Compact Modeling of Organic Thin-Film Transistors

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Outline

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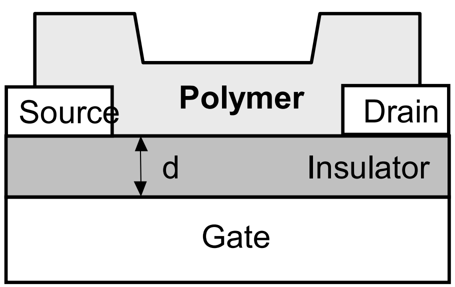
- Open questions in organic TFT physics
- Modeling approaches
- Summary of our results
- Conclusions

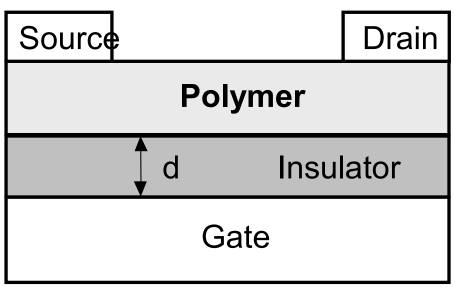
Our research in organic TFTs

- Understanding of the physical behaviour
- Development of compact models
- Study of the geometry dependences of parameters
- Development of adequate parameter extraction techniques

Research in organic TFTs

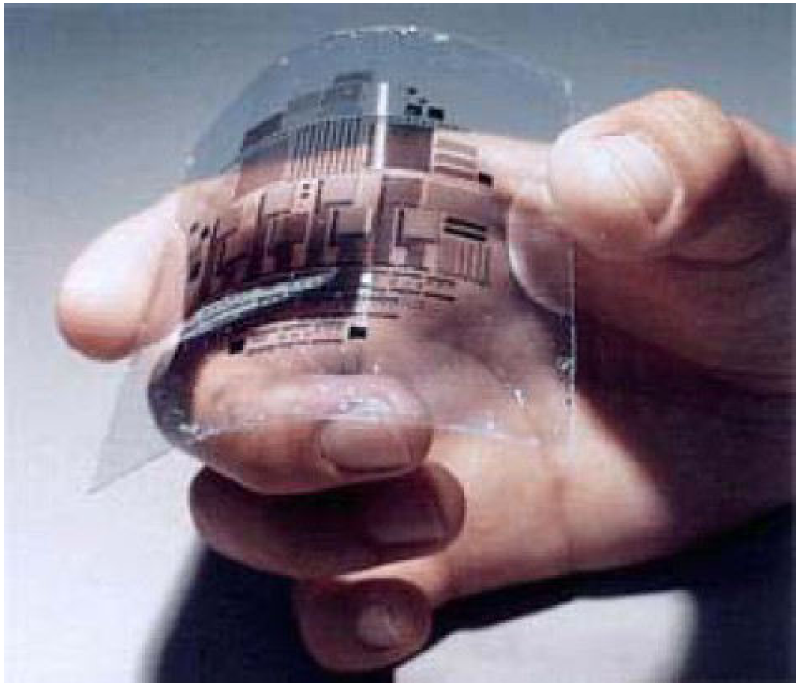
- Organic and polymer TFTs will probably become essential devices in niche applications, related to flexible or large ara electronics: electronic tags, drivers in AMLCDs, sensors
- Organic and polymer electronics allow flexible and low-cost substrates for large-area applications by relatively simple and low-temperature fabrication for disposable electronics





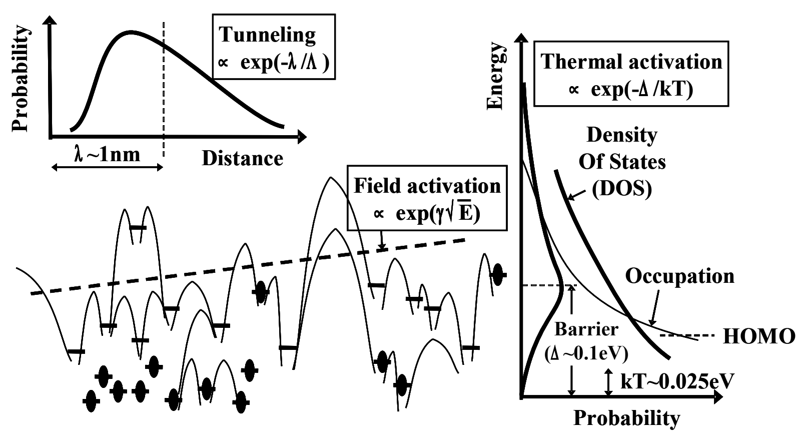
Research in organic TFTs

- **Some advantages**
  - Can be deposited on plastic even on paper.
  - Relatively simple deposition techniques.
  - Low deposition temperature.
- **Problems**
  - Low mobility.
  - Instability.

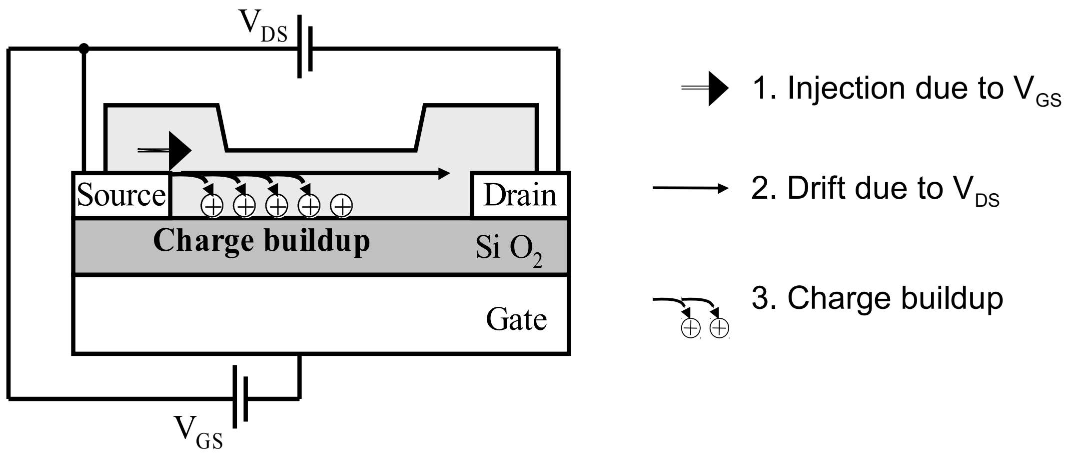


Open questions in organic TFT physics

- Gaussian density of state (DOS)
- States do not form continuous bands (HOMO and LUMO are approximations)
- Carriers localized in the organic film
- Hopping transport of localized carriers in the organic film



Open questions in organic TFT physics



Modeling approaches in organic TFTs

- 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

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

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

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

Modeling approaches in organic TFTs

- The analytical solution is only possible if the free charge density and the doping are neglected
- Transport occurs by means of hopping
- With these assumptions, well above threshold (linear regime), we obtain:

$$I_{DS} = \frac{W}{L} \cdot C_{diel} \frac{T}{2T_0} \mu_0 \cdot \left[\left(V_{GS} - V_{FB} \right)^{2T_0/T} - \left(V_{GS} - V_{DS} - V_{FB} \right)^{2T_0/T} \right]$$

- This expression has the same form as the current in a-Si:H TFT, although the assumed transport mechanism is different.
- It is equivalent to use a crystalline MOSFET model with a field-effect mobility:

$$\mu_{FET} = \mu_0 \left[\frac{\left(V_{GS} - V_{FB} \right)}{V_{aa}} \right]^{2T_0/T-2} = \mu_{FETo} \cdot \left(V_{GS} - V_{FB} \right)^{2T_0/T-2}$$

Modeling approaches in organic TFTs

- The expression of the drain current is obtained from:

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

- The expression for conductivity σ[δ(x),T] is obtained using percolation theory, where δ(x) is the carrier occupation for a given Fermi level
- The field-effect mobility is defined as:

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

Modeling approaches in organic TFTs

- The localized charge in the organic semiconductor in above threshold was considered to be much larger than the free charge, as it is done for inorganic amorphous TFTs in the subthreshold region:

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

$$\beta(T,To) = \frac{\sigma o}{\left[Bc\cdot\left(2\alpha_o\right)^3\right]^{\frac{To}{T}}}\cdot\left(\frac{k_b T}{\left(1-\frac{T}{To}\right)}\right)\cdot\left[\frac{\sin(\pi T/To)}{2\cdot k_b To}\right]^{\frac{To}{T}}\cdot\frac{\left(C_i\right)^{\left(\frac{2To}{T}-2\right)}}{\left(\varepsilon_S\right)^{\left(\frac{To}{T}-1\right)}}$$

- We can identify OTFT parameters with those of a-Si TFTs

Modeling approaches in organic TFTs

- In a-Si TFTs above threshold:

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

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

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

- Where an exponential DOS was assumed:

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

- *β(T,To)* turns to be equal to *P(T,To)*.

Modeling approaches in organic TFTs

- The field-effect mobility in organic TFTs can be related to the parameters of the exponential DOS:

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

$$\mu_{FET} = \frac{1}{\left(V_{aa}^{'}\right)^{\gamma}}\cdot\left(V_{GS}-V_{FB}\right)^{\gamma}$$

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

Modeling approaches in organic TFTs

- Our basic compact model writes the current expression in a more general way:

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

- where $V_{DSsat} = \alpha_S (V_{GS} - V_T)$ *R* is source plus drain resistance, I_0 is the leakage current and *m* and λ are adjustment parameters related to the sharpness of the knee region and to the channel length modulation respectively, and α_S is the non-ideal saturation parameter

$$\mu_{FET} = \mu_0 \left[\frac{(V_{GS} - V_T)}{V_{aa}}\right]^{\gamma} = \mu_{FETo} \cdot (V_{GS} - V_T)^{\gamma}$$

Modeling approaches in organic TFTs

- This model is valid in the above threshold regime with a smooth transition between the linear and the saturation regime.
- Simple parameter extraction techniques are possible.
- The integral operator is used to extract V_T and γ_a

$$H_a(V_{GS}) = \frac{\int_0^{V_{GS}} I_{ds}(x)dx}{I_{ds}(V_{GS})} = \frac{1}{2+\gamma}\left(V_{GS} - V_T\right)$$

Modeling approaches in organic TFTs

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.

Modeling approaches in organic TFTs

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}:

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

Modeling approaches in organic TFTs

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

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

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

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

Modeling approaches in organic TFTs

STEP 8: Model I-V characteristics using:

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

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

Modeling approaches in organic TFTs

STEP 8a:

$$m = \frac{\log 2}{\log\left[\dfrac{\dfrac{W}{L}\cdot C_i \cdot \left(\dfrac{\mu_o}{V_{AA}^{\gamma}}\right)\cdot \alpha_S \cdot \left(V_{DSsat1}\right)^{2+\gamma}}{I_{DSsat1}(V_{DSsat1})\cdot\left[1+R\dfrac{W}{L}\cdot C_i\cdot\left(\dfrac{\mu_o}{V_{AA}^{\gamma}}\right)\cdot\left(\dfrac{V_{Dsat1}}{\alpha_S}\right)^{1+\gamma}\right]}\right]}$$

m is calculated from this equation for $V_{DSsat1}=\alpha_S(V_{GS1}-V_T)$ at V_{GS1} equal or near V_{GSmax}, considering $\lambda=0$.

Modeling approaches in organic TFTs

STEP 8b:

$$\lambda = \frac{\left[\frac{I_{DS2}}{V_{DS2}^2}\right] \cdot \left[1 + R\frac{W}{L} \cdot C_i \cdot \left(\frac{\mu_o}{V_{AA}^\gamma}\right) \cdot (V_{GS1} - V_T)^{1+\gamma}\right] \cdot \left[1 + \left(\frac{V_{DS2}}{\alpha_s \cdot (V_{GS1} - V_T)}\right)^m\right]^{\frac{1}{m}}}{\frac{W}{L} \cdot C_i \cdot \left(\frac{\mu_o}{V_{AA}^\gamma}\right) \cdot (V_{GS1} - V_T)^{1+\gamma}} - \frac{1}{V_{DS2}}$$

λ is evaluated using the same expression, for the same value V_{GS1} and a value of V_{DS2} near the maximum value measured. I_{DS2} is the current measured at V_{DS2}.

Modeling approaches in organic TFTs

A. **For materials with high channel conductivity due to involuntary doping, e.g. Poly (3-hexyl thiophene), P3HT.**
   - Calculate the slope I_{DS} vd V_{DS} at $V_{GS}<V_T$ near V_{DSmax} ;
   - Substract the current due to this involuntary doping from measured curves;
   - Proceed with the extraction procedure for the corrected curves starting with STEP 1. After STEP 8, add the substracted current to obtain modeled device characteristics.

Modeling approaches in organic TFTs

A. Presence of non-linear contacts at drain and source.

$$V_{DSext} = V_{DS} + V_{diode} = \frac{I_{DS}}{G(V_{GS}, V_{DS})} + n \cdot \frac{k \cdot T}{q} \cdot \log\left(\frac{I_{DS}}{I_{do}}\right) =$$

$$= \frac{I_{DS}}{G(V_{GS}, V_{DSext}) \cdot \xi} + n \cdot \frac{k \cdot T}{q} \cdot \log\left(\frac{I_{DS}}{I_{do}}\right)$$

Where ξ is a fitting parameter accounting for the real voltage across the transistor, when the diode resistance is significant.

$$G(V_{GS}, V_{DSext}) = \frac{K\mu_{FET}(V_{GS}) \cdot (V_{GS} - V_T) \cdot (1 + \lambda \cdot V_{DSext})}{(1 + R \cdot \mu_{FET}(V_{GS}) \cdot (V_{GS} - V_T)) \cdot \left[1 + \left(\frac{V_{DSext}}{V_{DSsat}}\right)^m\right]^{1/m}}$$

Modeling approaches in organic TFTs

- Select a value of V_{DS1}=V_{DSext} outside the region affected by the non-linear contact;
- Proceed with steps 1 to 8a;
- Calculate diode parameters:
  1. **Select an output characteristic with $V_{GS}=V_{GS2}$ where the non-ohmic contact effect is clearly seen.**
  2. **Plot the curve log(I_{DS}) vs. V_{DSext} and determine the slope, *B*, and the intercept, *A*, of this curve near the origin.**
  3. **Calculate *n* and I_{do} as:**

$$n = \frac{\log e}{B \cdot \frac{k \cdot T}{q}} \qquad I_{do} = 10^{A}$$

Modeling approaches in organic TFTs

- Extraction of parameter ξ

The non-ohmic contact reduces I_{DS} at small bias, when the diode resistance is high.

As V_{DSext} is increased beyond the knee of the diode I-V curve, (near or after the maximum slope in the region of deformation), the applied voltage starts to fall mostly across the transistor. ξ is determined as:

$$\xi = \frac{\left[\left(\frac{I_{DS}(V_{GS2,},V_{DSext2})}{G1(V_{GS2})}\right) - \left(\frac{I_{DS}(V_{GS2,},V_{DSext1})}{G1(V_{GS2})}\right)\right]}{\left[V_{DS2} - V_{DS1}\right]}$$

V_{DSext2} and V_{DSext1} define an approximately linear region of I_{DS} *vs.* V_{DSext}, containing the maximum slope of this curve.

V_{DS2}, (V_{DS1}) are determined substituting *n*, I_{do}, V_{DSext2} , (V_{DSext2}) and their corresponding I_{DS2}, (I_{DS1}) in the expression for I_{DS} *vs.* V_{DSext}.

$G1(V_{GS2})$ is the conductance in the linear region for $V_{GS}=V_{GS2}$:

Modeling approaches in organic TFTs

- Step 9, calculate λ from:

$$V_{DSext} = \frac{I_{DS}}{\dfrac{\dfrac{W}{L}\cdot C_i \mu_{FET}(V_{GS})\cdot(V_{GS}-V_T)\cdot(1+\lambda\cdot V_{DSext})}{\left(1+R\cdot\mu_{FET}(V_{GS})\cdot(V_{GS}-V_T)\cdot\left[1+\left(\dfrac{V_{DSext}}{V_{DSsat}}\right)^m\right]\right)^{1/m}}\cdot\xi} + n\cdot\frac{k\cdot T}{q}\cdot\log\left(\frac{I_{DS}}{I_{do}}\right)$$

Modeling approaches in organic TFTs

A. Presence of localized states:

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

For OTFTs, in all the operating regimes, $Q_{loc} >> Q_{free}$ and Poisson´s equation has analytical solution for the electric field, and the induced sheet charge in the channel, obtaining the drain current as:

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

Where μ_{FET} is:

$$\mu_{FET}(V_{GS}, T, To, g_{do}) = \mu_0 \cdot q \cdot k_b \cdot T \cdot N_V \cdot \varepsilon_s \cdot \left[\frac{\sin(\pi T / To)}{2 \cdot \pi \cdot q \cdot \varepsilon_S \cdot k_b T \cdot k_b To \cdot g_{do}}\right]^{\frac{To}{T}} \cdot [C_i]^{\left(\frac{2To}{T} - 2\right)} \cdot (V_{GS} - V_T)^{\left(\frac{2To}{T} - 2\right)}$$

Modeling approaches in organic TFTs

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

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

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

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

Modeling approaches in organic TFTs

After step 8a, proceed with:

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

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

1. Calculate g_{do} as:

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

Modeling approaches in organic TFTs

- Therefore, the fundamental model parameters have a clear technological meaning, and can be introduced in numerical 2D device simulators such as ATLAS (Silvaco), which considers an exponential DOS which depends on T_0 and g_{d0}
- The model has been applied to both oligomeric and polymeric TFTs

Charge modeling in OTFTs

The mobile charge of free electrons in the mobility band dependent on a potential V applied along the channel may be found by:

$$Q_{mob} = \frac{Ci(V_{GT} - V)^{1+\gamma}}{Vaa^{\gamma}}$$

Therefore, from:

$$I_D = W \cdot \mu_0 \cdot Q_{mob} \frac{dV}{dx}$$

$$dx = \frac{W * \mu_0 * Q_{mob}}{I_D} dV$$

Integrating:

$$I_D = \frac{-WC_i}{L}\left(\frac{\mu_0}{Vaa^{\gamma}}\right)\frac{\left[(V_{GT} - V_{DSe})^{2+\gamma} - V_{GT}{}^{2+\gamma}\right]\cdot\left[1 + \lambda V_{DSe}\right]}{(2+\gamma)}$$

Charge modeling in OTFTs

By definition, the total <u>accumulated</u> charge at the channel Q_{CH} is expressed by:

$$Q_{CH} = W\int_0^L C_i\left(V_{GS} - V_T - V\right)dx$$

Therefore:

$$Q_{CH} = W\int_0^{V_{DS}} C_i\left(V_{GS} - V_T - V\right)\frac{W\mu_0 Q_{mob}}{I_D}dV$$

$$Q_G = -Q_{CH} = WLC_i\frac{(2+\gamma)}{(3+\gamma)}\frac{\left[\left(V_{GT} - V_{DSe}\right)^{3+\gamma} - V_{GT}{}^{3+\gamma}\right]}{\left[\left(V_{GT} - V_{DSe}\right)^{2+\gamma} - V_{GT}{}^{2+\gamma}\right]}$$

And, from Ward's partitioning scheme:

$$Q_D = \frac{W}{L}\int_0^L x\cdot(-Q_G)dx = \frac{WLC_i(2+\gamma)}{\left[\left(V_{GT} - V_{DSe}\right)^{2+\gamma} - V_{GT}{}^{2+\gamma}\right]}\cdot$$

$$\left[\frac{\left[\left(V_{GT} - V_{DSe}\right)^{5+2\gamma} - V_{GT}{}^{5+2\gamma}\right]}{(5+2\gamma)} - \frac{V_{GT}{}^{2+\gamma}\left[\left(V_{GT} - V_{DSe}\right)^{3+\gamma} - V_{GT}{}^{3+\gamma}\right]}{(3+\gamma)}\right]$$

$$Q_S = Q_{CH} - Q_D$$

Charge modeling in OTFTs

The nonreciprocal capacitances are defined as:

$$C_{ij} = -\frac{\partial Q_i}{\partial V_j} \qquad i \neq j$$

$$C_{ij} = \frac{\partial Q_i}{\partial V_j} \qquad i = j$$

Besides, we can apply:

$$C_{GG} = C_{GS} + C_{GD} = C_{SG} + C_{DG}$$
$$C_{DD} = C_{DS} + C_{DG} = C_{SD} + C_{GD}$$
$$C_{SS} = C_{SG} + C_{SD} = C_{GS} + C_{DS}$$

Only four capacitances are independent to the others: C_{GG}, C_{GD}, C_{DD} and C_{DG}.

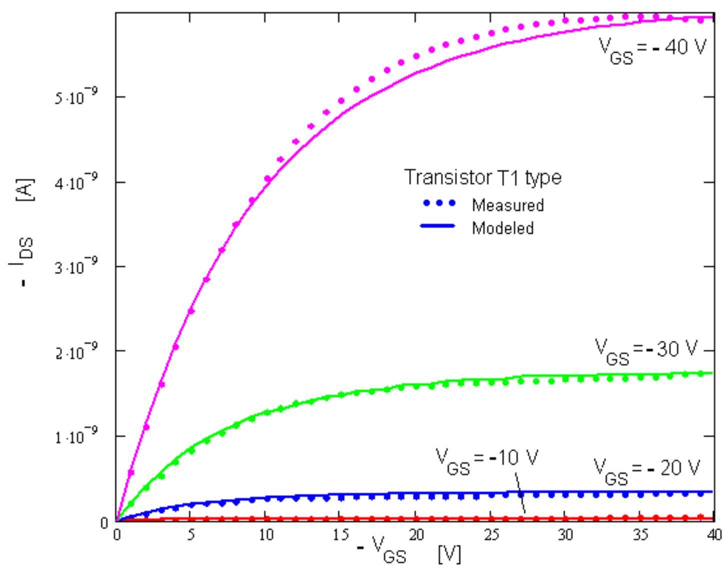
Results

Different pentacene OTFTs
have been
analyzed and modeled

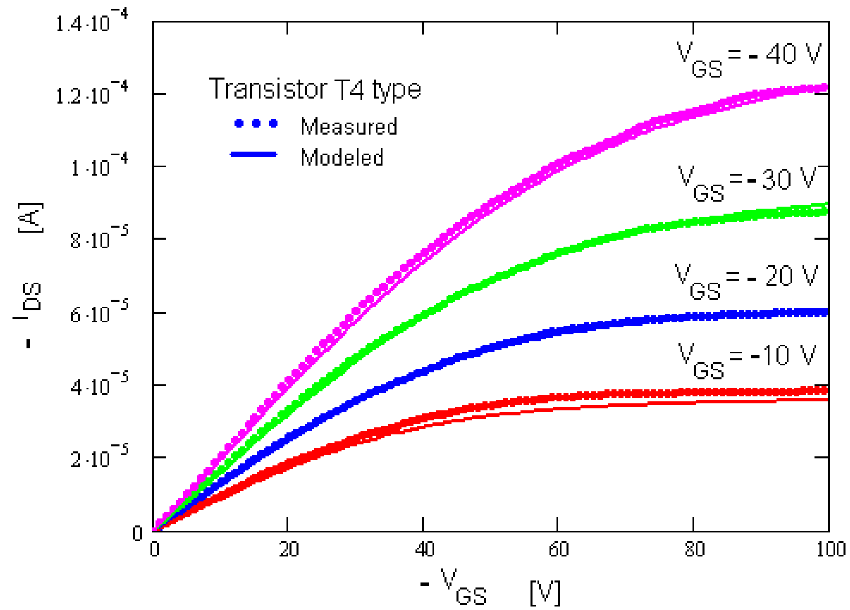
T1: from UPC
T2, T3: from Infineon
T4: form PSU

Transistor	Pentacene layer [nm]	Dielectric gate Type	Dielectric gate [nm]	W [µm]	L [µm]
T1	160	PMMA	700	600	120
T2	30	PVP	100	500	50
T3	30	PVP	120	50	5
T4	50	SiO_2	400	220	20

Results

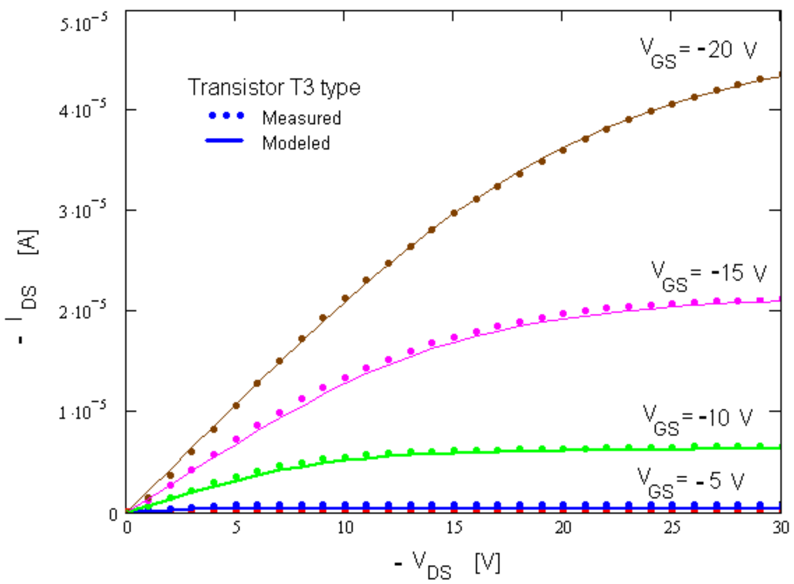


Transistor T1 type
Measured
Modeled
V_{GS} = - 40 V
V_{GS} =- 30 V
V_{GS} = -10 V
V_{GS} = - 20 V
- I_{DS} [A]
- V_{GS} [V]

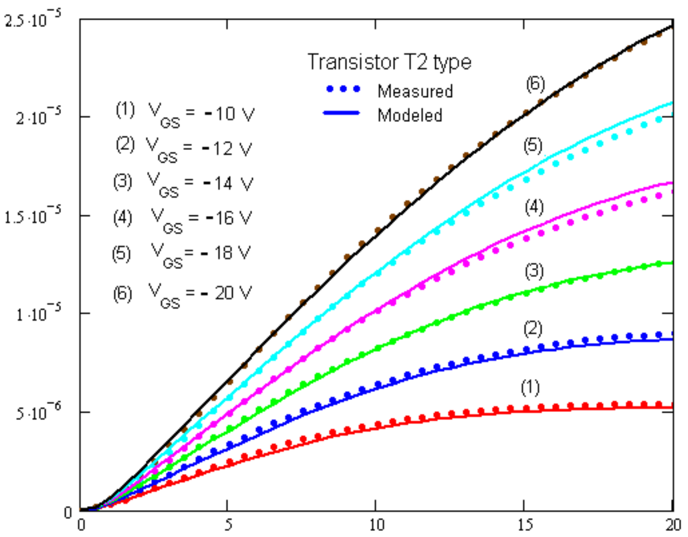


Transistor T4 type
Measured
Modeled
V_{GS} = - 40 V
V_{GS} = - 30 V
V_{GS} = - 20 V
V_{GS} = -10 V
- I_{DS} [A]
- V_{GS} [V]

Results



Transistor T3 type
Measured
Modeled
V_{GS} = -20 V
V_{GS} = -15 V
V_{GS} = -10 V
V_{GS} = - 5 V
- I_{DS} [A]
- V_{DS} [V]



Transistor T2 type
Measured
Modeled
(1) V_{GS} = -10 V
(2) V_{GS} = -12 V
(3) V_{GS} = -14 V
(4) V_{GS} = -16 V
(5) V_{GS} = - 18 V
(6) V_{GS} = - 20 V

Results

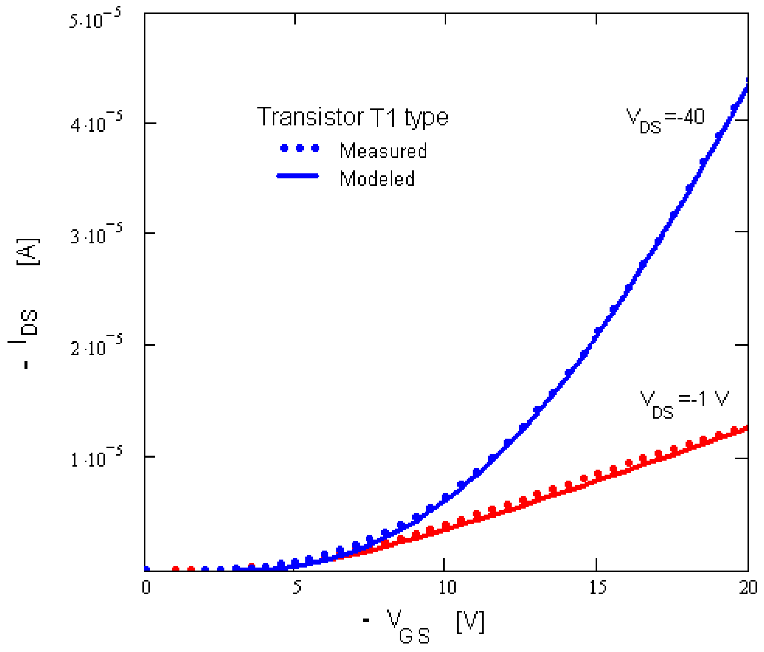
	T1	T2	T3	T4
Voltage range Linear region	-(35-39)	-(8-11)	-(10-20)	-(60-100)
Voltage range Saturation region	-(38-40)	-(8-11)	-(15-20)	-(80-100)
Output charact. V_{GS} [V]	-40	-14	-20	-40
V_T [V]	-4.1	-2.6	-3.9	+12.3
γ	1.9	0.6	0.15	-0.072
Vaa [V]	$1.7x10^{3}$	106	$1.4x10^{3}$	$1.7x10^{-4}$
μ_{FET0}	$7.4x10^{-7}$	0.058	0.52	0.7
R [Ω]	$1.1x10^{7}$	$2x10^{5}$	$1.4x10^{4}$	0
αs	0.39	1.7	1.4	0.935
m	1.27	2.8	2.97	2.8
λ [1/V]	$-3.5x10^{-3}$	$-1.1x10^{-2}$	$9.6x10^{-5}$	$-2x10^{-4}$

Results

- Exponent γ_a is in most cases larger than 0, which leads to a super-linear increase of I_{DS} with V_{GS}
- For T4 $\gamma < 0$. The device seems to be polycristalline and is affected by mobility degradation
- Agreement is good in the linear and saturation regimes

Results

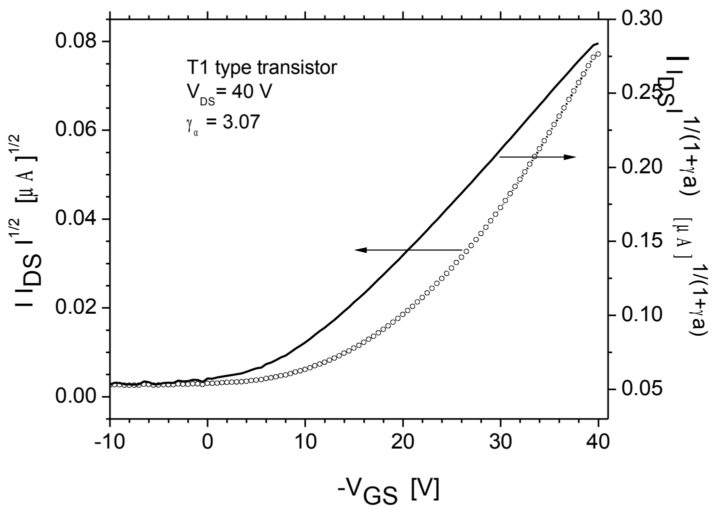
- Transfer characteristics



Results

- Threshold voltage extraction from the $I_{ds}^{½}$ vs V_{GS} plot in saturation, as in crystalline MOSFETs, may lead to wrong values when applied to organic TFTs, since it ignores bias dependence of the field-effect mobility.

- The integral method takes into account the bias dependence of the field-effect mobility.



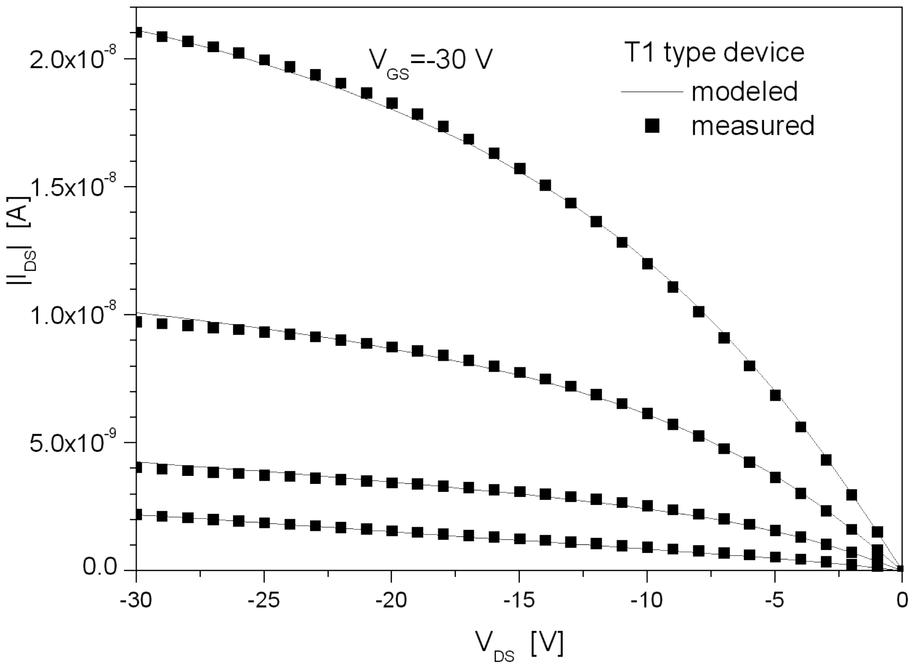
Results

Transistor type	Active layer		Dielectric		W [μm]	L [μm]	Ref.
	Material	Xc [nm]	Material	Xi [nm]			
T1 top gate (Au) bottom contact (Au)	P3HT	80	PMMA	320	150	50	**CINVE STAV**
T2 bottom gate (Si) top contact (Au)	P3HDT	38	SiO_2	200	15000	10	McMas ter
T2A bottom gate (Si) top contact (Au)	P3HDT	17	SiO_2	200	15000	10	McMas ter
T3 bottom gate (Si) top contact (Au)	P3DDT	38	SiO_2	200	15000	10	McMas ter
T3A bottom gate (Si) top contact (Au)	P3DDT	17	SiO_2	200	15000	10	McMas ter
T4 bottom gate (Si) top contact (Au)	Pentacene	30	PVP	280	170	130	Infineo n
T5 bottom gate (Si) top contact (Au)	Pentacene	30	PVP	120	500	50	Infineo n
T6 bottom gate (Si) bottom contact (Au)	Dec-6T-dec	30	PPV	270	20	20	Infineo n

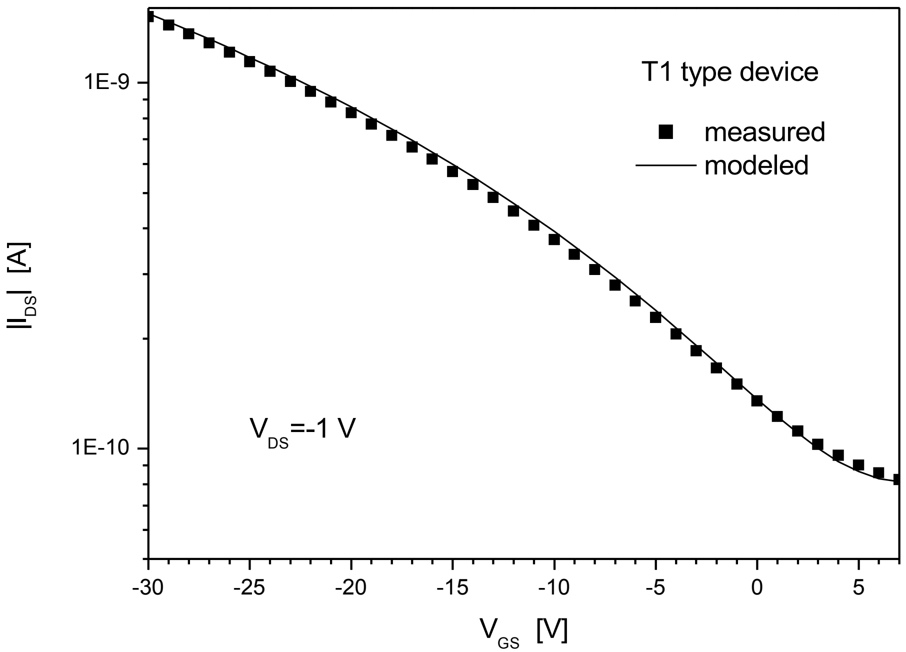
Results

	T1 P3HT	T2 P3HDT	T2A P3HDT	T3 P3DDT	T3A P3DDT	T4 Penta-cene	T5 Penta-cene	T6 Dec-6T-dec
γ	1	0.3	0.25	1.8	1.8	0.58	0.15	1.5
To [K]	445	353	337	567	563	386	322	524
g_{do} [cm^{-3}/eV]	$1.5x10^{23}$	$1x10^{24}$	$1.47x10^{24}$	$2.3x10^{23}$	$2.6x10^{23}$	$1x10^{21}$	$4x10^{21}$	$2x10^{21}$
μ_{FET1} [cm^2/Vs]	$5x10^{-5}$	$3x10^{-4}$	$3.9x10^{-4}$	$2x10^{-7}$	$3.5x10^{-7}$	0.43	0.34	$3.6x10^{-3}$
μ_{FET}(-30) [cm^2/Vs]	$1.5x10^{-3}$	$7.5x10^{-4}$	$7.5x10^{-4}$	$8x10^{-5}$	$6x10^{-5}$	2.87	0.56	0.7
R [Ω]	$\approx 10^7$	$5x10^4$	$5x10^4$	$\approx 10^6$	10^6	10^5	$1x10^4$	$6x10^4$
α	0.43	0.64	0.66	0.5	0.34	1	1.5	1.1
m	1.7	1.7	1.7	1.5	2.3	2.5	2.5	2.4
λ [1/V]	$-1.4x10^{-4}$	$-3.5x10^{-3}$	$-3.1x10^{-3}$	$-2x10^{-3}$	$3x10^{-3}$	$1.3x10^{-3}$	$-3x10^{-4}$	$4x10^{-4}$

Results

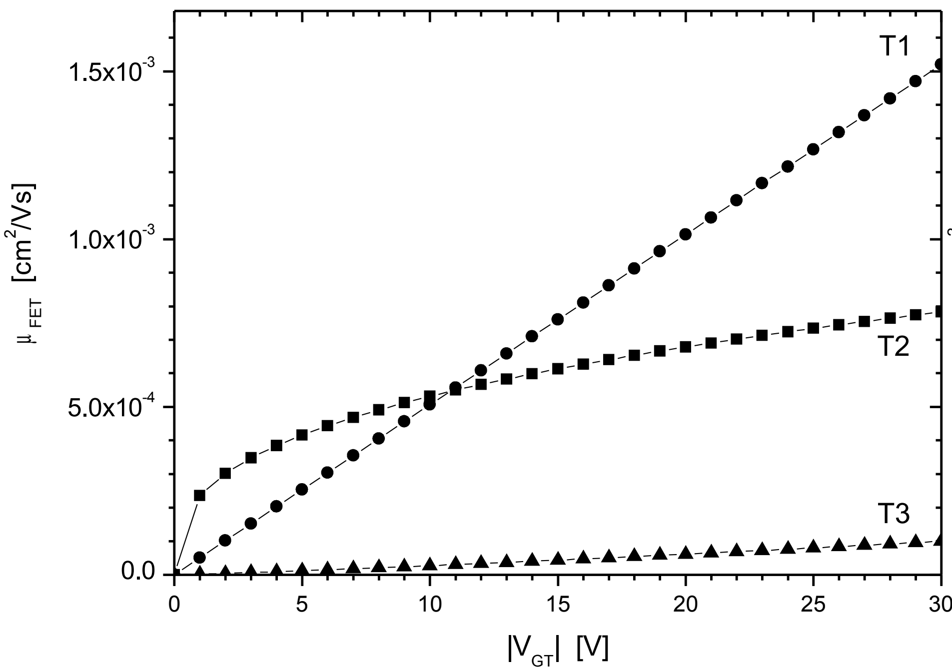


V_{GS}=-30 V
T1 type device
modeled
measured
2.0x10^-8
1.5x10^-8
1.0x10^-8
5.0x10^-9
0.0
$|I_{DS}|$ [A]
-30
-25
-20
-15
-10
-5
0
V_{DS} [V]

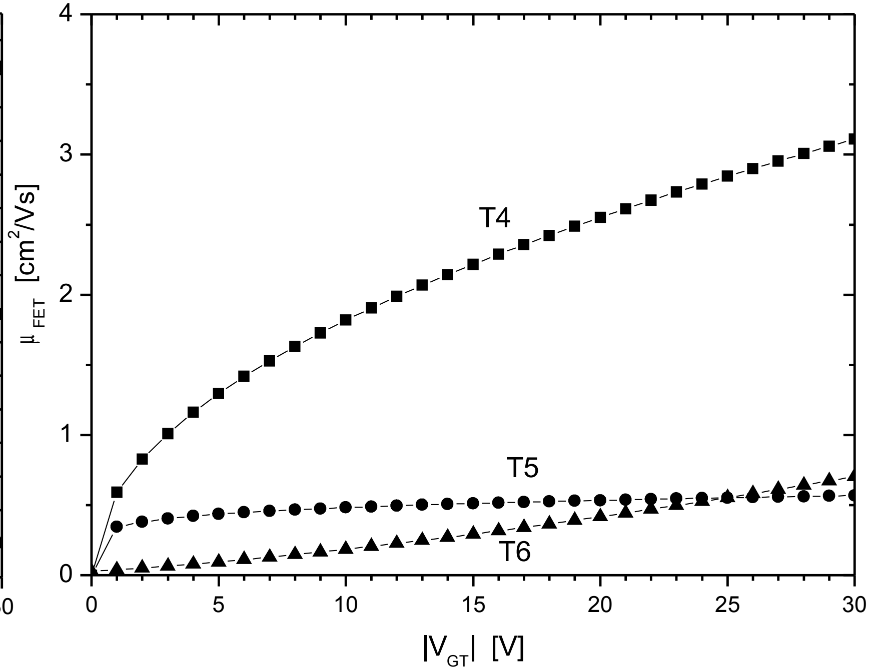


T1 type device
measured
modeled
V_{DS}=-1 V
1E-9
1E-10
$|I_{DS}|$ [A]
-30
-25
-20
-15
-10
-5
0
5
V_{GS} [V]

Results

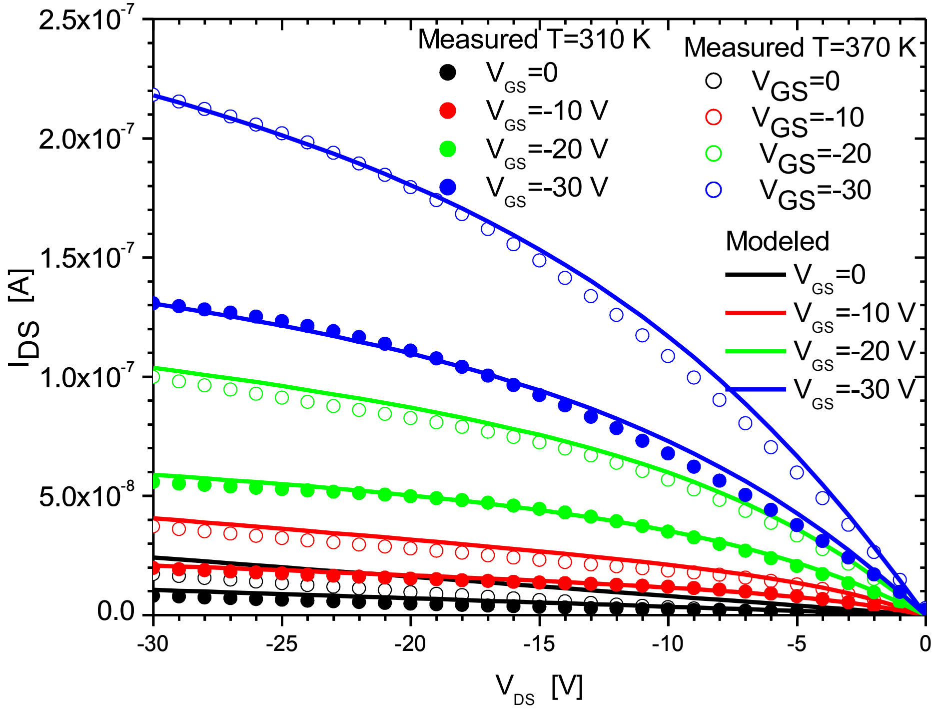


T1
T2
T3
1.5x10-3
1.0x10-3
5.0x10-4
0.0
μ FET [cm2/Vs]
0
5
10
15
20
25
30
|VGT| [V]



T4
T5
T6
4
3
2
1
0
μ FET [cm2/Vs]
0
5
10
15
20
25
30
|VGT| [V]

Results



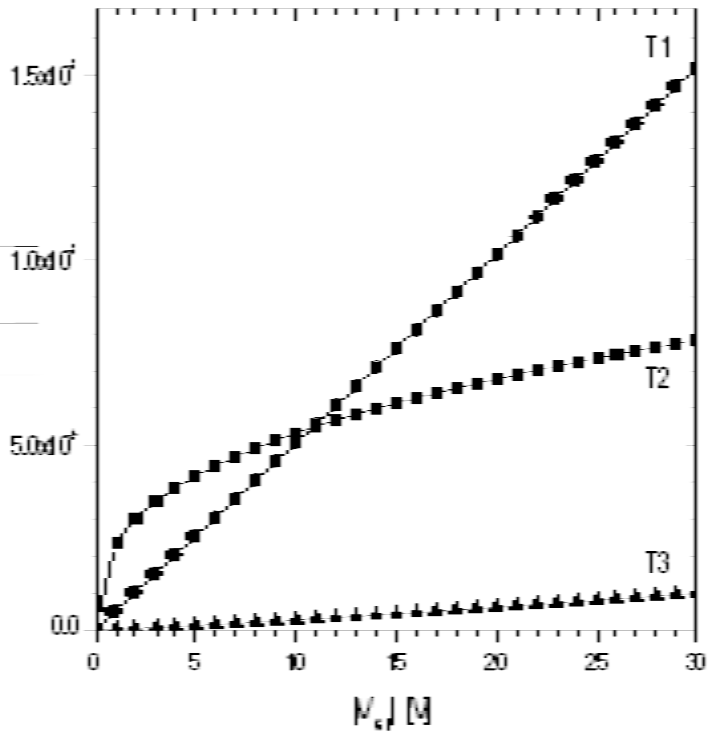
Comparison of modeled and measured at T=310 and 370 K

Results

Model Param.	Temperature [K]							
	300	**310**	**320**	**330**	**340**	**350**	**360**	**370**
γ	0.67	0.67	0.64	0.63	0.64	0.62	0.58	0.51
μ_{FET1} [cm²/Vs]	$3.9\ x10^{-4}$	$4.2x10^{-4}$	$5.3x10^{-4}$	$5.6x10^{-4}$	$5.9x10^{-4}$	$6.9x10^{-4}$	$8.5x10^{-4}$	$1.1x10^{-3}$
$\mu_{FET(-30)}$ [cm²/Vs]	$3.9x10^{-3}$	$4.3x10^{-3}$	$4.7x10^{-3}$	$5.1x10^{-3}$	$5.5x10^{-3}$	$5.8x10^{-3}$	$6.3x10^{-3}$	$6.6x10^{-3}$
***To* [K]**	401	414	421	434	448	458	463	464
g_{do} [cm⁻³/eV]	$1.2\ x10^{23}$	$1.1\ 10^{23}$	$1.\ x10^{23}$	$1.\ x10^{23}$	$9\ x10^{22}$	$8.5x10^{22}$	$8.6x10^{22}$	$9\ x10^{22}$

Results

Analysis of the effect of To



[*] M. Estrada et al., 52 (2008) 787-794.

At low V_{GS}:

To_{T1}=445 K is greater than *To_{T2}=353 K;*

so $\mu_{FETT2} > \mu_{FETT1.}$ and γ_{T1}= 1 > γ_{T2}=0.3;

As **V_{GS} increases**

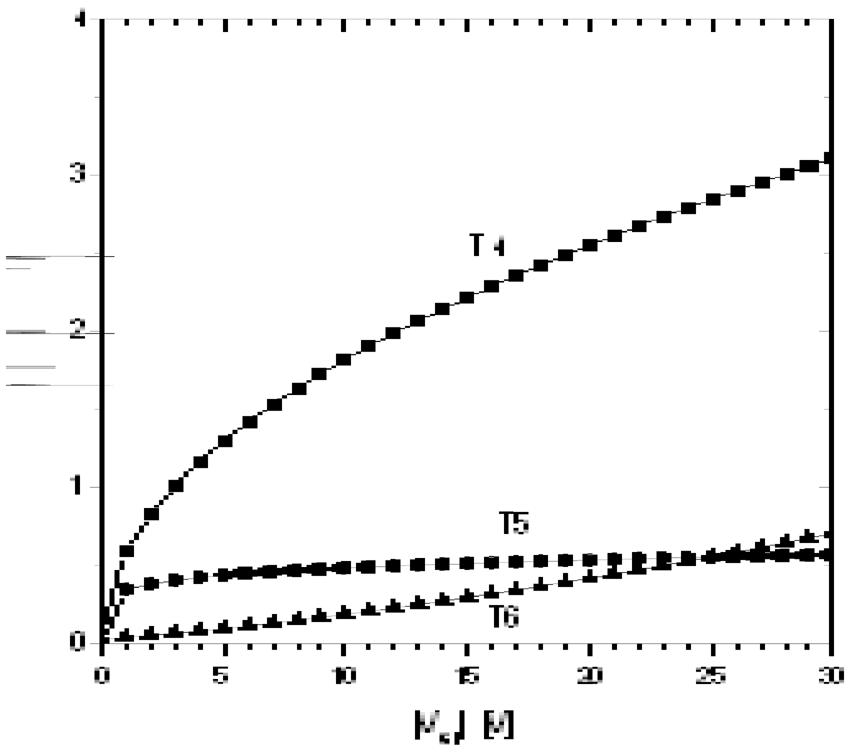
$\mu_{FET}(V_{GS})_{T1}$ increases more rapidly than $\mu_{FET}(V_{GS})_{T2}$; at V_{GS}>13 V, $\mu_{FETT1}> \mu_{FETT2}$.

This behavior can give the wrong idea that increasing *To* will provide higher mobility at high gate voltage.

However, as *To* increases, mobility at low V_{GS} is so small, that even with high γ it will remain very small in all the operating voltage range, see T3 where *To_{T3}*=567 K.

Results

PTFTs made of the same material can behave quite different.



To_{T4}=383 K gdo_{T4}= 1x10^{21} cm^{-3}/eV so γ_{T4}=0.58 .

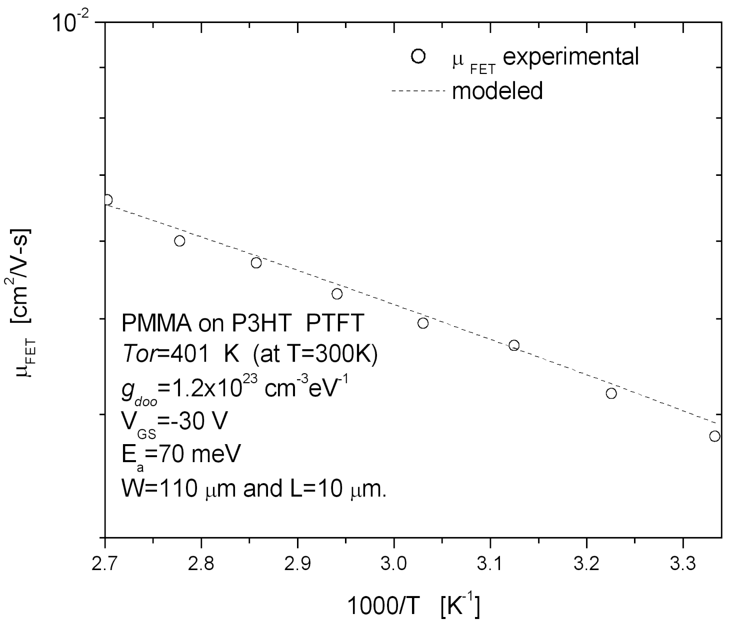
To_{T4}=322K gdo_{T4}= 4x10^{21} cm^{-3}/eV so γ_{T5}=0.15.

The combination of high γ and low *gdo* provides significant values of μ_{FET}.

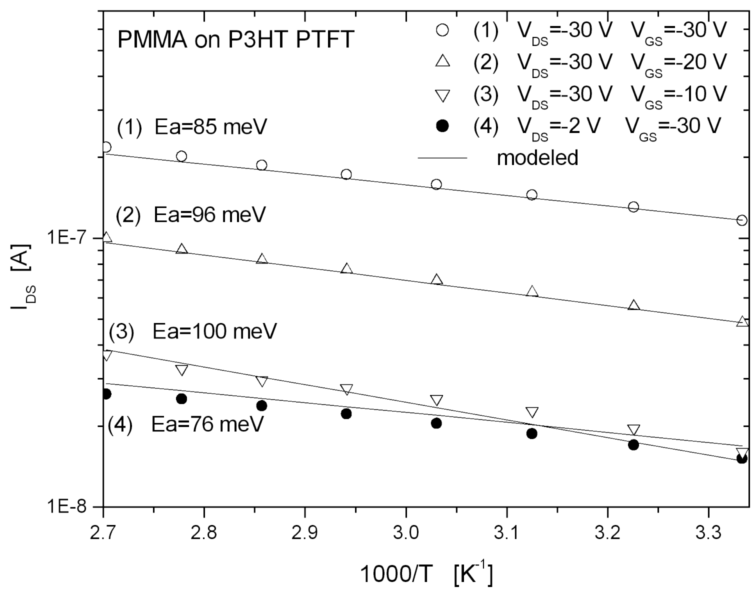
At V_{GS}=*-30 V*
μ_{FETT4}= 2.9 cm^2/V-s
compared to
μ_{FETT5}= 0.54 cm^2/Vs

[*] M. Estrada et all, “Mobility model for compact device modeling of OTFTs made with different materials”, SSE 52 (2008) 787-794.

Results

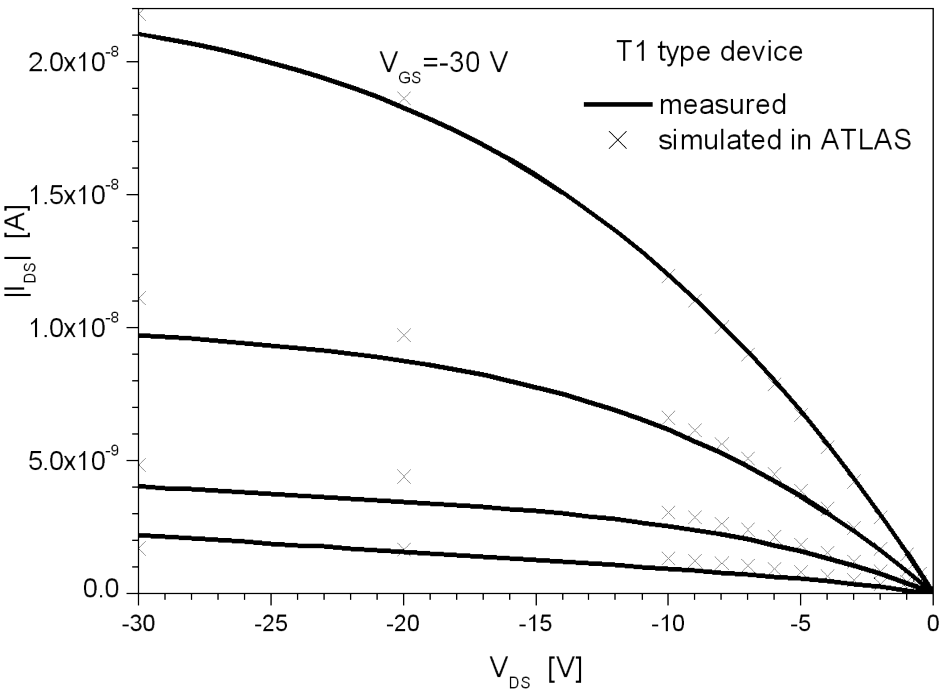


10^{-2}
μ_{FET} experimental
modeled
μ_{FET} [cm^2/V-s]
PMMA on P3HT PTFT
Tor=401 K (at T=300K)
g_{doo}=1.2x10^{23} cm^{-3}eV^{-1}
V_{GS}=-30 V
E_a=70 meV
W=110 μm and L=10 μm.
2.7 2.8 2.9 3.0 3.1 3.2 3.3
1000/T [K^{-1}]



PMMA on P3HT PTFT
(1) V_{DS}=-30 V V_{GS}=-30 V
(2) V_{DS}=-30 V V_{GS}=-20 V
(3) V_{DS}=-30 V V_{GS}=-10 V
(4) V_{DS}=-2 V V_{GS}=-30 V
modeled
(1) Ea=85 meV
(2) Ea=96 meV
(3) Ea=100 meV
(4) Ea=76 meV
I_{DS} [A]
1E-7
1E-8
2.7 2.8 2.9 3.0 3.1 3.2 3.3
1000/T [K^{-1}]

Results

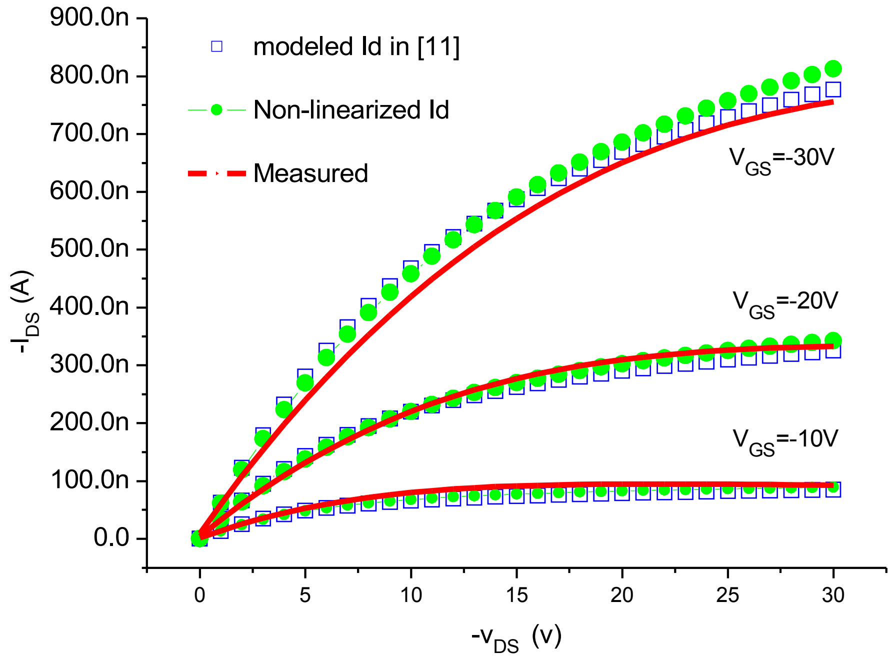


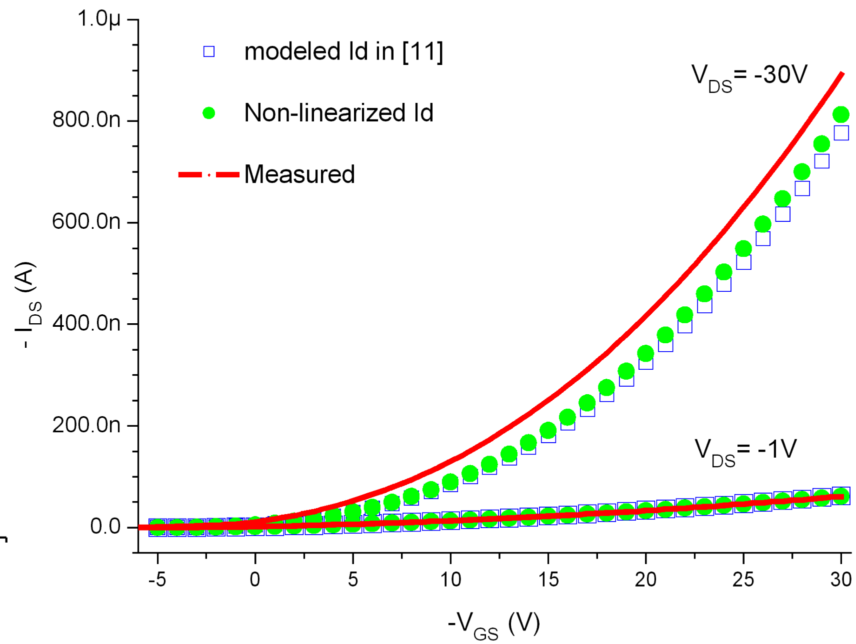
The extracted model parameters of the exponential DOS where introduced in ATLAS

Excellent agreement observed

ATLAS can reproduce the OTFT behaviour with an exponential DOS by extracting the parameters of the compact model

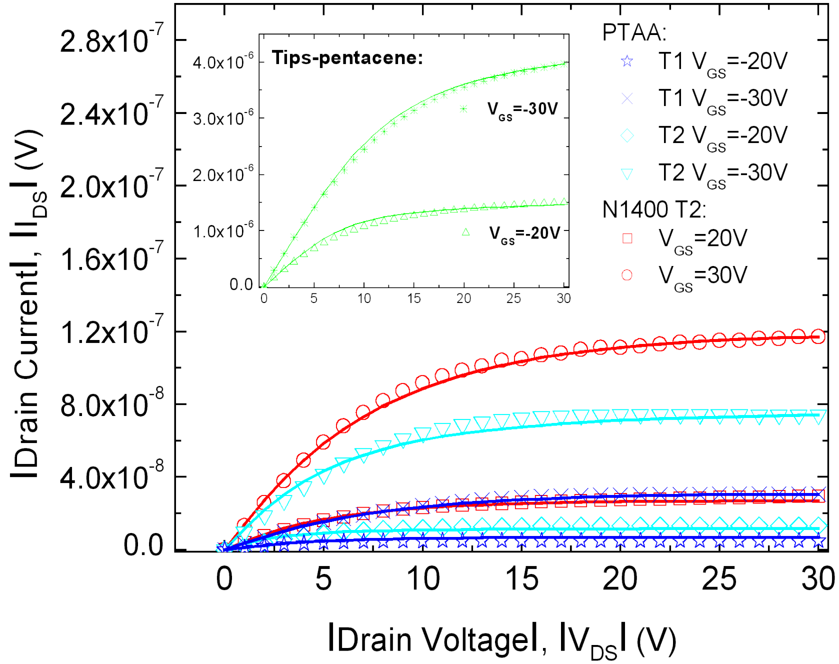
Results





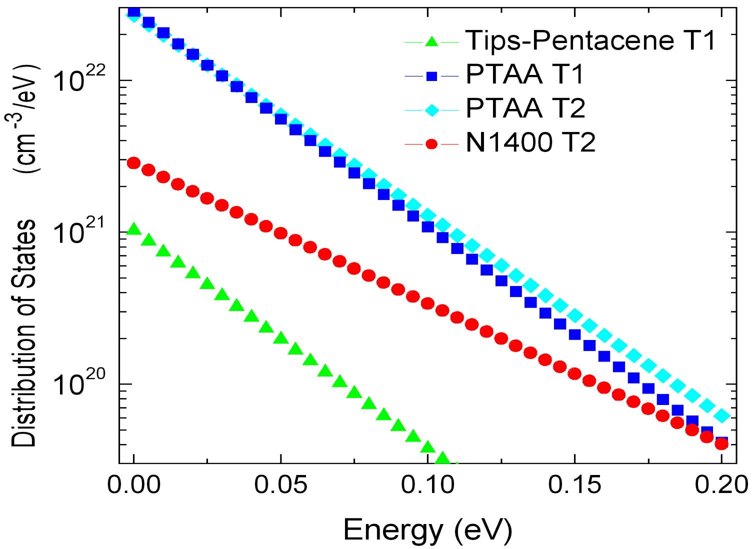
Transfer characteristics for upper contact PMMA /P3HT TFT

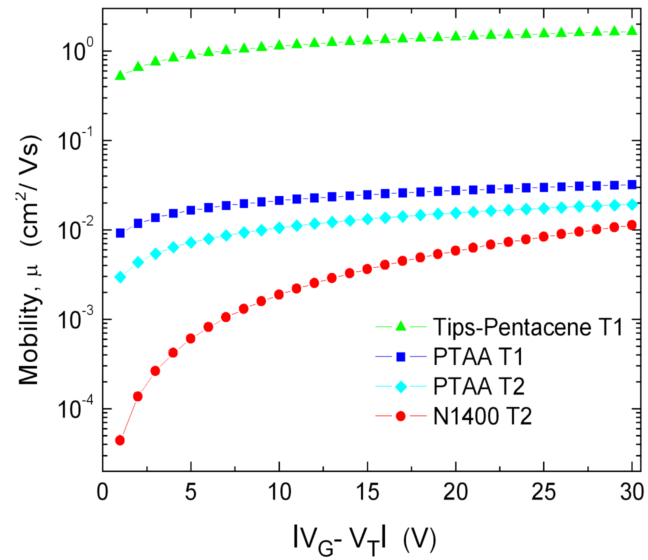
Results



Experimental (symbols) and modeled (straight lines) output characteristics at lV_{GS}l=20 V and 30 V. Devices fabricated by CEA-LITEN

Results



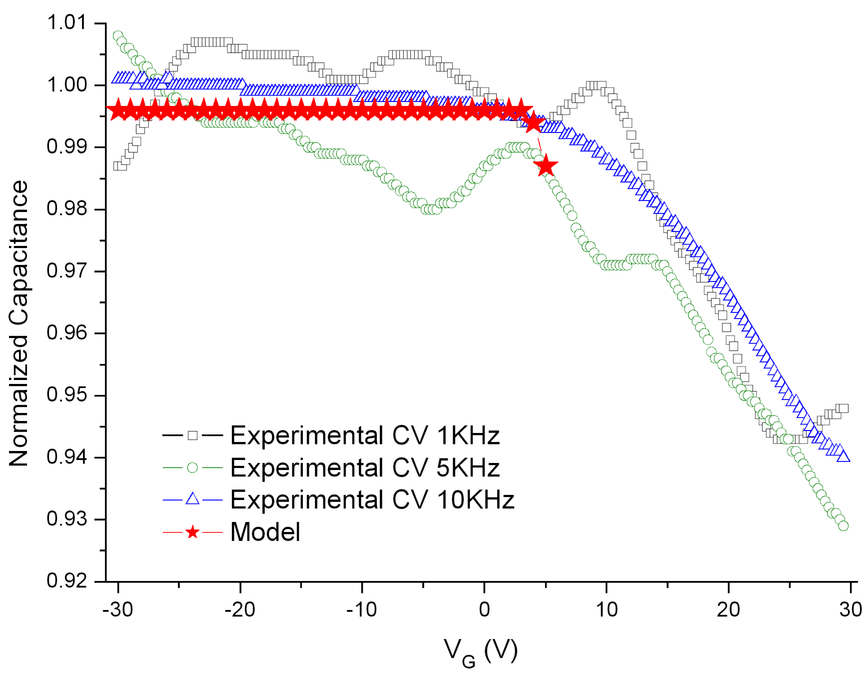


TIPS-Pentacene has the highest mobility, and suggests the carrier transport is given by free charge rather than localized

N1400 has similar DOS, but 2 order lower mobility, and suggests the transport is dominated by hopping through localized states at low VGT

T1 and T2 PTAA has hopping and free charge conduction

Results



Experimental capacitance measurements of PMMA / P3HT capacitors at different frequencies compared to the modeled C_{gg} capacitance with V_{DS}≈0V and $V_{GS} > V_{FB}$

Conclusions

- We presented a compact modelling framework for organic TFTs, valid at different temperatures
- This modelling has a physical basis and allows an easy parameter extraction
- This model has been the basis of the UOTFT model, implemented in the commercial version of SmartSpice (SIMUCAD, Silvaco)
- The model parameters have a technological meaning and can be introduced in a numerical 2D device simulator such as ATLAS