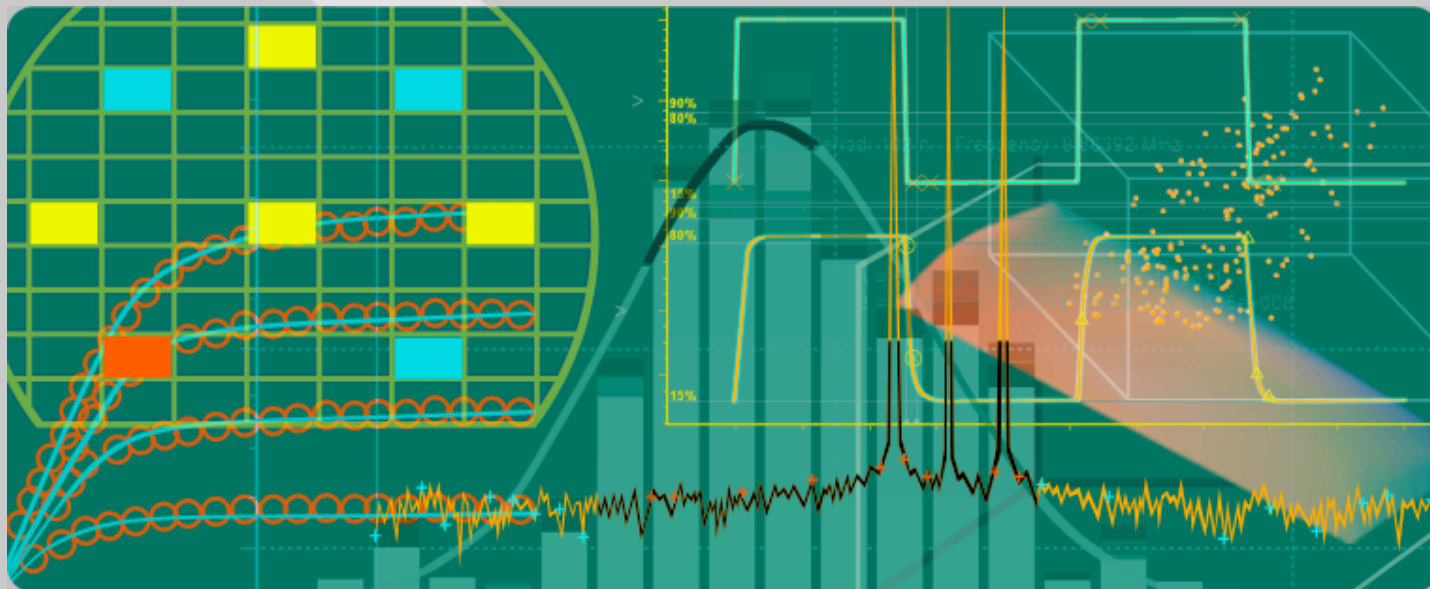


UOTFT: Universal Organic TFT Model for Circuit Design



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Overview

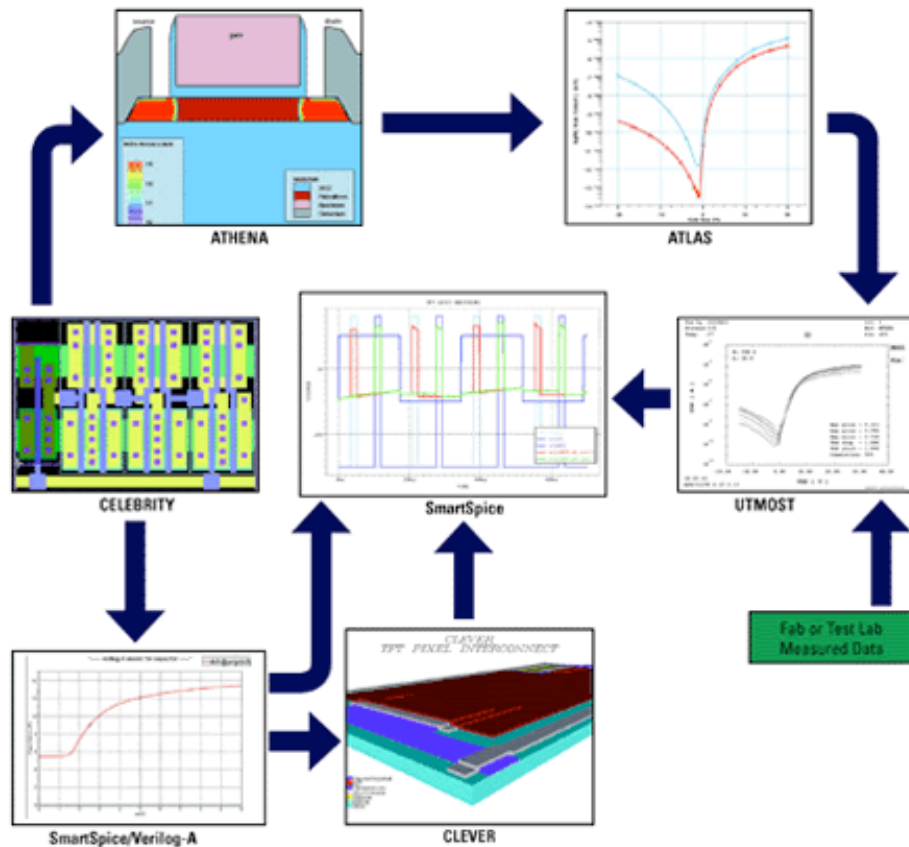
- Introduction
 - organic electronics as a challenge for EDA
 - TSB Project PMOS
- UOTFT Model Description
 - objectives and close relatives
 - model features
 - physics behind the model
 - UCCM for OTFTs
 - intrinsic drain-source current
- Model verification
 - DC characteristic and temperature scaling for different OSC materials and device architectures

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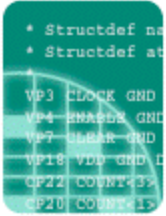
* Structdef na
* Structdef at
VP3 CLOCK GND
VP4 SHARED GND
VP7 BLANK GND
VP18 VDD GND
CP22 COUNT433
CP20 COUNT433

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Organic Electronics: Challenge for Electronic Design Automation (EDA)



- Inorganic semiconductor industry relies extensively on EDA software to support the iterative cycles of process, device and circuit technology improvements.
- To further develop organic electronics industry, equivalent design tools are needed.
- EDA tools essentially depend on numerical and compact device models which are, in case of OSCs, not yet matured and quite sparsely implemented in commercial EDA tools.
- Cambridge Display Technology (CDT) and Silvaco Europe have joined forces in a TSB funded project entitled PMOS to enhance EDA tools for use in the organic electronics.



UK Technology Strategy Board (TSB) Project: *Physical Modelling of Organic Semiconductors (PMOS)*

Project partners

- **Cambridge Display Technology (CDT)**
 - Expert in polymer light emitting diode (PLED) technologies.
 - Leader in development of solution processable (printable) organic semiconductors for display fabrication.
 - Expertise in development of PLED materials and deposition processes.
- **Silvaco**
 - Leading provider of TCAD and EDA software for IC design
 - Provides established products for TCAD process and device simulation, spice modelling and parameter extraction, circuit simulation, custom IC design and verification.

Project activities

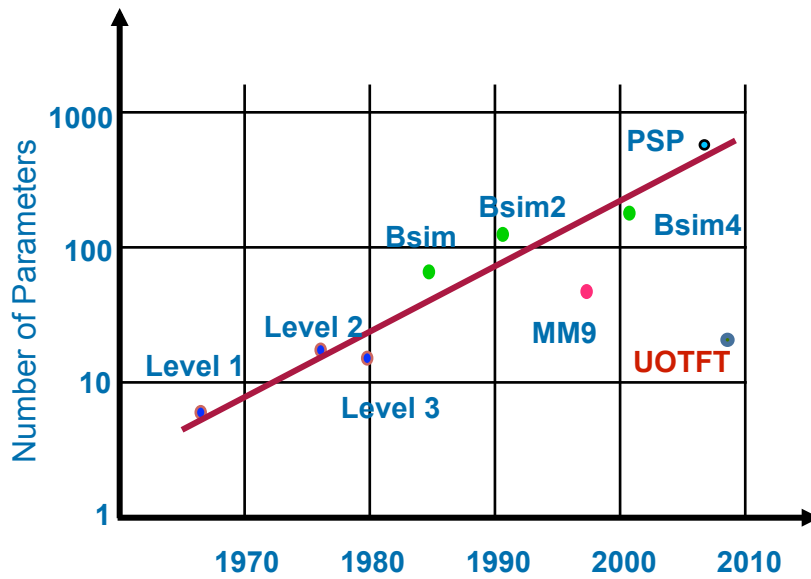
- Design of OTFT devices using physical TCAD modelling.
- OTFT spice model development
- Measurements and modelling of device reliability and aging effects.
- The focus is on display device (OLED) drivers as these will be the first large scale organic semiconductor products.



UOTFT Model: *Objectives and Close Relatives*

Objectives:

- physical (charge or surface potential based)
- compact model dedicated to OTFTs
- small number of ease to extract parameters
- compatible to simple Vth-based OTFT models in over-threshold region
- suitable for different OSC materials and OTFT device architectures



Universal FET Modelling Approach

Prof. Michael Shur et al.

Prof. Benjamin Iñiguez et al.

MOSA1, NPMOSA1-3, etc.

Silicon Mosfets, Hfet, Mesfet

AIM-Spice

RPI Thin-Film Transistor Models

Amorphous and Polysilicon TFTs

AIM-Spice, Spectre, Hspice, SmartSpice

UOTFT

Organic TFTs

SmartSpice



UOTFT Model Features:

Original (Checked) and Common with RPI (Dots) Model Features

Intrinsic Model:

- ✓an accurate implementation of the UCCM for OTFTs operating in the channel accumulation mode in the presence of the exponential density of states and interface traps.
- ✓a universal power mobility law valid in all operation regions
- ✓the smooth interpolation of the drain current between linear and saturation operation regions including the channel length modulation effect
- ✓physical description of the drift and diffusion drain-source current components
- ✓implicit non-linear gate bias dependent parasitic resistance model
- drain-source leakage current model (RPI)
- a unified Meyer's capacitance model (RPI)
- Leroux's charge model (extended RPI in SmartSpice)
- ✓a physical temperature scaling of the model parameters

Extrinsic Model:

- ✓explicit source and drain contact series resistances
- ✓a thermal network for the modeling of self-heating effects
- extrinsic RC network for the behavioral modeling of frequency dispersion effects (RPI)
- overlap capacitances (RPI)
- noise model (extended RPI in SmartSpice)
- ✓temperature scaling of contact series resistances



Physics Behind UOTFT: Carrier Concentration and OSC Conductivity

Exponential DOS distribution

$$g_A(E) = \frac{N_A}{kT_0} \exp\left[\frac{q(E - E_C)}{kT_0}\right]$$

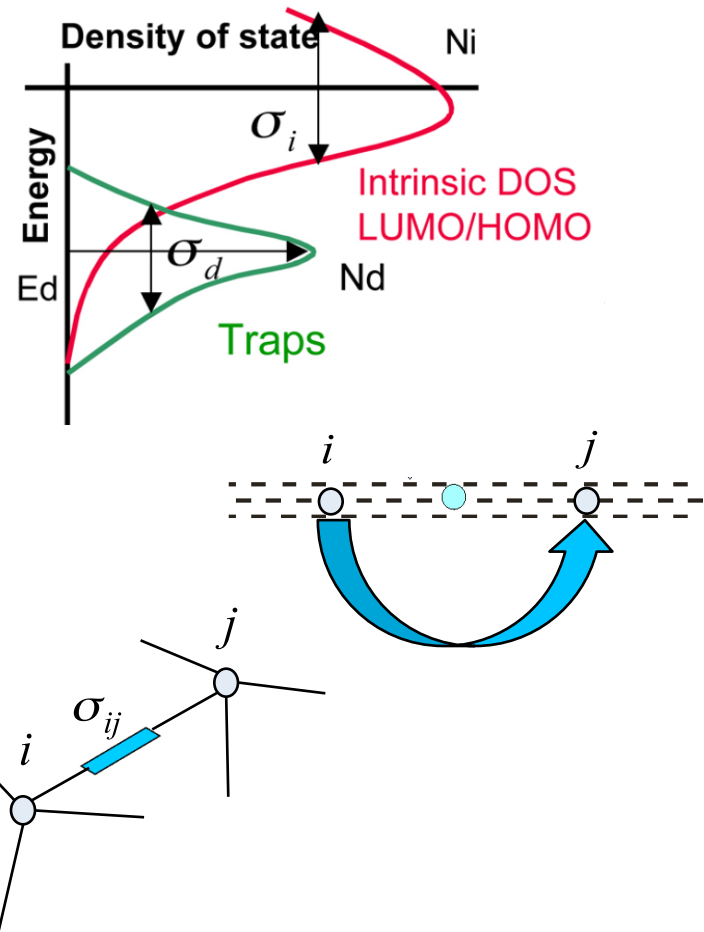
$$n = n_i(T) \exp\left[\frac{q(\varphi - V_C)}{kT_0}\right]$$

$$n_i(T) = n_{i0} \frac{\pi T / T_0}{\sin(\pi T / T_0)}$$

Percolation Theory

$$\sigma = \sigma_0 \left\{ \frac{\pi(T_0 / T)^3}{(2\alpha)^3 B_c} n_{i0} \exp\left[\frac{q(\varphi - V_C)}{kT_0}\right] \right\}^{T_0 / T}$$

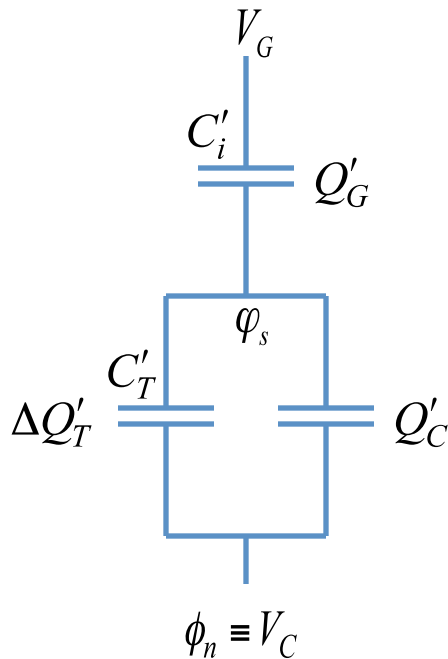
Vissenberg and Matters, *Phys. Rev. B*, 1998.





UOTFT Electrostatics: Unified Charge Control Model (UCCM) for OTFTs

$$Q'_G = Q'_C + \Delta Q'_T$$



Surface Potential Description

$$Q'_G = C'_i(V_G - V_{FB} - \varphi_s)$$

$$Q'_C = -Q_0 \sqrt{h\left(\frac{\varphi_s - V_C}{V_{t0}}\right)} \quad h(x) = \exp(x) - x - 1 \quad Q_0 = \sqrt{2q\epsilon_s n_i V_{t0}}$$

$$\Delta Q'_T = C'_T(\varphi_s - V_C)$$

$$h(x) \approx \exp(x)$$

UCCM

$$1 - \frac{Q'_C}{Q'_{CP}} + \ln\left(\frac{Q'_C}{Q'_{CP}}\right) = \frac{V_P - V_C}{2\eta V_{t0}}$$

$$Q'_{CP} = -2\eta C'_i V_{t0} \quad V_P = V_G - V_T \quad \eta = 1 + \frac{C'_T}{C'_i} \quad C'_i = \frac{\epsilon_0 \epsilon_{ins}}{t_{ins}}$$



UOTFT Electrostatics: Accurate Implementation of UCCM

$$1 - \frac{Q'_C}{Q'_{CP}} + \ln\left(\frac{Q'_C}{Q'_{CP}}\right) = \frac{V_G - V_T - V_C}{2\eta V_{t0}}$$

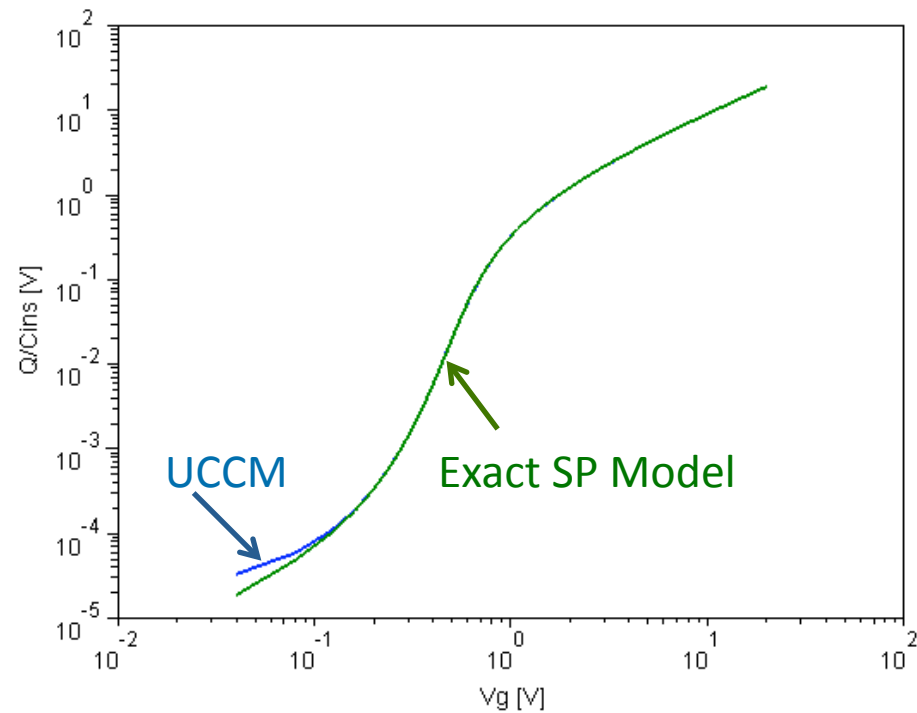
$$\bar{q} = \frac{Q'_C}{Q'_{CP}}$$

$$u = \frac{V_G - V_T - V_C}{2\eta V_{t0}}$$

$$1 - \bar{q} + \ln \bar{q} = u$$

$$\bar{q} = \ln\left[1 + \frac{e^{u+1}}{1 + k(u+2)\ln(1 + e^{u+1})}\right]$$

$$k(x) = 1 - \frac{84.4839}{x^2 + 150.8640}$$



A.I.A. Cunha, "A model of the MOS transistor for integrated circuit design", Ph.D. Thesis, UFSC, December, 1996



UOTFT Effective Conductivity (Mobility) Model: *Applied Percolation Theory*

$$G'_C = \int_0^{\varphi_s} \frac{\sigma(\varphi_s)}{K_x} d\varphi_s$$

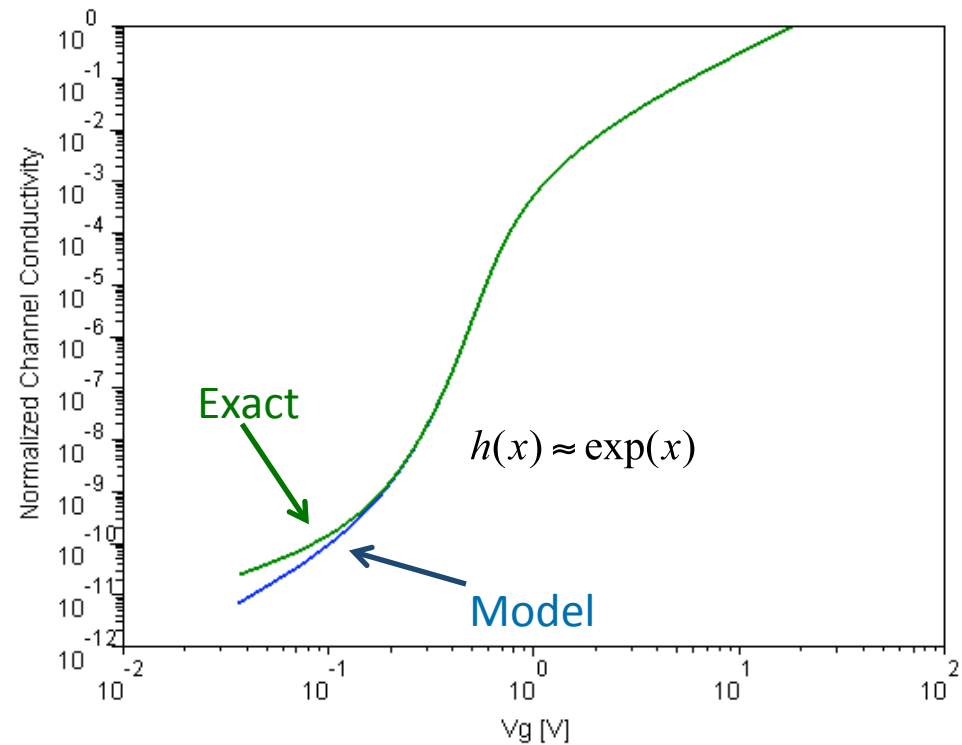
$$G'_C = \mu_C (-Q'_C)$$

$$\mu_C = \mu_C^0 \left(\frac{(-Q'_C)}{C_i V_C} \right)^\gamma$$

$$V_C = \frac{\sqrt{2kT_0 n_{i0} \epsilon_S}}{C_i}$$

$$\gamma = 2 \left(\frac{T_0}{T} - 1 \right)$$

$$\mu_C^0 = \frac{\sigma_0}{qn_{i0}} \left[\frac{n_{i0} (T_0/T)^4 \sin(\pi T/T_0)}{(2\alpha)^3 B_c} \right]^{T_0/T}$$





UOTFT DC Model: Intrinsic Drain-Source Current

$$I_{ds} = G_{ch} V_{dse}$$

$$V_{dse} = \frac{V_{ds}}{\left\{ 1 + \left[\frac{G_{ch} V_{ds}}{I_{sat} (1 + \lambda V_{ds})} \right]^m \right\}^{1/m}}$$

$$G_{ch} = \frac{G_{ch0}}{1 + G_{ch0} \cdot R_{ds}}$$

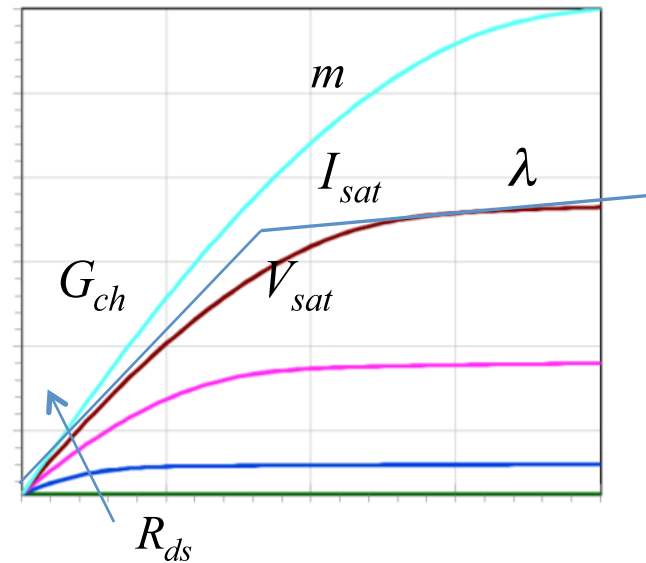
$$G_{ch0} = \frac{W}{L} G'_{C0}$$

$$R_{ds} = \frac{R_{ds0}}{1 + \frac{Q'_{C0}}{C'_i \cdot V_{rds}}}$$

$$I_{sat} = G_{ch} V_{sat}$$

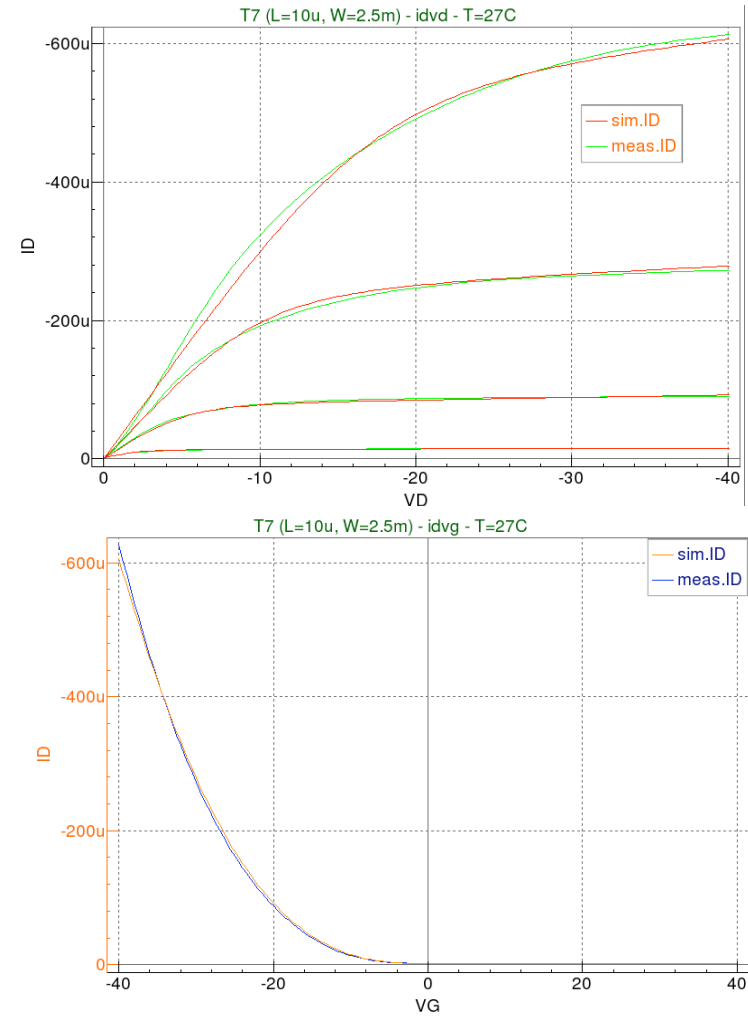
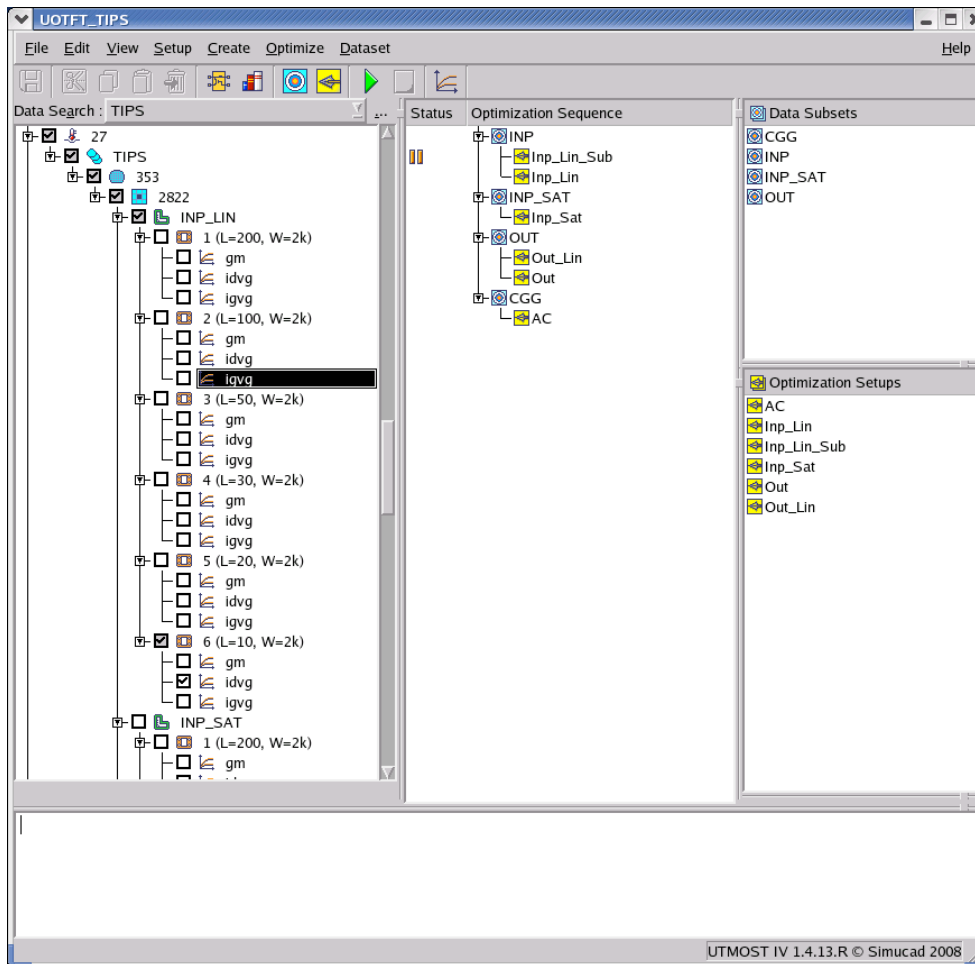
$$V_{sat} = \frac{Q'_C}{C'_i (\gamma + 2)} + \frac{2\eta V_{to}}{\gamma + 1}$$

drift diffusion



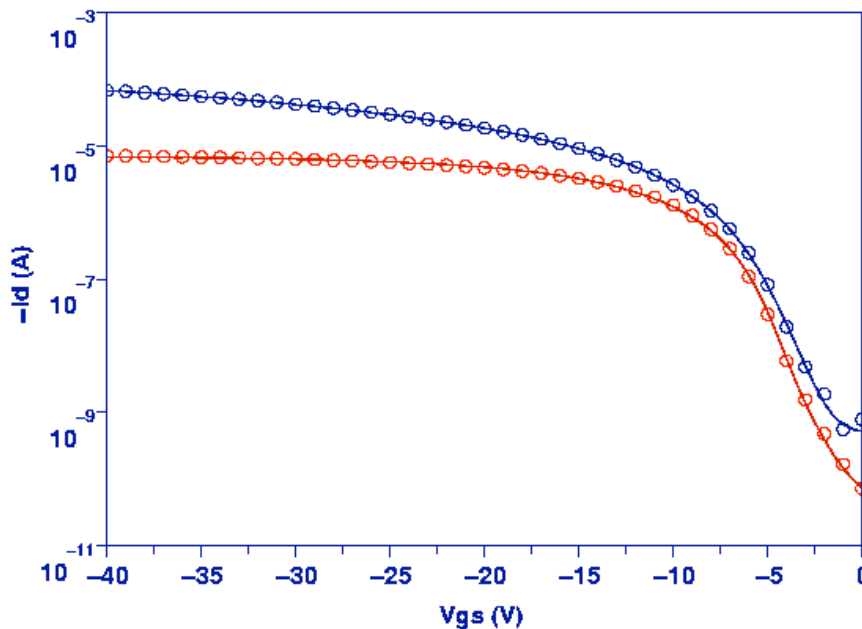


Parameter Extraction in UTMOST IV

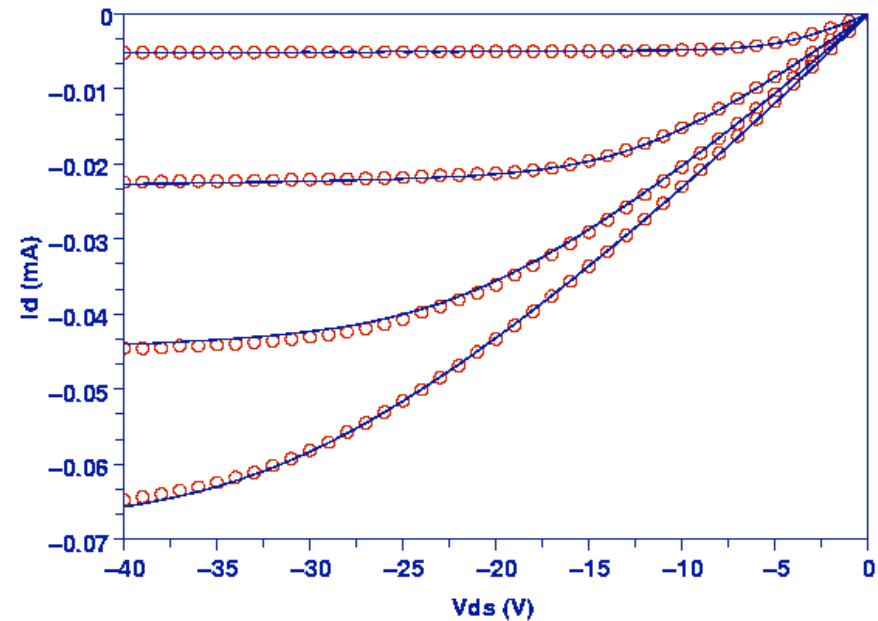




Model Verification: Bottom Gate Bottom Contact (BGBC) OTFT Devices (3rd party OSC material: material A)



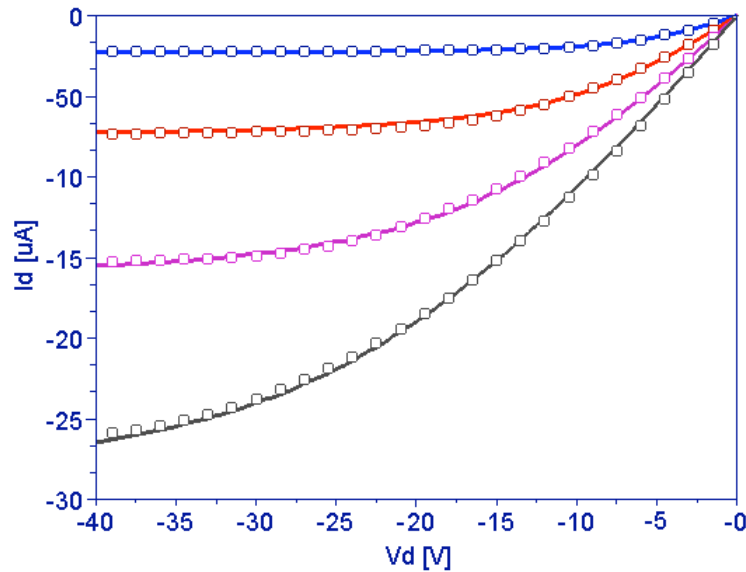
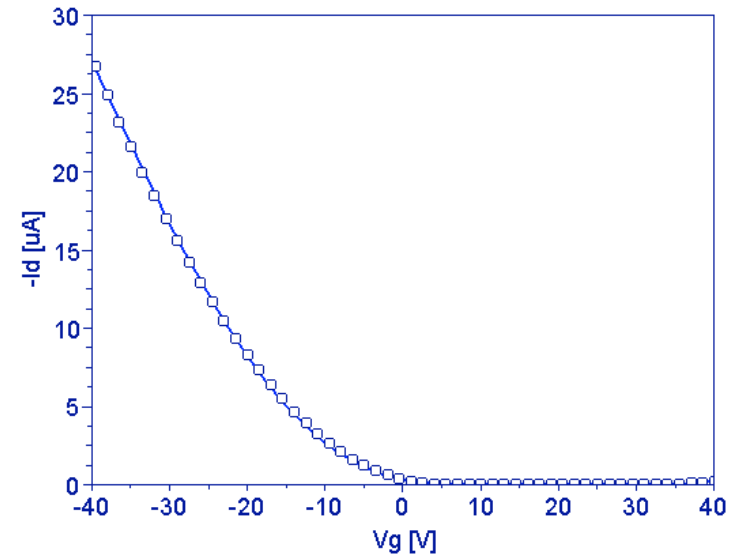
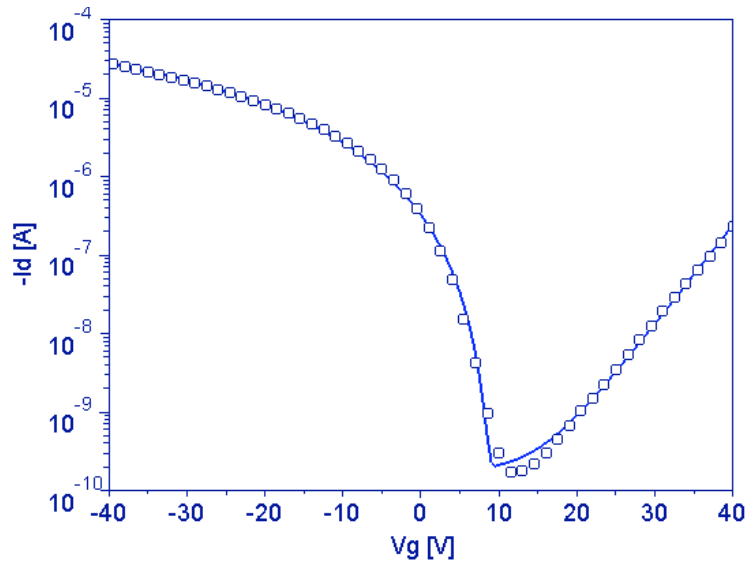
Comparison between simulated (lines) and measured (circles) transfer characteristics of the OTFT in the linear operation region with $V_{ds} = -3V$ (blue line and circles) and saturation operation region with $V_{ds} = -30V$ (red line and circles)



Comparison between simulated (lines) and measured (circles) output characteristics of the OTFT for $V_g = -10V, -20V, -30V$ and $-40V$.



Model verification: Top Gate Bottom Contact (TGBC) OTFT Devices (3rd party OSC material: material B)

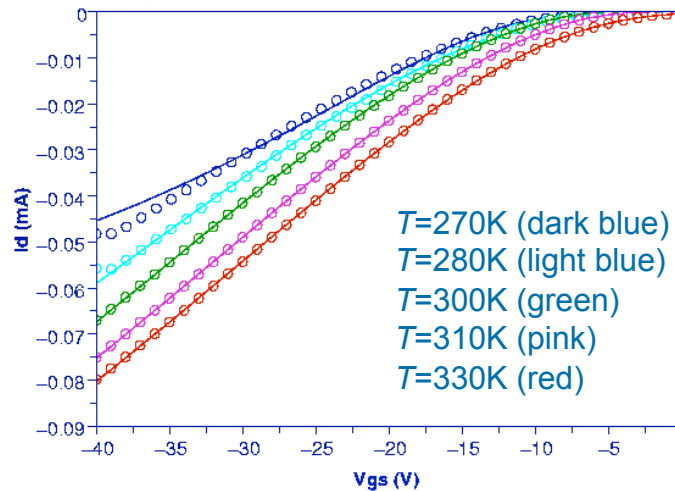


Comparison between simulated (lines) and measured (circles) transfer ($V_{ds}=-30V$) and output characteristics of the OTFT with a polymer OSC.

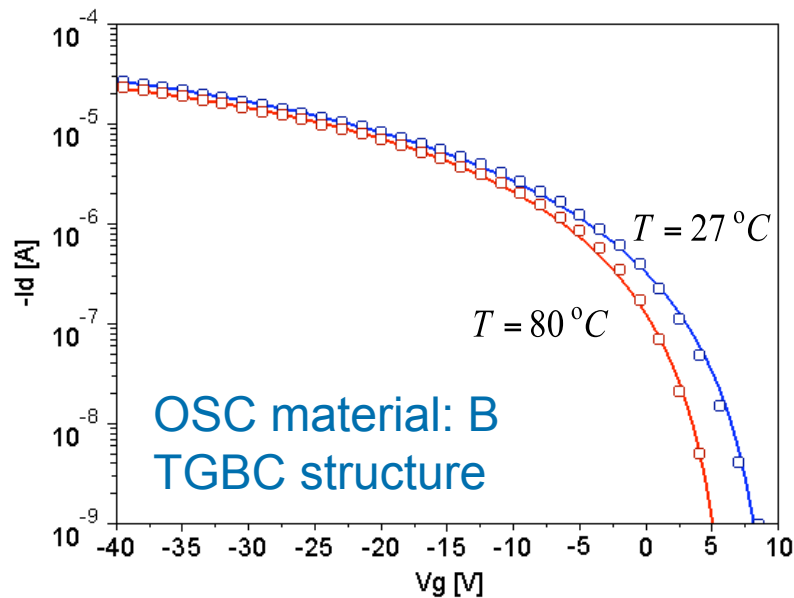


Model Verification: Temperature Scaling (BGBC and TGBC with different 3rd party OSC materials)

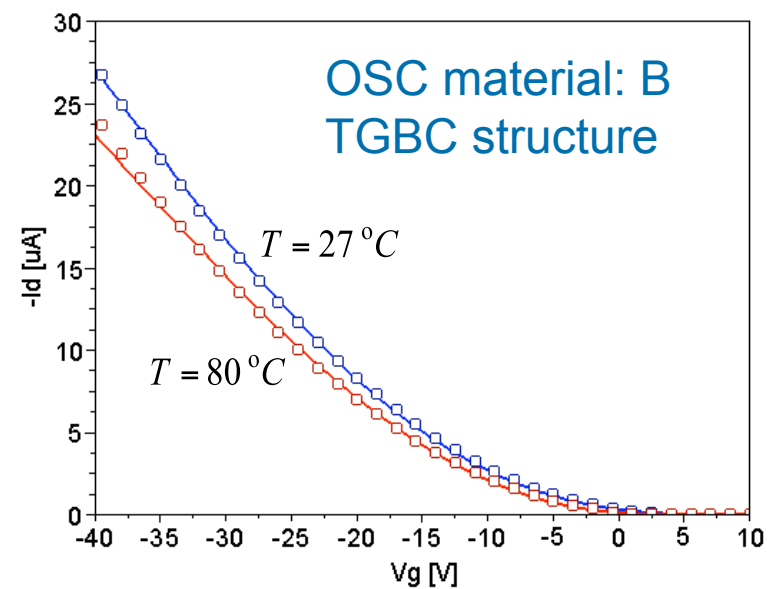
Comparison between simulated (lines) and measured (circles) transfer characteristics for two different device architectures and two different materials in the saturation operation region at different temperatures



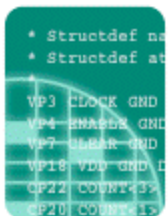
OSC material: A
BGBC structure



OSC material: B
TGBC structure

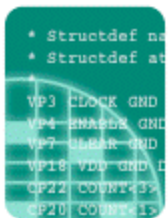


OSC material: B
TGBC structure



UOTFT Model Features Under Development: *The Next Six-Month-Roadmap*

- **Gate leakage-current model**
 - Poole-Frenkel trap assisted tunneling in the insulator.
 - Source/drain partitioning scheme.
 - Temperature dependence of the model parameter.
- **Physical drain-source leakage current**
 - Advanced temperature scaling of the leakage current model parameters
- **Short channel effects**
 - improved channel length modulation model,
 - effects of the depletion and strong lateral electric field on the drain side,
 - space-charge limited transport.
- **Effective channel conductivity for poly-crystalline OSC materials**
 - effective poly-crystalline mobility



Acknowledgement

We want to thank Prof. Benjamin Iñiguez and his group for valuable recommendations regarding compact organic TFT modelling.

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