

# Theory and modeling of organic field effect transistors

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## Abstract

In organic FET's (OFET) the active layer is an organic material. Until now measured current characteristics have been analyzed by using the most simple equation for the current. But the design of the OFET is not common in electronics. As demonstrated by our 2D simulations of analogous silicon devices this design leads to several peculiarities. We developed analytical models which incorporate these peculiarities and reproduce the simulated current characteristics with less than 3 to 5% error. As first applications we fitted published current characteristics of OFET's and determined in this way material parameters. Zero field mobility  $\mu_0$  is low and indicate hopping transport. Large flat band voltages must origin from oxide/interface charges. Satisfactory fits are possible only by assuming velocity saturation unknown till now for hopping systems. The ratio  $v_s/\mu_0 \sim 1.5 \cdot 10^4 \text{V/cm}$  can be explained theoretically.

## 1 Introduction

In recent years there is an increasing interest in thin film field effect transistors with an active layer made from an organic material, organic FET's (OFET) [1-3]. Even an all-polymer transistor has been reported [4]. Among the rather different organic materials especially oligo- and polythiophens seem to be promising. Till now OFET's are essentially used to determine the mobility of the organic materials by analyzing the current characteristics. But there are also reports on circuits and ring oscillators and proposals for possible applications [5-6]. In all investigations the current characteristics have been analyzed only by using the most simple equation for the current (symbols with the usual meaning)

$$I_D = \mu \frac{w}{L} C_{ox} \left[ (U_{GS} - U_{th}) U_{DS} - \frac{U_{DS}^2}{2} \right] \quad (1)$$

below  $U_{DS} = U_{GS} - U_{th}$  and constant above. According to Brown et al. [10] the mobility determined by using this expression is expected to be erroneous by up to 50 percent. Thus, significant determination of transport properties from measured current characteristics require better models. We developed such models on the base of 2D simulations of analogous silicon devices. Fitting these models to published measured current characteristics we determined several material parameters of the organic layers. Theoretical models are presented to understand the results which are partly rather unexpected.

## 2 Analytical model based on 2D simulations of the analogous silicon device

The design of the OFET's (Fig.1) is not common in electronics. The layer sequence chosen from technological reasons is as follows:  $n^+$ -substrate (as gate)/oxide/active p-layer (organic). In some cases instead of a gate-substrate one has used a substrate covered by a metallic or graphitic gate (followed again by the insulator and the active layer). The organic

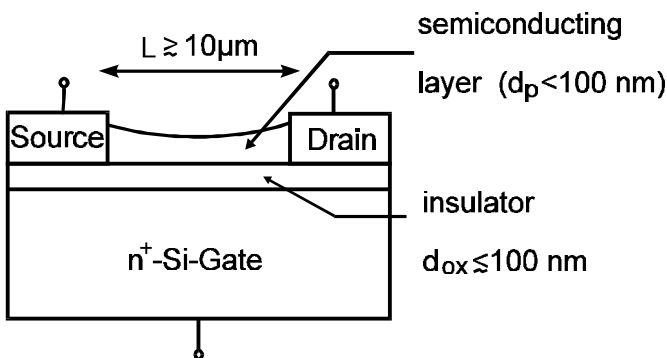


Fig.1 The OFET design

layer has a floating potential as e.g. the SOIFET or the new vertical MOSFET. Further, the OFET's operate in depletion or accumulation (till now it seems to be difficult to achieve inversion) and therefore the layer should be sufficiently thin. Such transistors show several peculiarities. This has been shown by 2D simulations of analogous Si-devices for which, of course, the material parameters are known. The following properties are especially of interest. (a) Since the OFET operates in depletion and accumulation depending on the gate voltage the surface potential can be shifted by more than twice the bulk potential (e.g. more than 0.8V in Si with  $10^{17}$  doping, in the wide-gap organics more than 1.5..2V) and therefore the use of a constant  $U_{th}$  in (1) is a serious error. (b) The operation of the device depends sensitively on the ratio of layer thickness and depletion length, which is smaller in the organics than in Si due to the smaller dielectric constant. (c) In both depletion and

accumulation the transverse field reduces the mobility but there is no transverse field at the transition from depletion to accumulation (flat band voltage). This peculiarity results in a hump in the transfer characteristics. (d) If one has accumulation at source and due to a high drain voltage depletion at drain than at some position between source and drain there is no transverse field. Thus, there is no monotonous decrease of the mobility due to the increasing lateral field from source to drain. Evidently, none of these peculiarities is described by the simple equation (1) with constant values for  $\mu$  and  $U_{th}$ . On the other hand, since for the organics little is known till now on the transport properties (compared to Si and other inorganic semiconductors) it is important to have an analytical model which allows to determine these properties by fitting the model to the experimental characteristics.

Based on the results of the 2D simulations we developed such analytical models of different complexity (depending on operation conditions and layer thickness) which describe the peculiarities (a) to (d). The analytical models have been tested in the following manner: Using the material parameters of the 2D simulations in the analytical model the latter reproduces the current with an error less than 3 to 5 percent. Further, fitting the analytical model to the 2D simulations results in material parameters which coincide within 5 to 10 % with those in the 2D simulations. A modification of the model accounts for the existence of polarons and bipolarons in some conducting polymers.

### 3 Applications to OFET's

The model has been applied to current characteristics of OFET's with thiophene films

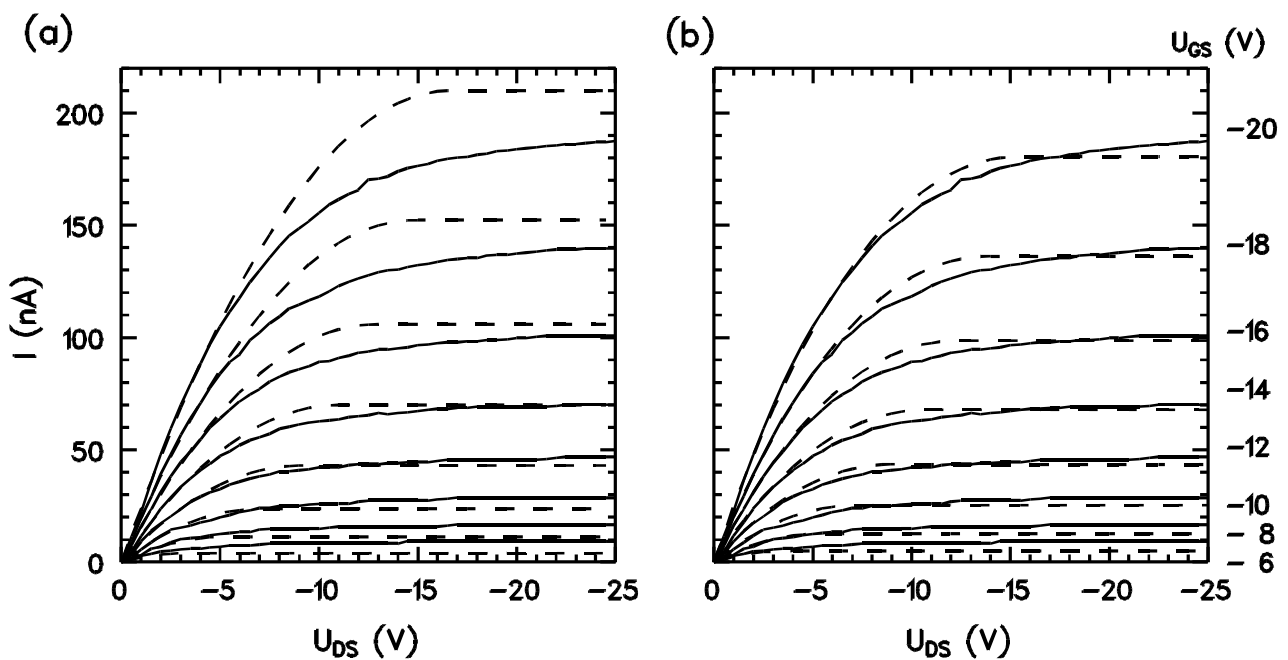


Fig.2. Measured current characteristics [7] (full lines) and fit (dashed lines) (a) without and (b) with velocity saturation

[3,4,7-9] with the following results. (a) The fits (Fig.2 as an example) lead to large flat band voltages (thick oxides) indicating oxide/interface charges up to  $10^{11}$ .. $10^{12}$ cm<sup>-2</sup>. (b) Zero field mobility  $\mu_0$  is roughly comparable with that obtained with Equ.(1) and  $\mu = \text{const}$ . (c) The small magnitude of the mobility (Fig.3) indicates hopping transport as discussed in [10].

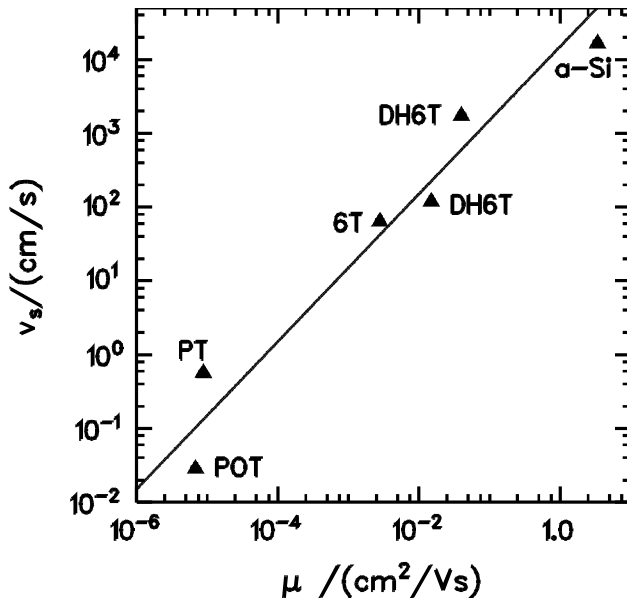


Fig.3. Saturation velocity in dependence on zero field mobility (resulting from the fits) for five thiophene OFET's [3] (DH6T, larger value), [4] (DH6T, smaller value), [7] (6T), [8] (PT), [9] (POT) and for a-Si [11]. From the regression one obtains the dependence:

$$v_s/(\text{cm/s}) = 1.5 \cdot 10^4 [\mu/(\text{cm}^2/\text{Vs})]^{1.04}$$

(d) Reasonable fits are possible only by supposing velocity saturation (Fig.2) which has been unknown till now for hopping systems (for still higher fields the mobility increases e.g. due to Pool- Frenkel detrapping [12]). (e) The ratio  $v_s/\mu_0$  (Fig.3) is roughly the same as in a-Si and crystalline Si. (f) Assuming hopping one can estimate  $v_s/\mu_0 = U_T/R_0$  ( $R_0$  effective hopping distance). (g) The same hopping model explains also the "universal relation between field effect mobility and conductivity" formulated empirically in [10].

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