Direct Extraction of Mobility in Pentacene OFETs Using *C–V* and *I–V* Measurements

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Abstract—**Mobility was extracted from top-contact pentacene organic field effect transistors with minimal assumptions. Low-frequency capacitance–voltage (*C–V*) measurements were used to calculate the sheet charge density of the channel, and current–voltage measurements with low drain-to-source voltage were used to extract mobility. The separation of charge and mobility with the use of *C–V* measurements illustrates that the mobility increases with gate voltage, differing significantly from mobility dependence on gate voltage in crystal silicon MOSFETs. The physical meaning of this mobility and the possible mechanism for the increase in mobility as a function of gate bias are discussed.**

Index Terms—**Capacitance, capacitance–voltage (*C–V*), characterization, mobility, organic field-effect transistors (OFETs), organic transistor, pentacene.**

I. INTRODUCTION

INTEREST in pentacene organic field effect transistors (OFETs) has recently increased with the demonstration of functional logic circuitry and active-matrix liquid crystal display backplanes built with OFETs [1], [2]. OFETs may be fabricated at significantly lower temperatures than inorganic thin-film transistors (TFTs), which allows deposition of OFETs on a wide variety of large flexible substrates that might one day support large-area electronic devices such as electronic billboard displays.

To facilitate interpretation of a growing number of research results on OFETs, the IEEE has recently published a standard to characterize organic devices and materials [3]. However, the carrier mobility extraction suggested in this publication is based on the silicon long channel MOSFET model. Although extracting mobility from the model may be simple, use of such a model is problematic because there is no *a priori* reason for assuming that conduction in OFETs is the same as that in silicon MOSFETs. In addition, mobilities in OFETs have been reported to depend on the gate bias [4]. Fig. 1 illustrates the difficulty of extracting OFET mobility from the I_{DS}–V_{GS} measurement by using the linear region MOSFET model. A linear fit to a different range of data gives threshold voltages and mobilities that differ by a factor of two.

In contrast to the published IEEE OFET standard [3], this letter describes a direct method of extracting the field effect mobility of an OFET with minimal assumptions and applies the analysis to top contact pentacene OFETs.

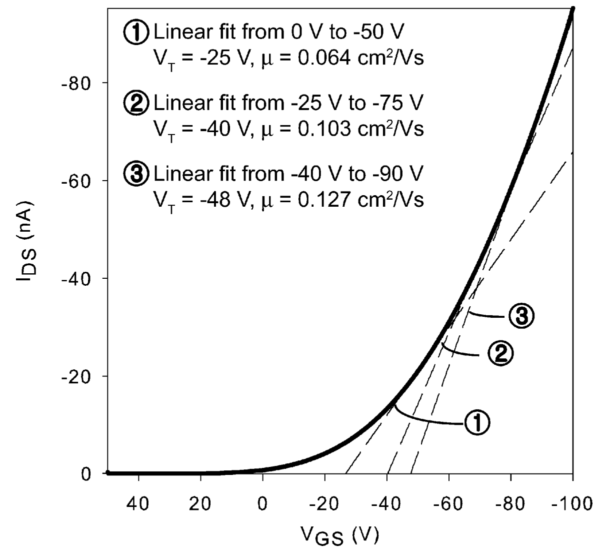

Fig. 1. Extraction of OFET mobility and threshold voltage fitting the silicon long channel MOSFET model to three different ranges of I_{DS}–V_{DS} measurement. The I_{DS}–V_{DS} sweep shown here is the average of the forward and reverse sweep shown in the Fig. 4 inset. As noted in the figure, extracted mobility and the threshold voltage change significantly with the range of data used for the linear fit.

II. EXTRACTION OF OFET MOBILITY

The drift mobility μ is defined as the velocity v of the charge carriers divided by the electric field E. In an OFET, mobility can be extracted from the fundamental relationship

$$\mu = \frac{v}{E} \quad v = \frac{I_{\mathrm{DS}}}{WQ} \tag{1}$$

where W is the width of the OFET channel and Q is the induced charge per channel area. If I_{DS} is measured under the bias condition $|V_{\mathrm{DS}}| \ll |V_{\mathrm{GS}} - V_{\mathrm{T}}|$, the electric field across the entire channel is approximately constant and E can be expressed as

$$E = \frac{V_{\mathrm{DS}}}{L} \tag{2}$$

where L is the length of the channel. Moreover, in this bias condition, Q can be determined through capacitance–voltage (*C–V*) measurements, as the total charge induced in the channel will be uniformly distributed along the channel. Such use of *C–V* measurements to determine the induced charge and mobility has been previously used in early attempts to characterize silicon MOSFETs [5], and it is repeated in this letter for OFETs to establish an understanding of OFET conduction mechanism.

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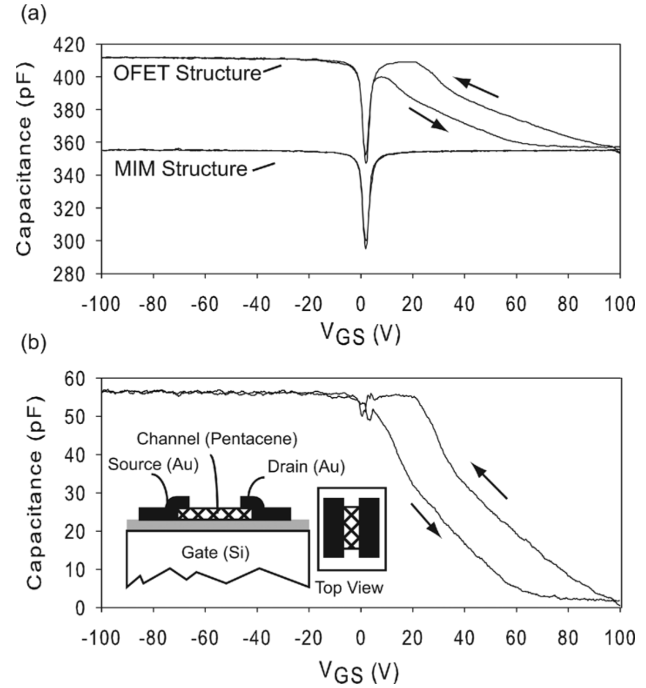

Fig. 2. (a) Quasi-static *C–V* measurements of the MIM structure and the OFET ($W/L = 1950/200$ μm). The dip around zero volts is due to the depletion effect in the underlying silicon. (b) Channel capacitance C_{ch} is derived by subtracting the capacitance present in the MIM structure from capacitance of the OFET structure. The inset shows the cross section and the top view of the inverted top-contact transistor. The top contact provides a low contact resistance to the pentacene semiconducting layer.

III. EXPERIMENT

Top-contact pentacene transistors of $L = 50$, 75, 100, 125, 150, 175, and 200 μm were fabricated on heavily doped n-Si substrates with 2000 Å of thermally grown oxide by depositing pentacene and then gold source/drain contacts through two different shadow masks (inset of Fig. 2).

To minimize effects of contact resistance, I_{DS} versus V_{GS} at $V_{\mathrm{DS}} = -100$ mV is taken from the longest channel transistor with $W/L = 1950/200$ μm (Fig. 1). The induced charge in the channel at different V_{GS} is determined by measuring the capacitance of the channel with V_{DS} set to -100 mV and varying V_{GS} from $+100$ to -100 V. The quasi-static *C–V* technique is used to measure capacitance because OFETs have high contact resistance, which makes the use of a capacitance bridge problematic. The ramp rate of the QSCV measurement was 1 V/s. The overlap and parasitic capacitances were determined by comparing the capacitance of an OFET to the capacitance of a similar structure with no pentacene, which we will refer to as a metal–insulator–metal (MIM) structure. The sheet charge density in the OFET channel at a set gate voltage V_{GS} can then be calculated as

$$Q = \int_{+\infty}^{V_{\mathrm{GS}}} \left(\frac{C_{\mathrm{ch}}}{WL}\right) dV,\ C_{\mathrm{ch}} = (C_{\mathrm{OFET}} - C_{\mathrm{MIM}}) \qquad (3)$$

where C_{OFET} and C_{MIM} are the capacitance measured in the OFET and the MIM structure, respectively, and C_{ch} is the capacitance due to the charge induced in the pentacene semiconductor. For practical purposes, (3) is integrated from $+100$ V.

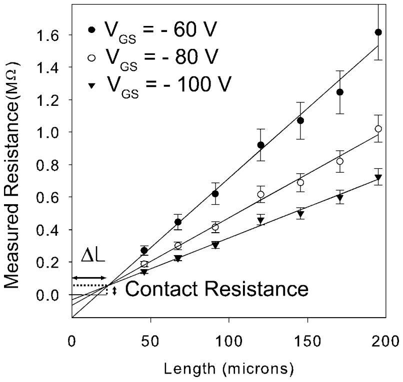

Fig. 3. Graph of channel resistance versus channel length at different V_{GS}. The sample size of each plotted data point is four transistors, with the standard deviation shown as the error bar. Contact resistance is extracted from the point where all the linear fits converge, as described in [6], [7]. The shift in channel length ΔL is also observed. The contact resistance is less than 5% of the channel resistance of the long channel OFETs.

Comparison between the C_{MIM} and the C_{OFET} in Fig. 2 measurement shows that the C_{OFET} in the depletion region ($V_{\mathrm{GS}} =$ 100 V) is due to the overlap capacitance. The overlap capacitance can then be extracted directly from the OFET *C–V* measurement, obviating the need for measuring MIM structures. In the accumulation region, where $V_{\mathrm{GS}} < 0$ V, $C_{\mathrm{ch,accumulated}}$ is nearly constant at 56 pF resulting in $C_{\mathrm{ch,accumulated}}/(WL) =$ 14 nF/cm^2. A model parameter V_{ON}, can be set so that the amount of induced channel charge is approximately

$$Q = -\frac{C_{\mathrm{ch,accumulated}}}{WL}(V_{\mathrm{GS}}\text{–}V_{\mathrm{ON}}). \qquad (4)$$

The observed hysteresis in Fig. 2 is attributed to dynamic processes in the organic film charging.

It was noted earlier that large contact resistances in OFETs may introduce error into the calculated mobility. In Fig. 3 the contact resistance was extracted from I_{DS}–V_{DS} measurements (for $V_{\mathrm{DS}} = -100\ \mathrm{meV}$) of different length OFETs ($L = 50$, 75, 100, 125, 150, 175, and 200 μm) at different V_{GS}, as described in [6] and [7]. For each value of V_{GS}, the $V_{\mathrm{DS}}/I_{\mathrm{DS}}$ ratio linearly increases with increasing channel length, with the cross point of linear regressions indicating the contact resistance. The contact resistance is significantly smaller ($< 5\%$) than the channel resistance for long channel OFETs. Additionally, consistent decrease in the channel length ΔL, is observed and associated with the contact geometry and possibly contact doping.

Charge carrier mobility in Fig. 1 OFET channel was extracted using (1), with E determined by (2) and Q from *C–V* measurement and (3). The extracted mobility is plotted in Fig. 4 as a shaded area to reflect the uncertainties introduced by the hysteresis in the channel capacitance measurement and the I_{DS}–V_{GS} sweep (Fig. 4 inset). Although significant errors were introduced from hysteresis in both *C–V* and *I–V* measurements, it is evident that the mobility is a strong function of gate voltage and varies from 0.002 to 0.05 cm^2/Vs.

The increase in mobility with gate bias, shown here and earlier in [4], illustrates that the conduction mechanism in pentacene OFETs is different from that in crystalline silicon MOSFETs, but is similar to charge transport in amorphous Si (a-Si) TFTs. Akin to a-Si, electronic states of organic crystal

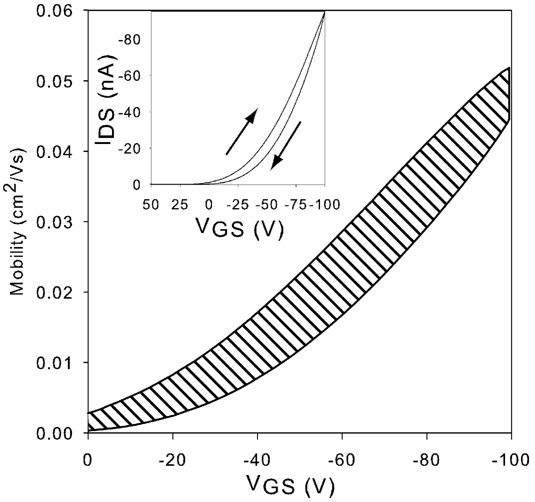

Fig. 4. Mobility extracted from the method proposed in this paper is shown as a shaded band with the upper and lower bound set by hysteresis in *C–V* and *I–V* measurements. Mobility dependence on V_{GS} is observed. The inset shows the *I–V* measurement from which mobility was extracted (same device as Fig. 1).

semiconductors are extended in the periodic structure of the crystal and localized at the crystal grain boundaries. The localized states that arise from the disorder in the organic film, lead to trapping of the induced charges, with the charge transport in the OFET channel alternating between trapped and free states. By adopting the analysis of charge mobility in disordered inorganic semiconductors [8], the apparent OFET channel mobility is given by

$$\mu_{\mathrm{OFET}} = \mu_{\mathrm{free}} \frac{Q_{\mathrm{free}}}{Q_{\mathrm{induced}}} = \mu_{\mathrm{free}} \frac{Q_{\mathrm{free}}}{Q_{\mathrm{free}} + Q_{\mathrm{trapped}}} \qquad (5)$$

where μ_{free} is the mobility of the carrier when it is in an extended state of the organic crystals, while Q_{free} and Q_{trapped} are the free and trapped fraction of the gate bias-induced charge, Q_{induced}. With increase in magnitude of the negative gate bias, the Fermi energy level sweeps into the pentacene trap-state energies, filling the deep hole-traps and increasing the Q_{free} fraction of the induced charge. Consequently, with fewer unfilled traps and larger Q_{free}, μ_{OFET} increases.

We note that the mobility calculated from the proposed method is significantly smaller than that derived from the MOSFET equation (see Fig. 1). The MOSFET equation necessitates a choice of the threshold voltage, which sets the starting limit of the (3) integral. The integral, then, significantly underestimates charge in the channel, which is offset in (1) by the apparent increase in the calculated mobility. In contrast, our analysis avoids using an arbitrary threshold voltage and calculates the number of carriers in the channel by integrating all the charge carriers that are induced in the channel. We note that this carrier count also includes carriers that are trapped at the organic/dielectric interface, with the consequence that the measured mobility is the average mobility of all the carriers, trapped and free, induced in the channel.

IV. CONCLUSION

The recently published IEEE standard to characterize OFETs (based on crystal silicon long channel MOSFET model) [3] can yield mobilities and threshold voltages that differ by a factor of two for the same device, depending on the range of data used to extract the parameters. We demonstrated that a more accurate measurement of OFET mobility can be directly and simply obtained through the use of *C–V* and *I–V* measurements. For the top contact pentacene OFETs we observe a clear dependence of charge carrier mobility in the channel with the applied gate bias, exemplifying one source of inadequacy of the standard MOSFET model in describing the response of OFETs.

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