New analytical model for AOSTFTs

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Why Amorphous Metal-Oxide Semiconductor Thin-Film Transistors (AOSTFTs)?

Because AOSTFTs are important devices used as drivers of Organic Light Emission Diodes (OLED) pixels in flat panels for Monitors and TV.

This transistor has a future with many potential applications and requires a suitable model, both static and dynamic, for circuit simulation.
In 2001, we developed the **Universal Model and Extraction Method (UMEM)** that is applicable for different types of **TFTs**, where all model parameters are extracted individually and analytically.

The UMEM model was updated to be able to obtain the DC and DYNAMICS characteristics of the AOSTFTs, that include specific behavior of this type of transistor.

As require this new **full AOSTFT model** was described in **Verilog-A** language in order to be used in circuit simulators like SmartSPICE.
Introduction

The main characteristics of this full model are:

- The Density-Off-States (DOS) can be considered formed only by tail states;
- Was used the Extended Mobility Edge Model, which considers different conduction mechanisms;
- The density of acceptor states at CB, \( g_{ato} \) is calculated analytical;
- Was defined an effective carrier density \( n_{eff} \) equal to the total carrier density;
- Field-effect mobility is calculated using the internal parameters;
- The effect of the Top-Metal-Overlap is considered in the C-V characteristics.
AOSTFT DOS characteristics

Amorphous TFTs have a Density of States (DOS) that can be described as two non-symmetrical types of states exponentially dependent, *deep* and *tail*.

For AOSTFTs, the DOS can be considered formed only by *tail states*, due to the relatively low density of states and that typically, the Fermi level lies inside this tail region, very close to the conduction band (CB).

For these devices, it was proposed the **Extended Mobility Edge Model**, which considers different conduction mechanisms: the mobility edge or *multiple trapping and release mechanism* typical of amorphous TFTs, as well as band conduction, including *percolation*.

The predominant conduction mechanism will depend on the characteristics of the materials, of the fabrication process and on the operation regime.
AOSTFT  Typical transistor characteristics

- AOS involuntary doped charge concentration $N_d$ usually in the range from $1 \times 10^{16}$ to $5 \times 10^{18}$ cm$^{-3}$.

- Operation voltage range is around 10 V for SiO$_2$, but can be reduced to less than 5 V if high-k dielectrics are used.

- Operation temperature range between 300 and 370 K.

- DOS with localized states density at CB, $g_{ato} < 1 \times 10^{20}$ cm$^{-3}$eV$^{-1}$ and $kT_t < 100$ mV.

- Transistors are accumulation type, without doping or junctions.

- The most frequent structure is the bottom gate staggered.
AOSTFT Internal model parameters

DEFINING THE FOLLOWING INTERNAL PARAMETERS [*]

\( \varphi_t = \frac{kb \, T}{q} \)
\( \varphi_f = -\varphi_t \ln \left( \frac{N_d}{N_c} \right) \)
\( T_{eff} = T \left(1 + \frac{\gamma}{2}\right) \)
\( T_t = 2T_{eff} - T \)
\( g_{ato} = \frac{N_c}{kb \, T_t} \left( e^{-\frac{\varphi_f}{kb \, T}} - e^{-\frac{\varphi_f}{kb \, T_{eff}}} \right) \)
\( J1 = 0.695 \left( \frac{T_t}{T} \right)^{0.18} \)
\( J0 = 1 - \frac{1}{1.185 \left( 1 - 1.185 \frac{T_t}{T} \right)} \)

kb Boltzmann constant
\( \varphi_t \) Thermal potential at T
\( \varphi_f \) Fermi potential
\( N_d \) Involuntary doping concentration
\( N_c \) Density of states at the bottom of the CB

\( T_t \) Characteristic temperature
\( T_{eff} \) Effective characteristic temperature
\( g_{ato} \) Density of acceptor states at CB

Internal parameters are calculated analytically.

[*] Y. Hernandez-Barrios, et all., “An insight to mobility parameters for AOSTFTs, when the effect of both, localized and free carriers, must be considered to describe the device behavior”, Solid State Electronics 149 (2018) 32–37.
AOSTFT Internal model parameters - carriers

- Localized carrier density $n_{loc}$
- Free carrier density $n_{free}$
- Total carrier density $n_{tot}$

Effective carrier density $n_{eff} = n_{tot}$

\[
\begin{align*}
    n_{loc} &= g_{ato} \cdot k_b \cdot T_t \cdot \frac{e^{\frac{\phi_s - \phi_f}{k_b T_t}}}{1 + \frac{z}{T_t}} \\
    n_{free} &= N_c \frac{2}{\sqrt{\pi}} \int_{0}^{\infty} \frac{\sqrt{x}}{1 + e^{-\frac{\phi_s - \phi_f}{k_b T}}} \, dx \\
    n_{tot} &= n_{free} + n_{loc} \\
    n_{eff} &= N_{eff} e^{k_b T_{eff}} \\
    N_{eff} &= N_c + g_{ato} k_b T_t J_f
\end{align*}
\]

$N_{eff}$ - effective carrier density, when the surface potential equals the Fermi potential

$T_{eff}$ - effective characteristic temperature;
In [*], the different carrier densities were calculated for an IGZO AOSTFT with:

\[
\begin{align*}
W &= 100 \mu\text{m} \\
L &= 40 \mu\text{m} \\
d_i &= 200 \text{ nm} \\
\varepsilon_i &= 5.2 \\
\varepsilon_s &= 9 \\
N_d &= 4 \times 10^{16} \text{ cm}^{-3}
\end{align*}
\]

It is seen that the free carrier density became predominant when surface potential was above 20 mV. This is the cause of their high mobility.

CURRENT-VOLTAGE MODEL FOR AOSTFT
The Field-Effect Mobility $\mu_{FE}$ is now calculated through AOSTFT internal parameters, considering the Boltzmann distribution;

- $\mu_0$ - the band mobility;
- $C_i$ - dielectric capacitance per unit area;
- $Q_S$ - total charge associated with the effective carrier density and
- $\gamma$ - mobility power parameter.

\[
Q_S = Q_0 e^{-\frac{\phi_f}{2 k_b T_{eff}}} \quad Q_0 = \sqrt{2q \varepsilon_S \varepsilon_0 N_{eff} k_b T_{eff}}
\]

\[
\mu_{FE} = \mu_0 \left[ \frac{n_{free}}{n_{tot}} \right] = \mu_0 \left[ \frac{n_{free}}{n_{eff}} \right] = \mu_0 \left[ \frac{N_C e^{\frac{-\phi_s - \phi_f}{k_b T}}}{N_{eff} e^{\frac{-\phi_s - \phi_f}{k_b T_{eff}}}} \right] = \mu_0 \left[ \frac{N_C}{N_{eff}} \right] \left( \frac{C_i}{Q_0} \right)^\gamma (V_g - V_t)^\gamma
\]
AOSTFT Calculation of the I-V characteristics

Auxiliary expressions

\[ V_{gt} = \frac{V_{min}}{2} \left[ 1 + \frac{V_g - V_t}{10^{-6}} + \sqrt{100 + \left( \frac{V_g - V_t}{10^{-6}} - 1 \right)^2} \right] \]

\[ V_{gf} = \frac{V_{min}}{2} \left[ 1 + \frac{V_g - V_{fb}}{10^{-6}} + \sqrt{100 + \left( \frac{V_g - V_{fb}}{10^{-6}} - 1 \right)^2} \right] \]

\[ V_{def} = \frac{V_d}{\left[ 1 + \left( \frac{V_d}{\alpha_s (V_g - V_t)} \right)^m \right]^{\frac{1}{m}}} \]

\[ K = \frac{W}{L} C_i \]
AOSTFT  Calculation of the I-V characteristics

Mobility

\[ \mu_{FE} = \mu_0 \frac{N_c}{N_{eff}} \left( \frac{C_i}{Q_0} \right)^{\gamma} V_{gt} \]

Current above \( V_t \)

\[ I_{at} = \frac{K \mu_{FE} V_{gt}}{1+R K \mu_{FE} V_{gt}} V_{def} \left( 1 + \lambda \left( V_d - V_{def} \right) \right) \]

Current below \( V_t \)

\[ I_{bt} = \left\{ K \mu_{1b} V_{gf} (V_g = V_t)^{1+\gamma_b} V_{dl} e^{\frac{v_g-V_t-V_{1}}{s}} + I_0 \right\}^{1/2} \left[ 1 - th \left( (V_g - V_{fb} - V1) Q1 \right) \right] + \]
\[ + \left\{ K \mu_{1b} (V_{gf})^{1+\gamma_b} V_{dl} \right\}^{1/2} \left[ 1 + th \left( (V_g - V_{fb} - V1) Q1 \right) \right] \]

Total current

\[ I_{ds} = \{ I_{bt} \}^{1/2} \left[ 1 - th \left( (V_g - V_t - V2) Q2 \right) \right] + \{ I_{at} \}^{1/2} \left[ 1 + th \left( (V_g - V_t - V2) Q2 \right) \right] \]
IGZO AOSTFT EXAMPLE

Staggered, bottom-gate top-contact (BGTC) structure with the following parameters:

- Channel width \( W = 900 \, \mu m \)
- Channel length \( L = 30 \, \mu m \)
- Gate dielectric thickness \( d_i = 200 \, nm \)
- Passivation dielectric thickness \( d_{ipas} = 200 \, nm \)
- Semiconductor thickness \( t_s = 12 \, nm \)
- \( D \) and \( S \) overlap length \( t_{ov} = 5 \, nm \)
- \( D \) and \( S \) top overlap length \( L_{tov} = 5 \, nm \)
Extraction of I-V model parameters using the UMEM extraction procedure [*].

**Above threshold:**
- Band mobility $\mu_0 = 9.1 \text{ cm}^2/\text{Vs}$
- Threshold voltage $V_T = 0.47 \text{ V}$
- Mob. power parameter $\gamma = 0.14$
- Series resistance $R = 190 \Omega$
- Saturation voltage parameter $\alpha_s = 0.83$
- Knee of output characteristic $m = 1.6$
- Output conductance param. $\lambda = -0.015$

**Below threshold:**
- Flat band voltage, $V_{FB} = 0.46 \text{ V}$
- Mob. power parameter $\gamma_b = 0.28$
- Mob. at $V_g=V_{fb}$ $\mu_b1 = 0.73$
- Subthreshold slope $S = 0.15$

Parameters of the smoothing functions used: $V1 = 0, \ Q1 = 10, \ V2 = 0.24 \text{ V}, \ Q2 = 3.$

**I-V model used 11 parameters and 4 adjusting.**

AOSTFT

I-V characteristics

I-V curves modeled, considering:
the structure parameters,
the internal parameters and
the model parameters

LINEAR \( V_d = 0.5 \) V
\( W/L = 900/30 \)

- simulation
- model

SATURATION \( V_d = 10 \) V
\( W/L = 900/30 \)

- simulation
- model
CAPACITANCE-VOLTAGE MODEL FOR AOSTFT
Capacitance-Voltage modeling

For dynamic circuit simulation, in addition to the current-voltage model, a capacitance-voltage model is required.

Internal capacitances must be a function of the applied bias and consider also, the parasitic capacitance values.

The developed model considers the effects of the top-metal-overlap (TMO) in the staggered, bottom-gate top-contact (BGTC) structure [*].

AOSTFT C-V characteristics. Top metal overlap

Cross section of a bottom gate AOSTFT using an Etch-Stop-Layer (ESL).

In AOSTFTs, the source/drain metal contacts extend on top of the passivation layer, producing an overlap with a length equal to $L_{tov}$, is known as Top-Metal-Overlap (TMO) [*].

The TMO introduces a capacitance $C_{topov}$ which depends on $Vd$ as follow:

$$C_{topov} = (C_{pasiv} W L_{tov})V_d^{0.8} M$$

[*] M. Estrada, et al., Effect of Drain Top Metal Overlap on the Current in Bottom-gate Thin Film Transistors, 2019 Latin American Electron Devices Conference (LAEDC), IEEE Xplorer 2019,
What is the TMO effect on capacitances?

Outside of the TMO region near the drain:
charges at the semiconductor-passivation (Semi-P) interface are much lower than those at
the gate-semiconductor interface (G/Semi).

Within the TMO region near the drain:
both charges at both interfaces are similar.

Why? Because the TMO near the drain, serves as a second gate with an applied gate voltage
equal to $V_d$. 
**AOSTFT**

**C-V characteristics. Effects of the TMO.**

**$C_{gg}$ vs. $V_{GS}$ at low drain voltage.**

$\left(V_d = 0.5V\right)$

In **subthreshold**, the capacitance is constant and increases with the TMO $[L_{tov}$ and $C_{topov}]$.

Above threshold, for **low drain voltage**, capacitances have a constant value in accumulation, independently of the TMO.
AOSTFT  

C-V characteristics. Effects of the TMO.

$C_{gg}$ vs. $V_{GS}$ at *higher drain voltages*

A shift of the transition voltage between saturation and linear regimes is observed. This transition voltage depends on the TMO.

$$V_{gc} = V_T + \frac{V_d}{\alpha_{ss}}$$

where $V_T$ is the threshold voltage and $\alpha_{ss}$ is a modified value of the saturation parameter $\alpha_s$ for amorphous thin film devices.

$\alpha_{ss}$ is extracted as a *fitting* parameter.
The voltage shift of C-V in saturation is modeled by the following expressions

In the C-V equations the parameter $\alpha_s$ must be substituted by $\alpha_{s2}$ with the adjusting parameter $\alpha_{ss}$

$$V_{gc} = V_t + V_d \cdot \frac{1}{\alpha_{ss}}$$

$$\alpha_{s2} = \alpha_s \cdot \frac{1}{2} \left[ 1 - \tanh(0.5 \cdot (V_g - V_{gc})) \right] + \alpha_{ss} \cdot \frac{1}{2} \left[ 1 + \tanh(0.5 \cdot (V_g - V_{gc})) \right]$$
Auxiliary expressions: \( V_{gt} \), \( V_{def} \) and their derivatives.

\[
V_{gt} := \frac{V_{g} - V_{t}}{2} \left[ 1 + \frac{V_{g} - V_{t}}{V_{min}} + \sqrt{\frac{V_{g} - V_{t}}{V_{min} - 1} + \frac{V_{g} - V_{t}}{V_{min}}} \right]
\]

\[
V_{def} := \frac{V_{d}}{\left[ 1 + \left( \frac{V_{d}}{\alpha s V_{gt}} \right)^{m} \right]^{1/m}}
\]

Derivative of \( V_{gt} / V_{g} \):

\[
D_{vgt} := \frac{1}{2} \left[ 1 + \left( \frac{V_{g} - V_{t}}{V_{min} - 1} \right) \right]
\]

Derivative of \( V_{def} / V_{g} \):

\[
D_{vdg} := \frac{\left( \frac{V_{d}}{\alpha s V_{gt}} \right)^{m+1}}{\alpha s D_{vgt}} \left[ 1 + \left( \frac{V_{d}}{\alpha s V_{gt}} \right)^{m} \right]^{1/m}
\]

Derivative of \( V_{def} / V_{d} \):

\[
D_{vd} := \frac{1}{1 + \left( \frac{V_{d}}{\alpha s V_{gt}} \right)^{m}^{m+1}}
\]
Auxiliary expressions A2, A3, A5 and their derivatives

\[ A2 := \left| (V_{gt})^{2+\gamma} - (V_{gt} - V_{def})^{2+\gamma} \right| \]
\[ A3 := \left| (V_{gt})^{3+\gamma} - (V_{gt} - V_{def})^{3+\gamma} \right| \]
\[ A5 := \left| V_{gt}^{5+\gamma \cdot 2} - (V_{gt} - V_{def})^{5+\gamma \cdot 2} \right| \]

Deriv \(A2 / V_g\): \[ Da2g := (2 + \gamma) \cdot A1 \cdot Dv_{gt} + (V_{gt} - V_{def})^{1+\gamma} \cdot Dv_{dg} \]

Deriv \(A3 / V_g\): \[ Da3g := (3 + \gamma) \cdot A2 \cdot Dv_{gt} + (V_{gt} - V_{def})^{2+\gamma} \cdot Dv_{dg} \]

Deriv \(A5 / V_g\): \[ Da5g := (5 + 2 \cdot \gamma) \cdot A4 \cdot Dv_{gt} + (V_{gt} - V_{def})^{4+2 \cdot \gamma} \cdot Dv_{dg} \]

Deriv \(A2 / V_d\): \[ Da2d := (2 + \gamma) \cdot (V_{gt} - V_{def})^{1+\gamma} \cdot Dv_{dd} \]

Deriv \(A3 / V_d\): \[ Da3d := (3 + \gamma) \cdot (V_{gt} - V_{def})^{2+\gamma a} \cdot Dv_{dd} \]
AOSTFT Analytical expressions for the charges

Transistor charges in the channel at drain and source

Total charge in the channel =

\[ Q_{ch} = -Q_g \]

\[ Q_{ch} := (WLC_i) \cdot \frac{(2 + \gamma)}{(3 + \gamma)} \cdot \frac{A_3}{A_2} \]

Charge at the drain

\[ Q_d := -(2 + \gamma) \cdot W \cdot L \cdot C_i \cdot \left( \frac{A_5}{5 + 2 \cdot \gamma} - \frac{V_{gt}^{2+\gamma} \cdot A_3}{3 + \gamma} \right) \]

Charge at the source

\[ Q_s := Q_{ch} - Q_d \]

Capacitance values are calculated using the derivative of each charge

\[ C_{gg} = \frac{dQ_g}{dV_g} \; ; \; \; \; C_{gd} = -\frac{dQ_g}{dV_d} \; ; \; \; C_{gs} = -\frac{dQ_g}{dV_s} \; ; \; \; C_{dg} = -\frac{dQ_d}{dV_g} \; ; \; \; C_{dd} = \frac{dQ_d}{dV_d} \; ; \; \; C_{ds} = -\frac{dQ_d}{dV_s} \]
AOSTFT Analytical capacitance expressions

AOSTFT has 9 trans-capacitance, 4 of them can be calculated analytically as:

\[
C_{gg} = (WLC_i) \cdot \frac{(2 + \gamma)}{(3 + \gamma)} \cdot \frac{1}{A^2} \left[ Da_{3g} - Da_{2g} \cdot \frac{A^3}{A^2} \right]
\]

\[
C_{gd} = (WLC_i) \cdot \frac{(2 + \gamma)}{(3 + \gamma)} \cdot \frac{1}{A^2} \left[ Da_{3d} - Da_{2d} \cdot \frac{A^3}{A^2} \right]
\]

\[
C_{gs} = -\frac{WLC_i(2 + \gamma)}{A^2} \left[ \frac{Da_{5g}}{5 + 2\gamma} - \frac{2 + \gamma}{3 + \gamma} \cdot V_{gt}^{1+\gamma} \cdot A^3 \cdot D_{vgtg} - \frac{V_{gt}^{2+\gamma}}{(3 + \gamma)} \cdot Da_{3g} - \left( \frac{A^5}{5 + 2\gamma} - \frac{V_{gt}^{2+\gamma} \cdot A^3}{3 + \gamma} \right) \cdot \frac{2}{A^2} \cdot Da_{2g} \right]
\]

\[
C_{dd} = -\frac{WLC_i(2 + \gamma)}{A^2} \left[ \frac{V_{gt}^{2+\gamma}}{(3 + \gamma)} \cdot \left( Da_{3d} - \frac{2 \cdot A^3}{A^2} \cdot Da_{2d} \right) - \frac{1}{5 + 2\gamma} \left( Da_{5d} - \frac{2 \cdot A^5}{A^2} \cdot Da_{2d} \right) \right]
\]

The other 5 as:

\[
C_{ds} := C_{gd} - C_{dd}
\]

\[
C_{sd} := C_{gd} - C_{dd}
\]

\[
C_{ss} := C_{gs} - C_{ds}
\]

\[
C_{sg} := C_{gg} - C_{gd}
\]
AOSTFT

Analytical capacitance expressions

Parasitic capacitances

The overlap capacitance, \( C_{ov} = W L_{ov} C_i \)

The top-metal-overlap capacitance, \( C_{topov} = (W L_{tov} C_{pasiv}) M (V_d)^{0.8} \)

The parasitic capacitances (extracted), \( C_{par0} \)

Factor \( f_a \)

\[ f_a = a \frac{1}{2} \left[ 1 - \tanh(0.5(V_g - V_{gc})) \right] \]

Adjusting parameters

- \( \alpha_{ss} \), \( M \), \( a \) and \( D \)

Parameters of the smoothing function

- \( V3 \), \( Q3 \)

<table>
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<th>( L_{tov} [\mu m] )</th>
<th>( \alpha_{ss} )</th>
<th>( M )</th>
<th>( a )</th>
<th>( D )</th>
<th>( V3 [V] )</th>
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<td>0.024</td>
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<td>0.55</td>
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C-V requires 6 additional parameters
AOSTFT

Analytical capacitance expressions

Total \( C_{gg} \) and \( C_{gd} \) in above threshold regime are calculated as:

\[
C_{ggB} := C_{gg} \cdot (1 - V_d \cdot f_a) + \left[ 2 \cdot \text{Cov} + C_{par0} + C_{topov} \cdot \left( V_d^{0.8} \right) \cdot M \right]
\]

\[
C_{dB} := (C_{gDA}) \cdot (1 - V_d \cdot f_a) + \left[ \text{Cov} + \frac{C_{par0}}{2} + C_{topov} \cdot \left( V_d^{0.8} \right) \cdot M \right]
\]

For above and below threshold regimes.

\[
C_{gP} := C_{gg0} \cdot \frac{1 - \text{tanh}[(V_g - V_3) \cdot Q_3]}{2} + C_{ggB} \cdot \frac{1 + \text{tanh}[(V_g - V_3) \cdot Q_3]}{2}
\]

\[
C_{dP} := \frac{1}{2} \cdot (C_{gg0}) \cdot \frac{1 - \text{tanh}[(V_g - V_3) \cdot Q_3]}{2} + C_{dB} \cdot \frac{1 + \text{tanh}[(V_g - V_3) \cdot Q_3]}{2}
\]

\[
C_{gsP} := C_{gP} - C_{dP}
\]
AOSTFT

Analytical capacitance expressions

Total $C_{dg}$ and $C_{dd}$ in above threshold regime are calculated as

$$C_{dgB} := C_{dg}(1 - V_d \cdot f_a) + C_{ov} + \frac{C_{par0}}{2} + C_{topov} \cdot \left(V_d^{0.8}\right) \cdot M$$

$$C_{ddB} := C_{dd}(1 - V_d \cdot f_a) + C_{ov} + \frac{C_{par0}}{2} + C_{topov} \cdot \left(V_d^{0.8}\right) \cdot M$$

For above and below threshold regimes.

$$C_{dgP} := \left(\frac{C_{gg0}}{2}\right) \cdot \frac{1 - \tanh[(V_g - V_d) \cdot Q_3]}{2} + C_{dgB} \cdot \frac{1 + \tanh[(V_g - V_d) \cdot Q_3]}{2}$$

$$C_{ddP} := \frac{1}{2} \cdot (C_{gg0}) \cdot \frac{1 - \tanh[(V_g - V_d) \cdot Q_3]}{2} + (C_{ddB}) \cdot \frac{1 + \tanh[(V_g - V_d) \cdot Q_3]}{2}$$

$$C_{dsP} := C_{dgP} - C_{ddP}$$
The first step is the comparison of measured (points) and modeled (lines) $C_{gg} - V_{GS}$ which is the only one C-V characteristic than can be measured.

Extraction of capacitance model and adjusting parameters:

$C_{gg}$ capacitance in depletion, $C_{gg dep}$
$C_{gg}$ capacitance in accumulation, $C_{gg acum}$

Adjusting parameters - $V3, Q3$
AOSTFT  C-V characteristics - Validation

GATE VOLTAGE SWEEP AT $V_{DS} = 0$ and 10 V

Comparison between simulated (*symbols*) and modeled capacitances (*lines*).

$C_{gg}$; $C_{gd}$; $C_{gs}$; $C_{ds}$ vs. $V_{GS}$

TMO length of 5 µm
AOSTFT  C-V characteristics - Validation

DRAIN VOLTAGE SWEEP AT V_{GS} = 8 V

Comparison between simulated (symbols) and modeled capacitances (lines).

\[ C_{gg}; C_{gd}; C_{gs}; C_{ds} \text{ vs. } V_{DS} \]

TMO length of 5 \( \mu \)m
DINAMYC MODEL AND ITS VALIDATION IN SMARTSPICE
The dynamic AOSTFT model, including the current-voltage and capacitance-voltage characteristics, was described in Verilog-A language and introduced in the circuit simulator SmartSPICE as an external model.

For the validation of the dynamic model, an inverter and a RING-OSCILATOR of 19 inverters were simulated and results compared with experimental measurements.

Load transistors have W/L = 15/15 and drivers have W/L=150/15.
Equivalent circuit using the calculated currents, capacitance and resistance values
Simulated inverter at $V_d = 10\, \text{V}$

Very good coincidence between simulated and measured transient characteristic.
AOSTFT  Ring-oscillator of 19 inverters

Load TFT  - $W = 15 \, \mu m$ and $L = 15 \, \mu m$.

Driver TFT  - $W = 150 \, \mu m$ and $L = 15 \, \mu m$. 
Ring-oscillator of 19 inverters

Measured oscillation frequency equal to **22 kHz**.

The simulated oscillator output signal has an excellent coincidence with the measured oscillator.
CONCLUSIONS
A new full analytical and continuous model for AOSTFTs was developed. It considers internal parameters of the transistors.

The model considers specific features of AOSTFTs: DOS; an Extended Mobility Edge Model, which considers different conduction mechanisms and the top-metal overlap, typical for the bottom gate staggered structure.

The description of the model in Verilog-A allows the simulation of DC and dynamic characteristics in circuit simulators.

This full AOSTFT model requires only 14 model parameters and 9 adjusting parameters.
Thanks for your attention