Compact Modeling Approaches for Organic and Oxide Thin Film Transistors

Benjamin Iñiguez,

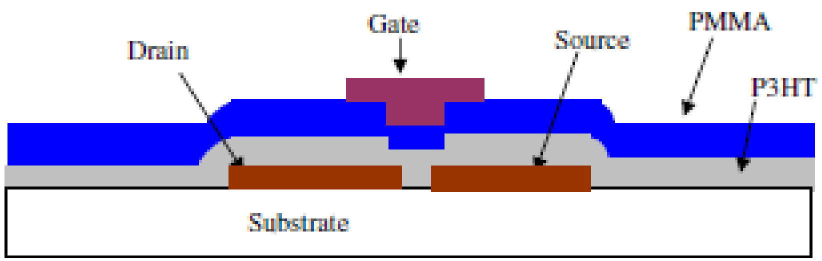
(*)DEEEA, Universidad Rovira i Virgili, Tarragona, Catalonia, Spain

UNIVERSITAT ROVIRA I VIRGILI

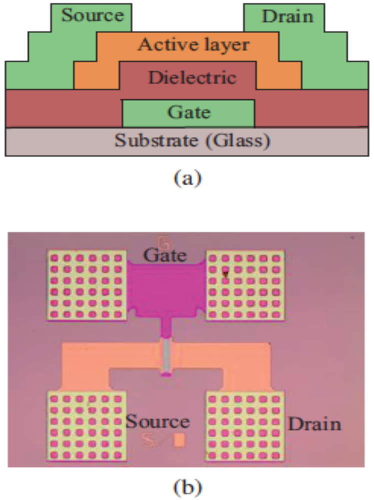
Introduction

- Organic (as well as polymer) and Amorphous Oxide (OTFTs and AOS TFTs, respectively) will probably become essential devices in niche applications, related to flexible, printed or large area electronics and also transparent electronics (in the case of AOS TFTs). Examples of applications are electronic tags, drivers in AMLCDs, sensors

- Organic and amorphous oxide electronics allow flexible and low-cost substrates for large-area applications by relatively simple and low-temperature fabrication for disposable electronics



Organic (polymeric) TFT structure

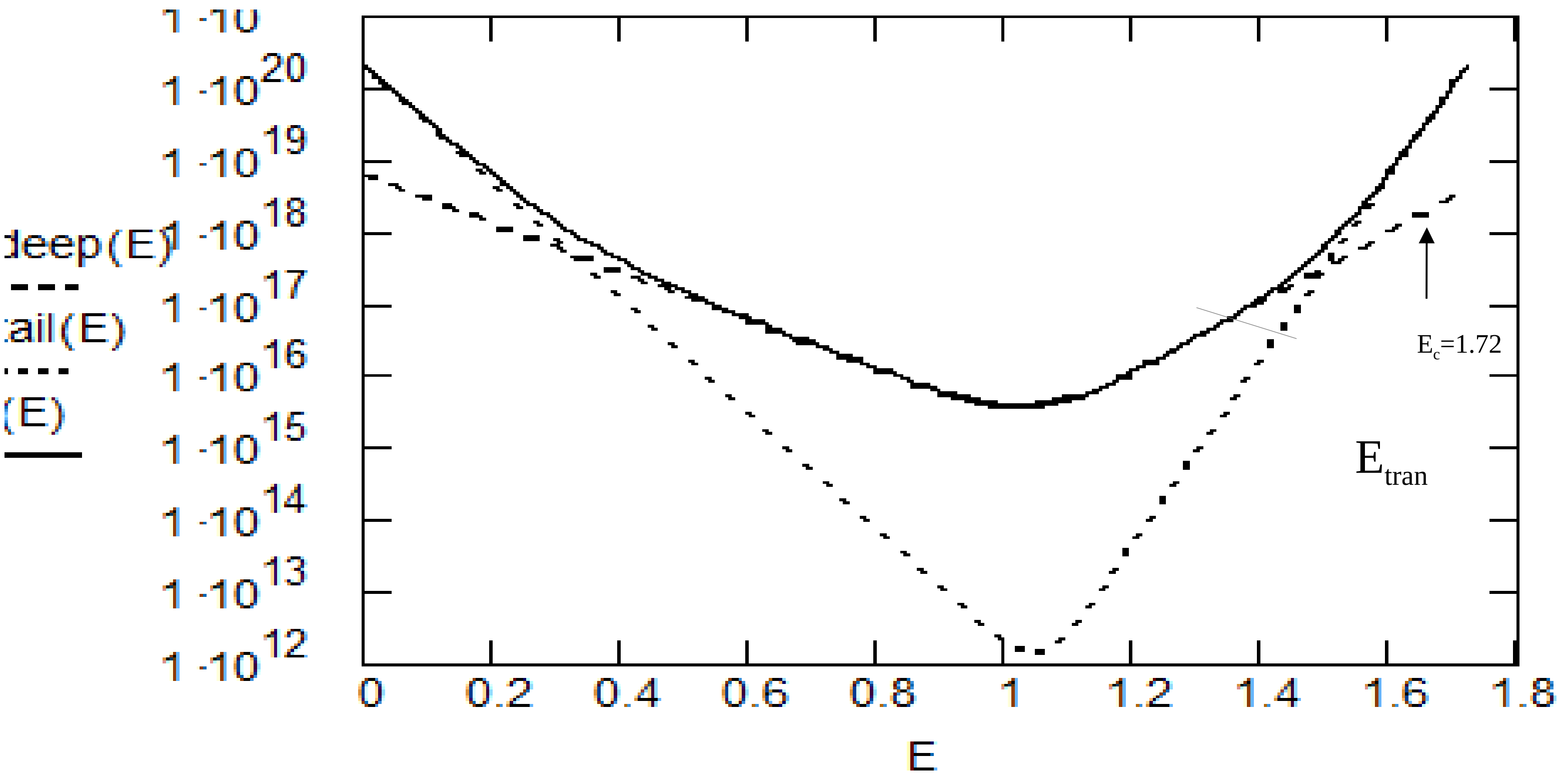


GIZO TFT structure

Outline

- Introduction
- OTFT drain current model and parameter extraction
- AOS TFT drain current model
- Conclusions

OTFT drain current model



For organic TFTs, $Q_{loc} >> Q_{free}$ and DOS with only one exponential dependence

$$\mu_{FET} = \mu_{FET1}(T, To) \cdot (V_{GS} - V_T)^{\gamma}$$

OTFT drain current model

- 1D Poisson's equation has no analytical solution if a Gaussian DOS is used
- An analytical solution is possible assuming an exponential DOS, as in a-Si:H TFTs

$$DOS_{gauss} = \frac{N_V}{\sqrt{2\pi}\sigma} \exp\left(-\left(\frac{\varepsilon - \varepsilon_0}{\sqrt{2\pi}\sigma} \right)^2 \right)$$

$$DOS_{\exp} = \frac{N_t}{kT_0} \exp\left(\frac{\varepsilon}{kT_0} \right)$$

$$\frac{d^2\psi}{dy^2} = N_t \delta_0 e^{\frac{q\psi}{kT_0}},$$

OTFT drain current model

In [*] it was shown that for OTFTs, it can be considered that Q_{loc}>>Q_{free} in above threshold regime and Poisson´s equation has analytical solution for the electric field and the induced sheet charge in the channel.

The DOS is represented as:

$$g_d(E) = g_{do} \exp\left(-\frac{(E - Ev)}{k_b To} \right)$$

[*] M. Estrada et all, Solid State Electronics, 52 (2008) 787.

OTFT drain current model

Mobility model development

The mobility expression is obtained from:

$$\mu_{\mathrm{FET}} = \frac{L}{W} \cdot \frac{1}{C_i V_{DS}} \cdot \frac{\partial I_{\mathrm{DS}}}{\partial V_{GS}}$$

t: channel thicness

where

$$I_{\mathrm{DS}} = \frac{W}{L} \cdot V_{\mathrm{DS}} \cdot \int_0^t \mathrm{d}x \cdot \sigma[\delta(x), T]$$

Vissenberg MCJM. Theory of the field effect mobility in amorphous organic transistors. Phys Rev B 1998;57:12964–7.

OTFT drain current model

The expression of the current obtained is:

$$I_{\mathrm{DS}} = P(T, T_0) \cdot C_i \cdot \frac{W}{L} \cdot \frac{T}{2T_0} \cdot \left[\left(V_{\mathrm{GS}} - V_{\mathrm{FB}}\right)^{\frac{2T_0}{T}} - \left(V_{\mathrm{GS}} - V_{\mathrm{FB}} - V_{\mathrm{DS}}\right)^{\frac{2T_0}{T}} \right];$$

where:

$$P(T, T_0) = P'(T, T_0) \cdot \frac{C_i^{\left(\frac{2T_0}{T} - 2\right)}}{\left(\varepsilon_s\right)^{\left(\frac{T_0}{T} - 1\right)}}$$

$$P'(T, T_0) = \frac{q \cdot k_b T \cdot N_V \cdot \exp\left[-\frac{E_{F_0} - E_V}{k_b T}\right]}{\left[\pi q \cdot k_b T \cdot g_{d0} \cdot \exp\left(-\frac{E_{F_0} - E_V}{k_b T_0}\right)\right]^{\frac{T_0}{T}}} \cdot \frac{T_0}{T} \cdot \left[\frac{\sin(\pi T / T_0)}{2 k_b T_0}\right]^{\frac{T_0}{T}}.$$

OTFT drain current model

If $V_{DS} < V_{GS}-V_{FB}$

$$I_{\mathrm{DS}} = \frac{W}{L} \cdot C_i \cdot P(T, T_0) \cdot \frac{T}{2T_0} \left(V_{\mathrm{GS}} - V_{\mathrm{FB}}\right)^{\frac{2T_0}{T}} \cdot \left[1 - \left[1 - \left(\frac{V_{DS}}{V_{GS} - V_{FB}}\right) \cdot \frac{2T_0}{T} + \cdots\right]\right]$$

which can be rewritten as:

$$I_{\mathrm{DS}} = \frac{W}{L} \cdot C_i \cdot \mu_{\mathrm{FET}} \cdot \left(V_{\mathrm{GS}} - V_{\mathrm{FB}}\right) \cdot V_{\mathrm{DS}};$$

OTFT drain current model

The expression of mobility obtained is:

$$\mu_{FET} = \left[\mu_o \cdot P'(T,To) \cdot \frac{C_i^{\left(\frac{2To}{T}-2\right)}}{(\varepsilon_S)^{\left(\frac{To}{T}-1\right)}} \right] \cdot \quad (V_{GS} - V_{FB})^{\left[\frac{2To}{T}-2\right]}$$

$$\mu_{FET} = \left[\frac{\mu_o}{V_{aa}^{\gamma}} \right] (V_{GS} - V_T)^{\gamma}$$

where:

$$P'(T,To) = \frac{q \cdot k_b T \cdot N_V \cdot \exp\left[-\frac{E_{Fo}-E_V}{k_b T}\right]}{\left[\pi q \cdot k_b T \cdot g_{do} \cdot \exp\left(-\frac{E_{Fo}-E_V}{k_b To}\right)\right]^{\frac{To}{T}}} \cdot \left[\frac{\sin(\pi T / To)}{2 k_b To}\right]^{\frac{To}{T}}$$

$$\frac{\mu_o}{(V_{aa})^{\gamma}} = \mu_o P'(T,To) \cdot \frac{C_i^{\left(\frac{2To}{T}-2\right)}}{\cdot (\varepsilon_S)^{\left(\frac{To}{T}-1\right)}}$$

and

$$\gamma = \frac{2To}{T} - 2$$

OTFT drain current model

$$I_{DS} = \frac{W}{L} \cdot C_i \cdot \mu_{FET} \cdot \frac{(V_{GS} - V_T) \cdot V_{DS} \cdot (1 + \lambda \cdot V_{DS})}{\left[1 + R \cdot \frac{W}{L} \cdot C_i \cdot \mu_{FET} \cdot (V_{GS} - V_T)\right] \cdot \left[1 + \left[\frac{V_{DS}}{\alpha_S \cdot (V_{GS} - V_T)}\right]^m\right]^{\frac{1}{m}}}$$

m and λ are fitting parameters related to the curvature and the saturation region of the curves, respectively

OTFT parameter extraction

An extraction procedure based on the properties of the integral function *H1(VGS).* was developed:

$$H1(V_{GS}) = \frac{\int_0^{V_{GS\max}} I_{DS}(V_{GS})dV_{GS}}{I_{DS}\ (V_{GS})} = \frac{1}{2+\gamma}\cdot\left(V_{GS} - V_{T)}\right)$$

If I_D can be represented as: $$I_{DS} \propto (V_{GS} - V_T)^n$$

Our parameter extraction method is called UMEM (Unified Modelling and Extraction Method).
It has been adapted and applied to several types of TFTs.

OTFT parameter extraction

If the measured transfer characteristic in the linear regime I_{DSlin}, is represented as:

$$I_{DSlin} = \frac{\left(\frac{W}{L}\right) \cdot C_i \cdot \mu_{FET}}{1 + R\left(\frac{W}{L}\right) \cdot C_i \cdot \mu_{FET} \cdot \left(V_{GS} - V_T\right)} \cdot (V_{GS} - V_T) \cdot V_{DS1}$$

Where μ_{FET} is modeled as a power dependence of the $(V_G - V_T)$:

$$\mu_{FET} = \frac{\mu_o}{V_{AA}^{\gamma}} \cdot (V_{GS} - V_T)^{\gamma}$$

then $$H1(V_{GS}) = \frac{\int_0^{V_{GS\max}} I_{DS\,lin}(V_{GS})\,dV_{GS}}{I_{DS\,lin}(V_{GS})} = \frac{1}{2+\gamma} \cdot \left(V_{GS} - V_T\right)$$

OTFT parameter extraction

If the measured transfer characteristic in the linear regime I_{DSlin}, is represented as:

$$I_{DSlin} = \frac{\left(\frac{W}{L}\right) \cdot C_i \cdot \mu_{FET}}{1 + R\left(\frac{W}{L}\right) \cdot C_i \cdot \mu_{FET} \cdot (V_{GS} - V_T)} \cdot (V_{GS} - V_T) \cdot V_{DS1}$$

Where μ_{FET} is modeled as a power dependence of the $(V_G\text{-}V_T)$:

$$\mu_{FET} = \frac{\mu_o}{V_{AA}^{\gamma}} \cdot (V_{GS} - V_T)^{\gamma}$$

then $$H1(V_{GS}) = \frac{\int_0^{V_{GS\max}} I_{DS\,lin}(V_{GS})\,dV_{GS}}{I_{DS\,lin}(V_{GS})} = \frac{1}{2+\gamma} \cdot (V_{GS} - V_T)$$

OTFT parameter extraction

STEP1: Calculate the slope and intercept of *H1(n1)*:

$$\gamma = \frac{1}{slope} - 2 \qquad V_T = \frac{intercept}{slope}$$

STEP 2: Calculate the slope, PA, of the equation:

$$y(V_{GS}) = I_{DSlin}(V_{GS})^{\frac{1}{1+\gamma}} = PA \cdot \left(V_{GS} - V_T\right)$$

Where:

$$PA = \left[\frac{\left(W/L\right) \cdot C_i \cdot \mu_o \cdot V_{DS1}}{V_{AA}^{\gamma}}\right]^{\frac{1}{1+\gamma}}$$

and V_{DS1} is the drain voltage at which the linear transfer curve was measured.

OTFT parameter extraction

STEP 3: Calculate : $\frac{\mu_o}{V_{AA}^{\gamma}}$

$$\frac{\mu_o}{V_{AA}^{\gamma}} = \left[\frac{PA^{1+\gamma}}{\left(W/L \right) \cdot C_i \cdot V_{DS1}} \right]$$

STEP 4: Calculate μ_{FET}:

$$\mu_{FET} = \left[\frac{PA^{1+\gamma}}{\frac{W}{L} \cdot V_{DS1}} \right] \cdot \left(V_{GS} - V_T \right)^{\gamma}$$

OTFT parameter extraction

STEP 5: Calculate *R* for the maximum measured V_{GS} :

$$R = \frac{V_{DS1}}{I_{DSlin}\left(V_{GS\max}\right)} - \frac{1}{\left(\frac{W}{L}\right) \cdot C_i \cdot \mu_{FET} \cdot \left(V_{GS\max} - V_T\right)}$$

STEP 6: Calculate the slope *Ps* of the curve:

$$y(V_{GS}) = I_{DSsat}(V_{GS})^{\frac{1}{1+\gamma}}$$

where I_{Dsat} is the transfer curve in saturation

STEP 7: Calculate α_S

$$\alpha_S = \left[\frac{V_{DS1}}{PA^{1+\gamma}}\right] \cdot Ps^{2+\gamma}\sqrt{2}$$

OTFT parameter extraction

A.1. Calculate the characteristic energy *To* of the DOS as:

$$To = (\gamma + 2)\frac{T}{2}$$

A.2. Calculate g_{do} as:

$$g_{do} = \left[qN_V k_b T\varepsilon_s\right]^{\frac{T}{To}} \cdot \left[\frac{\sin\left(\pi\frac{T}{To}\right)}{2\pi Tqk_b{}^2 To\varepsilon_s}\right] \cdot \left[V_{aa}C_i\right]^{\left(2-2\frac{T}{To}\right)}$$

OTFT parameter extraction

Modeling the subthreshold regime

The subthreshold regime is expected to present an exponential increase with the gate voltage than can be written as:

$$I_S = Io + I_{DS}(V_T + DV, V_{DS}) \cdot e^{\left(\frac{V_{GS} - V_T}{S}\right) \cdot 2.3}$$

V_T+ *DV* is the value of gate voltage near which the exponential dependence of I_{DS} starts and Io is the measured off current at a gate voltage sufficiently well below in the subthreshold region.

The total drain current is the sum of the two components, in above and below threshold regimes. The tahh function is used to sew both terms.

$$I_{DSt} = I_s \cdot \frac{1 - \tanh(V_{GS} - (V_T + DV) \cdot Q)}{2} + I_{DS} \cdot \frac{1 + \tanh(V_{GS} - (V_T + DV) \cdot Q)}{2}$$

Improvement of the output conductance

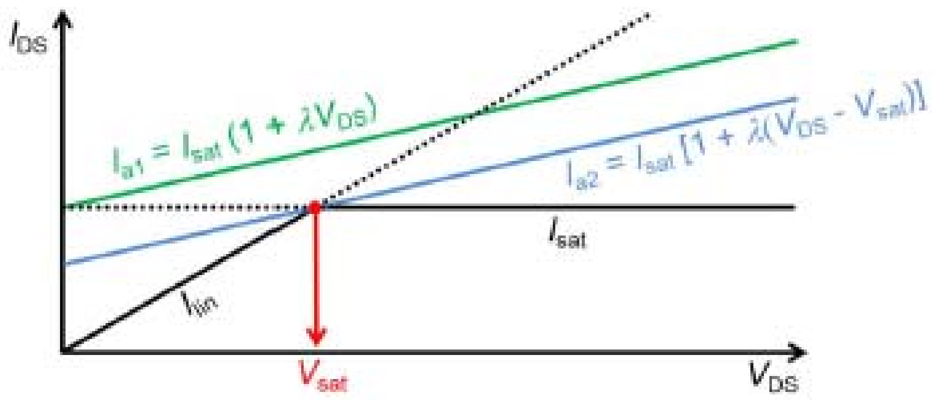
In saturation above threshold:

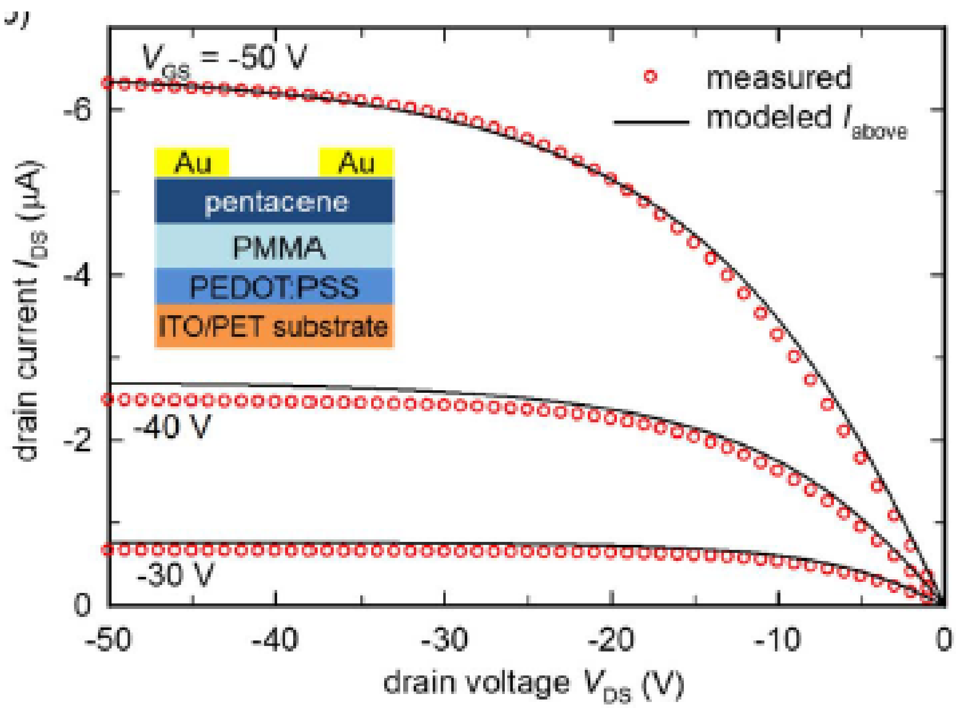
$$I_{\mathrm{above}} = \frac{-K\mu_{\mathrm{FET}}(V_{GS}-V_T)V_{DS}\left[1+\lambda(|V_{DS}|-\alpha_s|V_{GS}-V_T|)\right]}{\left[1-R_cK\mu_{\mathrm{FET}}(V_{GS}-V_T)\right]\left[1+\left|\frac{V_{DS}}{\alpha_s(V_{GS}-V_T)}\right|^m\right]^{\frac{1}{m}}}.$$

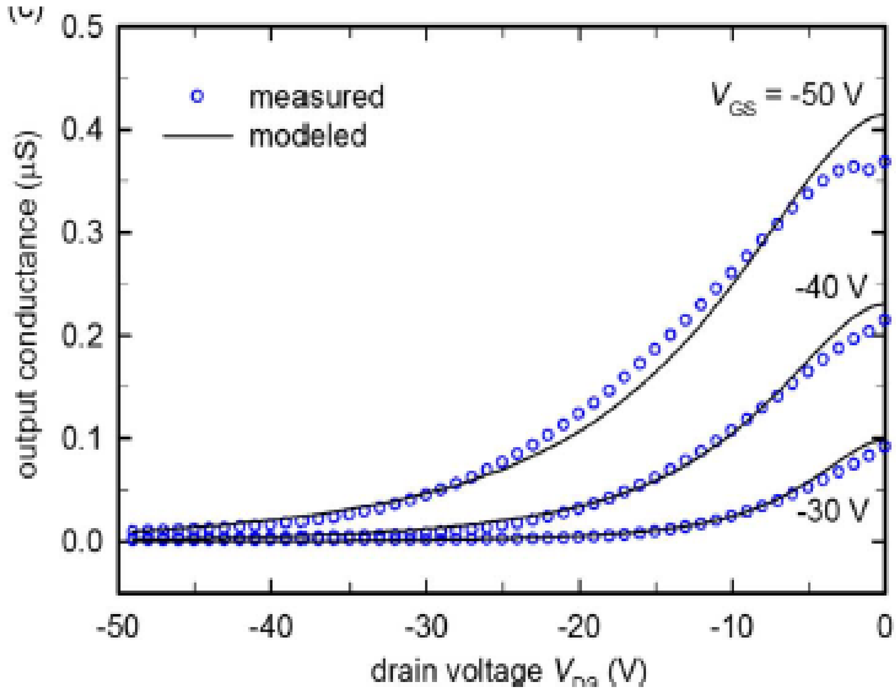
Extended to the linear regime by replacing V_{GS}-V_T with V_{DSe}

$$V_{\mathrm{DSe}} = V_{DS}\times\left[1+\left(\frac{V_{DS}}{V_{\mathrm{sat}}}\right)^m\right]^{-\frac{1}{m}}$$

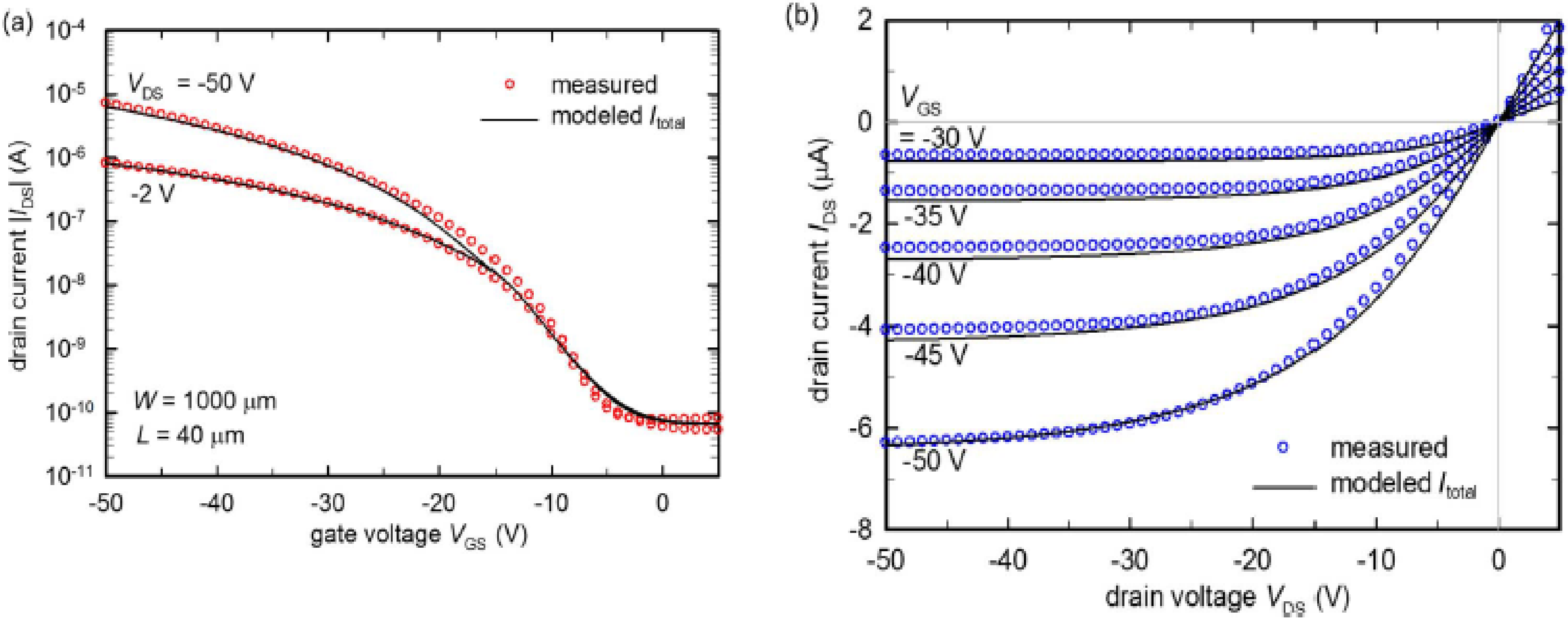
Results


I_{DS}
$I_{a1} = I_{sat}(1 + \lambda V_{DS})$
$I_{a2} = I_{sat}[1 + \lambda(V_{DS} - V_{sat})]$
I_{sat}
I_{lin}
V_{sat}
V_{DS}


V_{GS} = -50 V
measured
modeled I_{above}
Au
Au
pentacene
PMMA
PEDOT:PSS
ITO/PET substrate
-40 V
-30 V
drain current I_{DS} (μA)
-6
-4
-2
0
-50
-40
-30
-20
-10
0
drain voltage V_{DS} (V)


measured
modeled
V_{GS} = -50 V
-40 V
-30 V
output conductance (μS)
0.5
0.4
0.3
0.2
0.1
0.0
-50
-40
-30
-20
-10
0
drain voltage V_{DS} (V)

Results



(a)
V_{DS} = -50 V
-2 V
measured
modeled I_{total}
W = 1000 μm
L = 40 μm
drain current $|I_{DS}|$ (A)
gate voltage V_{GS} (V)
(b)
V_{GS}
= -30 V
-35 V
-40 V
-45 V
-50 V
measured
modeled I_{total}
drain current I_{DS} (μA)
drain voltage V_{DS} (V)

AOS TFT Drain Current Model

Distribution of acceptor type traps

Conduction band energy

$$g_a = g_{at0} \exp\left(-\frac{E_C - E}{kT_1}\right) + g_{ad0} \exp\left(-\frac{E_C - E}{kT_2}\right)$$

$$T_1 = \frac{(\gamma a + 2)}{2} T$$

Tail acceptor density of states

Deep acceptor density of states

$$T_2 = \frac{(\gamma b + 2)}{2} T$$

The V_{GS} variation above threshold modifies the population of the tail states.

The V_{GS} variation in subthreshold modifies the population of the deep states.

AOS TFT Drain Current Model

Unified Model and Parameter Extraction Method (UMEM) where the mobility is calculated by solving:

- Poisson’s equation assuming an exponential DOS and Qfree<<Qloc

- Free carrier transport in AOS TFTs

Multiple Trapping and Release

AOS TFT Drain Current Model

ABOVE THRESHOLD

Channel length modulation

$$I_{ab}(V_{GS},V_{DS}) = \frac{W}{L} C_i \mu_{FET} \frac{(V_{GS}-V_T)(1+\lambda|V_{DS}|)V_{DS}}{\left(1+R\frac{W}{L}C_i\mu_{FET}(V_{GS}-V_T)\right)\left(1+\left(\frac{V_{DS}}{\alpha(V_{GS}-V_T)}\right)^{m}\right)^{1/m}}$$

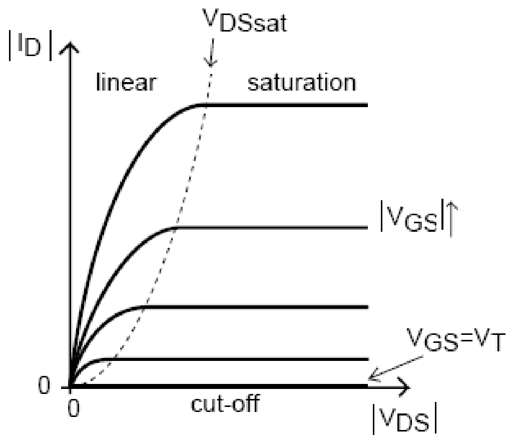
Saturation parameter

Sharpness of the knee region

where

Empirical parameters defining the variation of mobility with Vgs above threshold

$$\mu_{FET} = \frac{\mu_0 (V_{GS}-V_T)^{\gamma a}}{Vaa^{\gamma a}}$$



AOS TFT Drain Current Model

In [*] extraction procedure based on the properties of the integral function *H(VGS).* was developed and applied, first, to a-Si:H devices model :

$$H_{above}(V_{GS}) = \frac{\int_0^{V_{GS\max}} I_{DS}(V_{GS})dV_{GS}}{I_{DS}(V_{GS})} = \frac{1}{2+\gamma a}\cdot(V_{GS}-V_T)$$

$$Vaa = \left(\frac{\frac{W}{L}C_iV_{D1}}{slope^{1+\gamma a}}\right)^{\frac{1}{\gamma a}}$$

Parameters extracted from the transfer curve in linear regime, and with the ***slope*** and the abscissa intercept of the H function.

Now we can model the field dependent mobility μ_{FET}

Subsequently, parameters R, m, λ, α are extracted as indicated in:

-A. Cerdeira, M. Estrada, R. Garcia, A. Ortiz-Conde, and F.J.G. Sanchez, *Solid-St. Electron*, vol.45, no. 7, pp.1077-1080 (2001).

AOS TFT Drain Current Model

SUBTHRESHOLD

To model the subthreshold region of devices, the drain current can be described as [*]:

$$I_{bt}(V_{GS}, V_{DS1}) = K\frac{(V_{GS} - V_{FB})^{1+\gamma_b}}{V_{bb}{}^{\gamma_b}} V_{DS1}$$

γ_b depends on the temperature *T* and on the characteristic temperature of the deep states distribution (T_2) ⟹ $\gamma b = \frac{2T_2}{T} - 2$

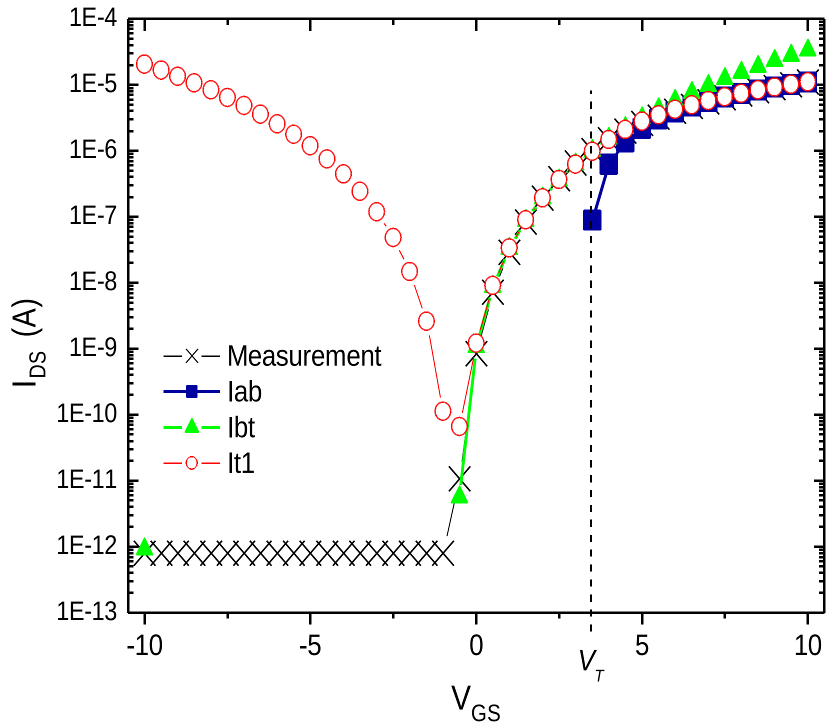
Vbb is obtained as indicated in [**]

[*] L. Resendiz, M. Estrada, and A. Cerdeira, *Solid State Electron* 2003;47:135–1358.
[**] A. Cerdeira, M. Estrada, B. S. Soto-Cruz, and B. Iñíguez, *Microelectron Reliab* vol. 52, pp.2532-2536 (2012).

AOS TFT Drain Current Model

To join the subthreshold and the above threshold regions, an expression I_{t1} is obtained where the *tanh* function is applied to sew $I_{ab}(V_{GS}, V_{DS})$ and $I_{bt}(V_{GS}, V_{DS})$.

$$I_{t1} = |I_{bt}| \left[\frac{1-tanh\left[\left(V_{GS}-(hi+V_0)\right)Q_0\right]}{2}\right] + |I_{at}| \left[\frac{1+tanh\left[\left(V_{GS}-(hi+V_0)\right)Q_0\right]}{2}\right]$$

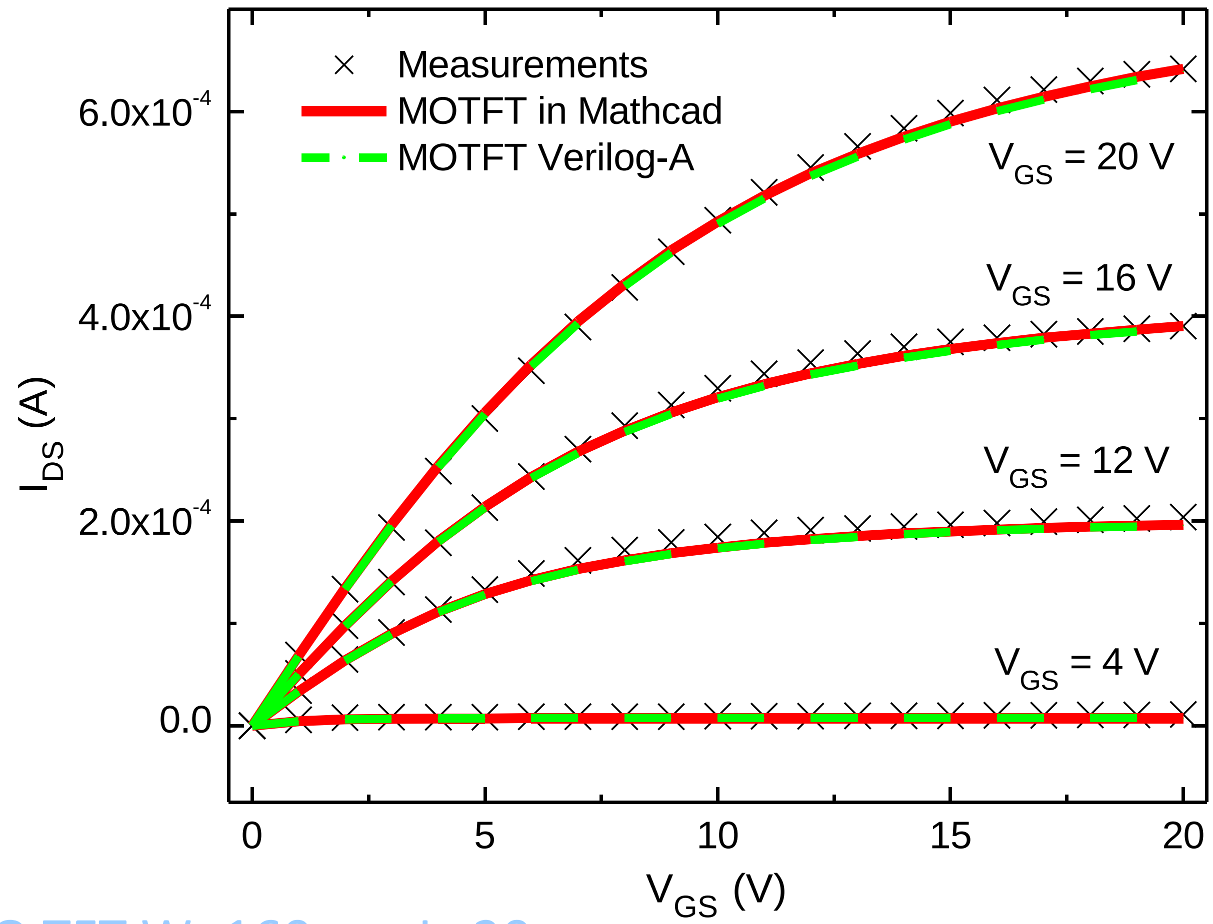


Typical non-stress transfer characteristic of a HIZO TFT in linear regime.

W=160 μm. L=20 μm. V_{DS}=0.1 V

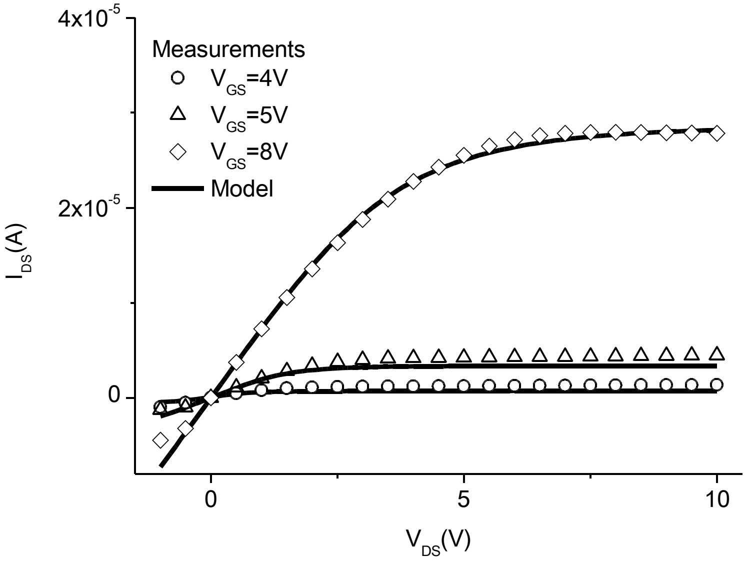
Experimental data is compared with I_{t1}, which is composed of the above threshold region ($V_{GS} > V_T$), modeled by *Iab*, and the subthreshold region, modeled by *Ibt*.

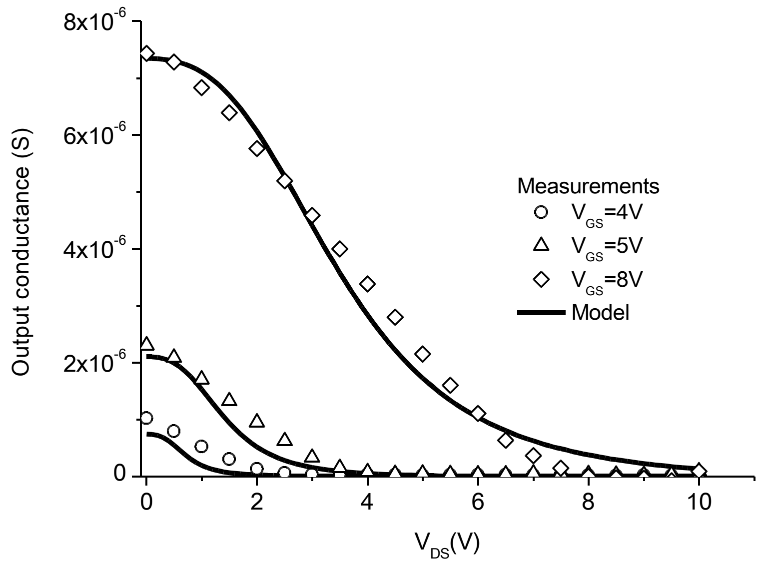
AOS TFT Results



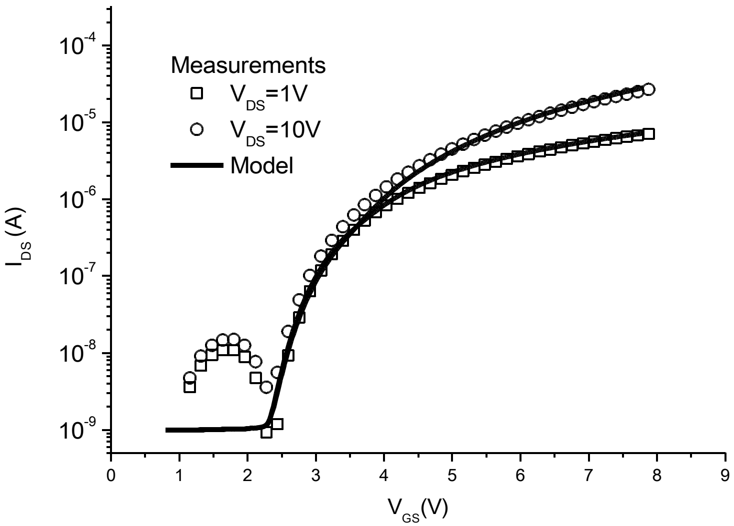
GIZO TFT W=160 µm L=20 µm

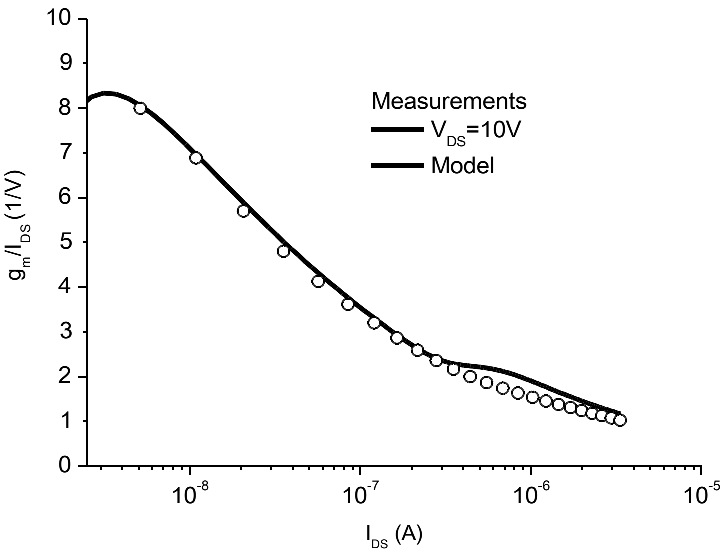
AOS TFT Results





AOS TFT Results





Conclusions

A physically-based compact modelling framework for Organic and Amorphous Oxide TFTs has been presented

➢

For both OTFTs and AOS TFTs our models predict *I-V* characteristics above and below threshold., with a smooth transition between both regimes The extraction procedure (UMEM) is simple and well defined.

Mobility as function of both bias and temperature is also modeled.

DOS parameters (*To* and g_{do}) in OTFTs and for deep states in AOS TFTs can be determined.

➢

Very good agreement is obtained with I-V experimental data from OTFTs and AOS TFTs fabricated with different technologies