlaoui, J. Appl. Phys. **87** (9 Pt1), 4456 (2000); H. Sirringhaus, N. Tessler, and R.H. Friend, Science **280**, 1741 (1998); C. Tanase, E. J. Meijer, P. W. M. Blom et al., Physical Review Letters **91** (21), 216601 (2003).

[4] E. J. Meijer, C. Tanase, P. W. M. Blom et al., Applied Physics Letters **80** (20), 3838 (2002).

[5] Y. Roichman, Y. Preezant, and N. Tessler, Physica Status Solidi a-Applied Research **201** (6), 1246 (2004).

[6] Roichman Y, Tal O, Rosenwaks Y, and Tessler N, Submitted for publication.

[7] Nonnenmacher M, O'Boyle M P, Wickramasinghe H K. "Kelvin probe force microscopy" Applied Physics Letters, **58**, (25), 2921 (1991).

[8] Lagowski L, Balestra C L, and Gatos H C, "Electronic characteristics of 'real' CdS surfaces" Surf. Sci. **29**, (1), 213 (1972).

[9] R. Shikler, N. Fried, T. Meoded et al., Physical Review B **61** (16), 11041 (2000).

[10] O. Tal, W. Gao, C. K. Chan, A. Kahn, Y.Rosenwaks, Applied Physics Letters, **85**, (18), 4148 (2004).