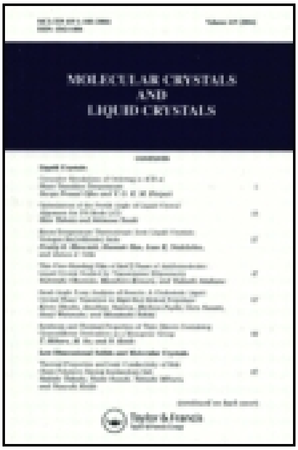

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

Theory of the Organic Field Effect Transistor

Gilles Horowitz [a]

[a] Laboratoire des Matériaux Moléculaires, CNRS, 2 rue Henry-Dunant, 94320, Thiais, France

Version of record first published: 24 Sep 2006

To cite this article: Gilles Horowitz (1998): Theory of the Organic Field Effect Transistor, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 322:1, 63-70

To link to this article: http://dx.doi.org/10.1080/10587259808030201

Mol. Cryst. Liq. Cryst., Vol. 322, pp. 63–70
Reprints available directly from the publisher
Photocopying permitted by license only

Theory of the organic field effect transistor

GILLES HOROWITZ
Laboratoire des Matériaux Moléculaires, CNRS, 2 rue Henry-Dunant, 94320
Thiais, France

Received 6 April 1998; accepted 25 April 1998

The performance of organic based field-effect transistors (OFETs) has considerably increased recently, and now compares to that of amorphous silicon. The operation mode of OFETs is described. It differs from that of the conventional MISFET in that it operates in the accumulation regime. Another important difference is the charge transport in organic materials, which occurs via hopping of self-localized polarons. As a result, the mobility is thermally activated and electric field dependent. Effects of this feature on the current-voltage characteristics are outlined.

Keywords: organic semiconductors; sexithiophene; pentacene; polarons

INTRODUCTION

Silicon has become the almost universal material in microelectronics. However, it is brittle, relatively expensive to produce, and not well fitted to large area devices. Moreover, its manufacturing requires high temperature processes, which is not compatible with the construction of very low cost devices made on plastic substrates. For these reasons, there is currently a worldwide interest in the realization of electronic devices based on organic materials, such as conjugated polymers and oligomers. Although a large majority of the work is devoted to the realization of light emitting diodes (LEDs), there is also an interest in the development of organic field effect transistors (OFETs) that could be used in applications where large areas are required, such as liquid crystal displays (LCDs) or smart cards. The first OFETs have been reported during the late eighties[1-3], and showed relatively modest performance, with a field effect mobility ranging between 10^{-4} and 10^{-3} $cm^2V^{-1}s^{-1}$, which is far too low for most applications. However, significant improvements have been reported recently, and the mobility of OFETs stands at present within the 0.1 to 1 $cm^2V^{-1}s^{-1}$ range[4-6], and compare with that of hydrogenated amorphous silicon.

In the present paper, we lay down the basis of a theoretical model for the organic field effect transistor. First, we describe what differentiates the geometry of the OFET from that of the conventional metal-insulator-semiconductor device (MISFET). Next, we concentrate on the charge transport in organic materials, which occurs via polaron hopping, with the important result that the mobility is electric field dependent. The consequences of that feature on the characteristics of the organic device are examined.

DEVICE GEOMETRY

The basic idea of a field effect transistor (FET) is to modulate the current that flows in a conducting channel between two ohmic contacts designated as the source and drain, by applying a voltage to a third electrode, the gate. Hence, the device can be viewed as a capacitor, where one plate constitutes the channel, and the other one the gate.

Metal-insulator-semiconductor FET (MISFET)

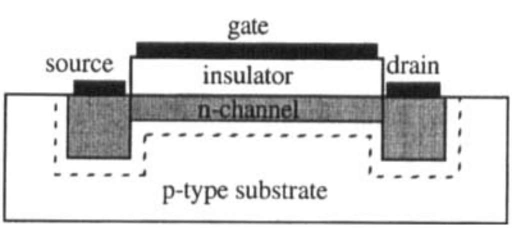

FIGURE 1. Schematic view of a MISFET. The dashed line delineates the depletion layer that separates the n-channel from the p-substrate

The geometry of a n-channel MISFET is given in Figure 1[7]. It comprises a p-type silicon substrate, on which two n-type regions are grown to form the source and drain. The gate is separated from the substrate by a thermally grown silicon oxide layer. The MISFET turns on when an *inversion* layer, that is, a n-type conducting channel, forms at the insulator-semiconductor interface in the gap between source and drain. This occurs when applying a sufficiently positive source-gate bias so that the Fermi level at the insulator-semiconductor interface crosses the middle of the forbidden gap. One of the prominent advantage of this geometry is the presence of a depletion layer between the n-channel and the p-substrate, which provides an isolation of the transistor from the substrate and any other device grown on the same substrate.

Thin film transistor (TFT)

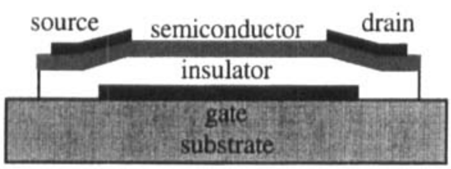

FIGURE 2. Schematic view of a thin film transistor

The geometry used in OFETs is that of the TFT, Figure 2, which was first introduced in 1962[8]. It differs from the MISFET by two major points. First, it is built on any kind of substrate, which is often a heavily doped silicon wafer that acts as a gate electrode, topped with a thermally grown silicon oxide that serves as the gate dielectric; but it can equally be a glass slide, or a plastic sheet. Next, the source and drain consists of ohmic contacts deposited directly on the semiconductor film; the device turns on when an *accumulation* layer forms at the insulator-semiconductor interface (for a p-type device, this corresponds to a negative source-gate bias), so that the conducting channel is not isolated from the rest of the semiconducting film. A low off current is only ensured by the low thickness and poor conductivity of the organic semiconductor. Also note that the OFET is built according to an inverted geometry, where the semiconductor is deposited on top of the insulator.

Current-voltage characteristics

A typical set of current-voltage characteristics of a p-type OFET is shown in Figure 3. At low drain voltage V_d, the drain current I_d is proportional to V_d; this is the linear regime. As V_d increases, I_d tends to level off; we now enter the saturation regime, where the drain current is constant. Note that the gate and drain voltages are both negative, an evidence for the device to operate in the accumulation regime.

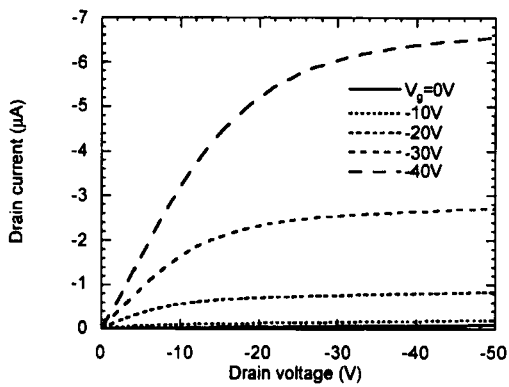

FIGURE 3. Current-voltage characteristics of a typical p-type OFET.

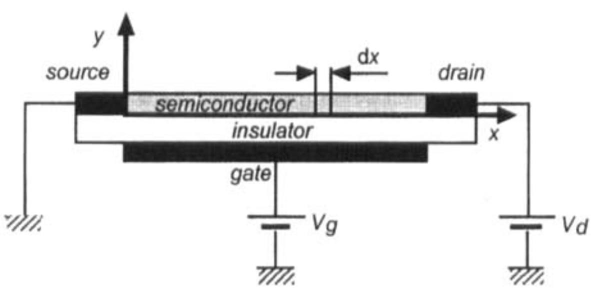

FIGURE 4. Calculation of the drain current in an OFET.

The principle of the computation of the current-voltage characteristics is schematized in Figure 4. It consists of estimating the magnitude of the elemental resistance dR of the elemental segment dx along the channel. The drain current is then obtained by integrating Equation 1, where Z is the channel width, μ the charge mobility, and $Q(x)$ the surface charge at x.

$$\mathrm{d}V = I_d\,\mathrm{d}R = \frac{I_d\,\mathrm{d}x}{Z\mu|Q(x)|} \tag{1}$$

In the accumulation regime, the charge is the sum of a thermal charge $Q_0=qp_0d$ (q: elemental charge, p_0: hole density, d: semiconductor film thickness), and the charge $Q_s=-C_i(V_g-V_x)$ induced by the gate voltage. Integrating Equation 1 from source ($x=0$, $V_x=0$) to drain ($x=L$, $V_x=V_d$), and assuming a voltage independent mobility yields

$$I_d = \frac{Z}{L}\mu C_i\left[\left(V_g - V_0\right)V_d - \frac{V_d^2}{2}\right] \tag{2}$$

where $V_0=qp_0d/C_i$. Note that V_0 is positive, that is, it has a sign inverse to that of the gate voltage. Under the same assumptions, the saturation current would be given by Equation 3.

$$I_{dsat} = \frac{Z}{2L}\mu C_i\left(V_g - V_0\right)^2 \tag{3}$$

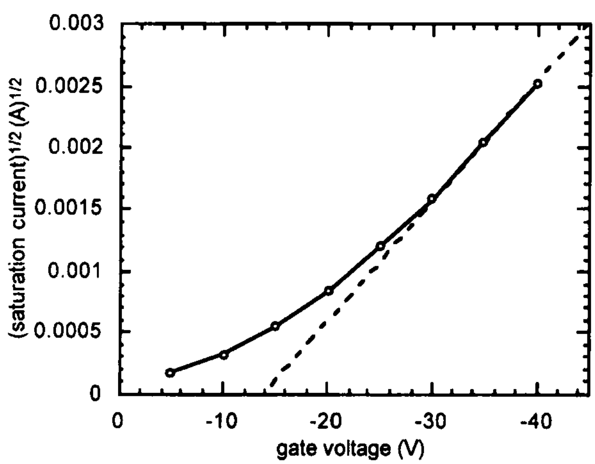

FIGURE 5. Plot of the square root of the saturation current as a function of the gate bias, for the same OFET as in Figure 3.

The plot of the square root of the saturation current would therefore give a straight line, the slope of which could be used to estimate the mobility, and which would intercept the voltage axis at V_0. Figure 5 shows that this is not really the case for the OFET of Figure 3. As will be shown in the following, this is due to a bias dependent mobility.

CHARGE TRANSPORT IN ORGANIC MATERIALS

Electrical current in conventional semiconductors occurs through the transport of nearly free electrons (or holes) in delocalized levels. This is not so in organic materials, where the strong electron-lattice interaction leads to the formation of self-localized polarons, a concept first introduced by Landau in 1933, and which can be described as a "charge trapped by digging its own hole". Depending on the strength of the electron lattice coupling, one deals with small or large polarons. Figure 6 shows the temperature dependence of the field-effect mobility of measure on a sexithiophene (6T) based OFET at various gate voltages[10]. Similar results have been reported for pentacene[11].

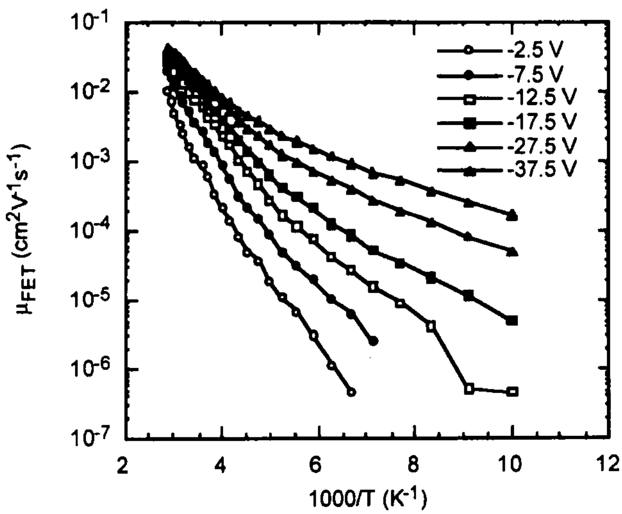

FIGURE 6. Arrhenius plot of the temperature dependent mobility of a sexithiophene-based OFET, for various gate voltages.

We note that the mobility is thermally activated, which would plead in favor of a charge transport by small polarons. At low gate voltage, we find an activation energy W_0~0.2 eV. Note that the activation energy tends to decrease as the gate voltage increases, a behavior that has been interpreted in terms of charge trapping induced by disorder. At low gate voltages, the Fermi level is located deep in the gap and transport occurs in the disorder induced deep levels. As the gate voltage increases, the Fermi level moves toward the polaronic level, which results in a decrease of the activation energy and a concomitant increase of the field-effect mobility.

An alternative explanation of the gate voltage dependence of the mobility could be the well-known electric field dependence of the mobility in organic materials[12]. A general expression of the electric field dependent mobility, is given by Equation 5.

$$\mu = \mu(0)\exp\left(\alpha\sqrt{F}\right) \qquad (5)$$

Here, F is the electric field, and α a (temperature dependent) constant. We note that, unlike in a sandwich (diode) structure, the electric field in OFETs is predominantly directed *perpendicular* to the current flow. In other words, because the thickness of the insulating layer is much lower than the length of the conducting channel, the electric field induced by the gate voltage at the insulator-semiconductor interface largely exceeds that generated by the source drain bias. To the best of our knowledge, the question of field dependent mobility has not been theoretically envisioned in such a geometry.

Aknowledgements

The author thanks Dr. Riadh Hajlaoui and Mr. Fayçal Kouki for assistance with the experiments, and Dr. Libero Zuppiroli for valuable discussions.

References

[1.] H. Koezuka, A. Tsumura and T. Ando, *Synth. Met.*, **18**, 699 (1987).
[2.] R. Madru, G. Guillaud, M. Al Sadoun, M. Maitrot, J. J. André, J. Simon and R. Even, *Chem. Phys. Lett.*, **145**, 343 (1988).

[3.] G. Horowitz, D. Fichou, X. Z. Peng, Z. G. Xu and F. Garnier, *Solid State Commun.*, **72**, 381 (1989).
[4.] J. G. Laquindanum, H. E. Katz, A. J. Lovinger and A. Dodabalapur, *Chem. Mater.*, **8**, 2542 (1996).
[5.] Y. Y. Lin, D. J. Gundlach, S. F. Nelson and T. N. Jackson, *Ieee Electron Device Lett.*, **18**, 606 (1997).
[6.] C. D. Dimitrakopoulos, B. K. Furman, T. Graham, S. Hegde and S. Purushothaman, *Synth. Metal.*, **92**, 47 (1998).
[7.] S. M. Sze, *Physics of Semiconductor Devices* (John Wiley, New York, 1981).
[8.] P. K. Weimer, *Proc. IRE*, **50**, 1462 (1962).
[9.] L. D. Landau, *Phys. Z. Sowietunion*, **3**, 664 (1933).
[10.] G. Horowitz, R. Hajlaoui and P. Delannoy, *J. Phys. III France*, **5**, 355 (1995).
[11.] A. R. Brown, C. P. Jarrett, D. M. deLeeuw and M. Matters, *Synth. Met.*, **88**, 37 (1997).
[12.] H. Bässler, *Phys Stat. Sol. (b)*, **175**, 15 (1993).