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Threshold-Voltage-Based Regional Modeling of MOSFETs with Symmetry and Continuity

Siau Ben Chiah[*], Xing Zhou[*], Karthik Chandrasekaran[*],
Khee Yong Lim[**], Lap Chan[**], and Sanford Chu[**]

[*] School of Electrical & Electronic Engineering, Nanyang Technological University,
Nanyang Avenue, Singapore 639798. exzhou@ntu.edu.sg

[**] Chartered Semiconductor Manufacturing Ltd.
60 Woodlands Industrial Park D, Street 2,
Singapore 738406

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❑ Abstract

A unified threshold-voltage-based (V_t-based) model, which maintains source-drain symmetry and allows accurate prediction with smooth transitions (in function as well as higher-order derivatives) across linear/saturation and weak/strong-inversion regions, is presented. This has been achieved based on the idea of our previous unified source-extrapolated V_t-based model but reformulated with bulk reference for the drain current. The experimental data from a 0.18-μm CMOS shallow trench isolation technology wafer is used for the verification of the model.

❑ Motivation

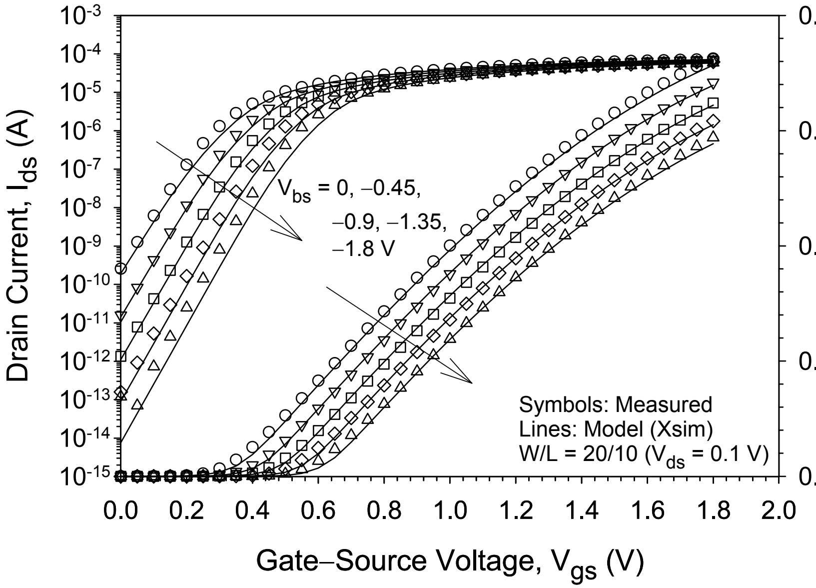
- Model symmetry and continuity across regions of operation are extremely important in the mixed-signal and low-power applications.
- Does unified threshold-voltage-based regional model really suffer from symmetry and continuity problems, or is it inherent to V_t-based models?

Bulk- vs. Source-Referenced I_{ds} Model

❑ Drift and Diffusion Model

$$I_{drift}(y) = \mu_{eff} W_{eff} Q_i(y)\, d\Psi_s(y)/dy$$

$$I_{diff}(y) = \mu_{eff} W_{eff} v_{th}\, dQ_i(y)/dy$$



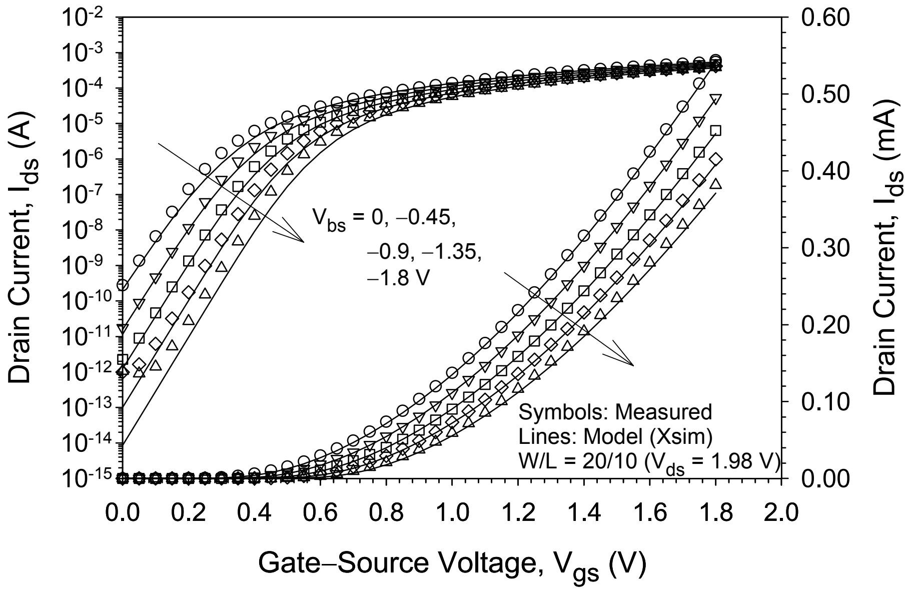
Bulk-referenced linear $I_{ds} - V_{gs}$ characteristics for V_{bs} = 0/−1.8 V fitted, and others predicted

❑ Bulk-Referenced I_{ds} Model

$$V_t = V_{FB} + \phi_{s0} + \gamma\sqrt{\phi_{s0}} - (A_b - 1)V_{bs}\ ;\ A_b = 1 + \gamma/\left(2\sqrt{\phi_{s0}}\right)$$

❑ Source-Referenced I_{ds} Model

$$V_t = V_{FB} + \phi_{s0} + \gamma\sqrt{\phi_{s0} - V_{bs}}\ ;\ A_b = 1 + \gamma/\left(2\sqrt{\phi_{s0} - V_{bs}}\right)$$



Predicted saturation $I_{ds} - V_{gs}$ characteristics

Unified Regional I_{ds} Model

Compact regional model

$$I_{drift} = \beta_n \left[\left(V_{gs} - V_t \right) V_{ds} - ½ A_b V_{ds}^2 \right]$$

$$I_{diff} = \beta_n v_{th}^2 \left(C_d / C_{ox} \right) e^{\left(V_{gs} - V_t \right)/\left(n v_{th} \right)} \left(1 - e^{-V_{ds}/v_{th}} \right)$$

Unified V_t-based model

$$I_{ds} = \beta_n V_{ge} = \beta_n \left(V_{gg} + V_{gd} \right)$$

$$I_{ds} = I_{drift} + I_{diff} \; ; \; I_{drift} = \beta_n V_{gg} \, , I_{diff} = \beta_n V_{gd}$$

Effective gate/drain voltage product

$$V_{gg} = \frac{2 n v_{th} \ln \left(1 + e^{\left(V_{gs} - V_t \right)/\left(2 n v_{th} \right)} \right) V_{de}}{1 + V_{de} \dfrac{2n \left(C_{ox} / C_d \right) e^{-\left(V_{gs} - V_t - 2V_{off} \right)/\left(2 n v_{th} \right)}}{v_{th} \left(1 - e^{-V_{ds}/v_{th}} \right)}}$$

$$V_{gd} = \frac{V_{gg}}{W_{ge}}, \; W_{ge} = \frac{n}{A_b} \frac{e^{\left(V_{gs} - V_t \right)/\left(2 n v_{th} \right)}}{1 - e^{-V_{ds}/v_{th}}}$$

$$\beta_n = \mu_{eff} C_{ox} \left(W_{eff} / L_{eff} \right)$$

Bulk-charge effect

$$V_{de} = \left(1 - \frac{A_b}{2} \frac{V_{deff}}{V_{geff}} \right) V_{deff}$$

Effective gate overdrive

$$V_{geff} = \frac{2 n v_{th} \ln \left(1 + e^{\left(V_{gs} - V_t \right)/\left(2 n v_{th} \right)} \right)}{1 + 2n \left(C_{ox} / C_d \right) e^{-\left(V_{gs} - V_t - 2V_{off} \right)/\left(2 n v_{th} \right)}}$$

V_{deff} smoothing function

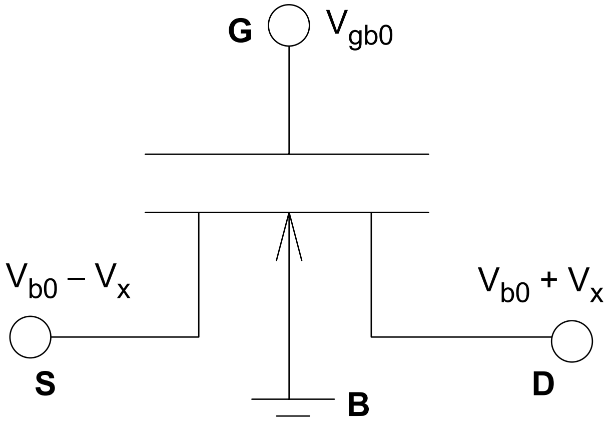
$$V_{deff} = V_{dsat} - ½ \Big[V_{dsat} - V_{ds} - \delta_s + \sqrt{\left(V_{dsat} - V_{ds} - \delta_s \right)^2 + 4 \delta_s V_{dsat}} \Big]$$

$$V_{dsat} = \frac{E_{sat} L_{eff} \left(V_{gs} - V_t \right)}{V_{gs} - V_t + A_b E_{sat} L_{eff}}$$

Gummel Symmetry

❑ Unified source-extrapolated V_t-based with bulk-referenced I_{ds} model

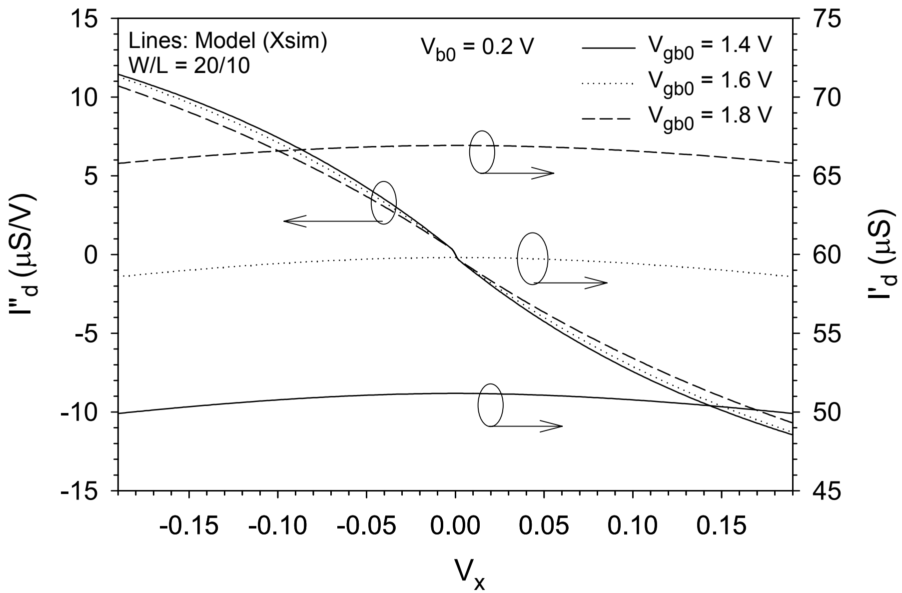
- Source/drain interchangable and exhibiting smooth transition at $V_x = 0$.
- Source-extrapolated V_t-based model does not necessarily mean asymmetry.



*Circuit diagram used for the **Gummel symmetry** test*

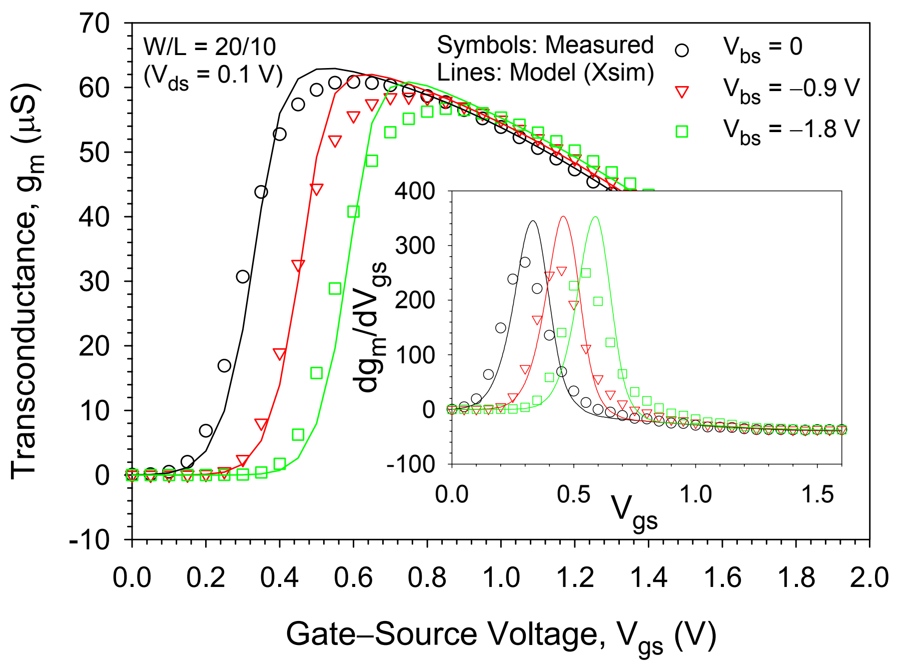
- $I_d(V_x) = -I_d(-V_x)$
- $I_d''(V_x=0) = 0$

Note: I_{ds}'' vs. V_{ds} is ***not*** Gummel symmetry test

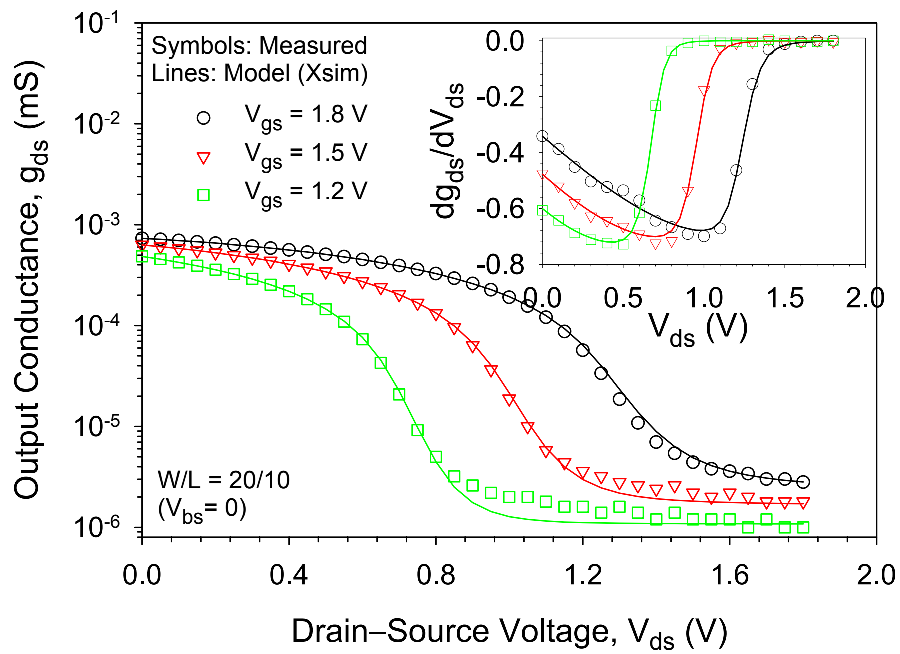


The first and second order derivatives of I_d with respect to V_x

Model Continuity in Higher-Order Derivatives

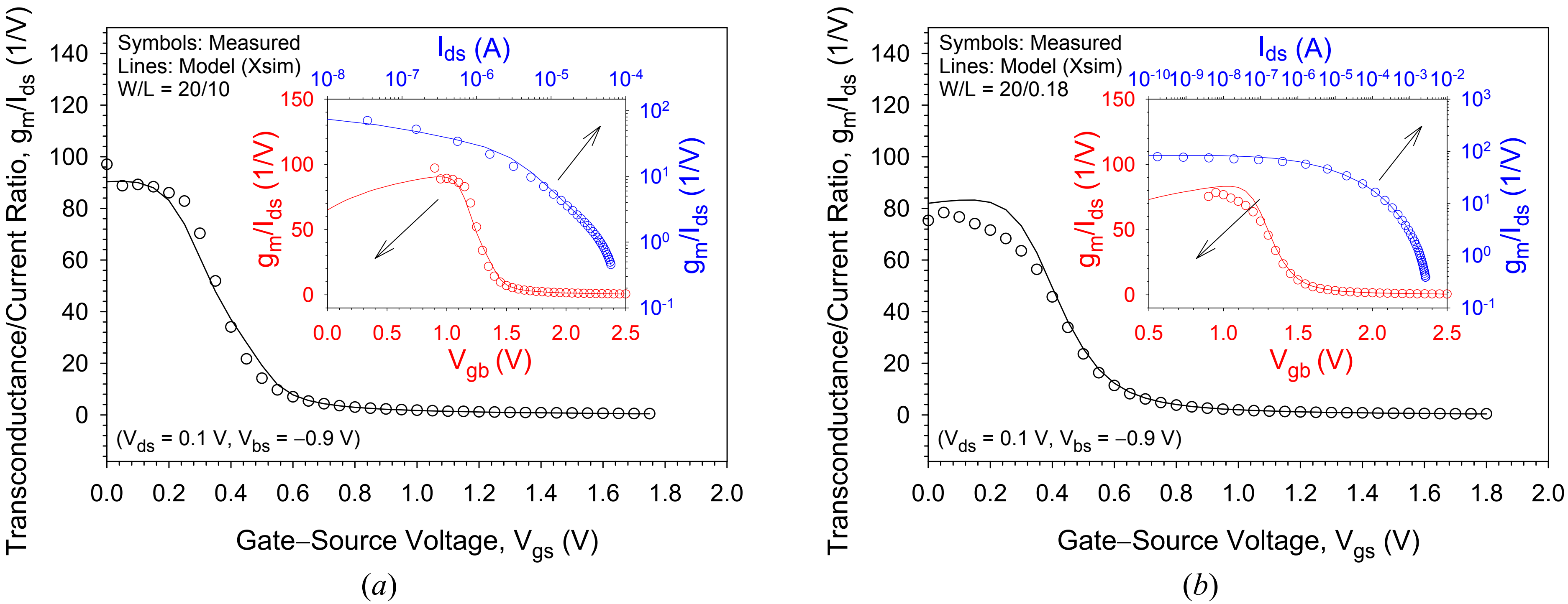


Predicted transconductance and its derivative (inset) with smooth transition across regions of operation (subthreshold/strong-inversion) at various terminal bias conditions.



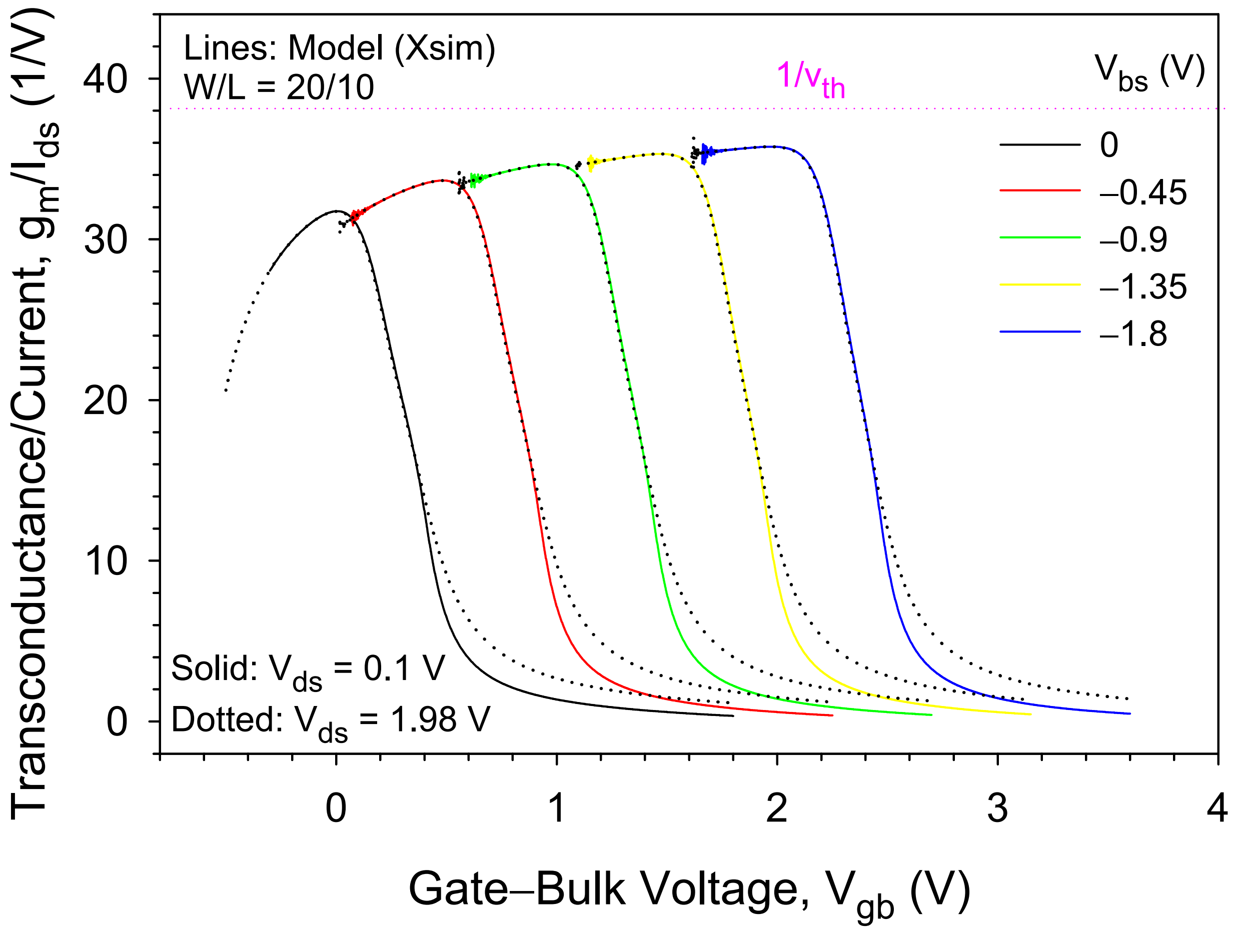
Predicted output conductance and its derivative (inset) with smooth transition across regions of operation (linear/saturation) at various terminal bias conditions.

g_m/I_{ds} Smoothness



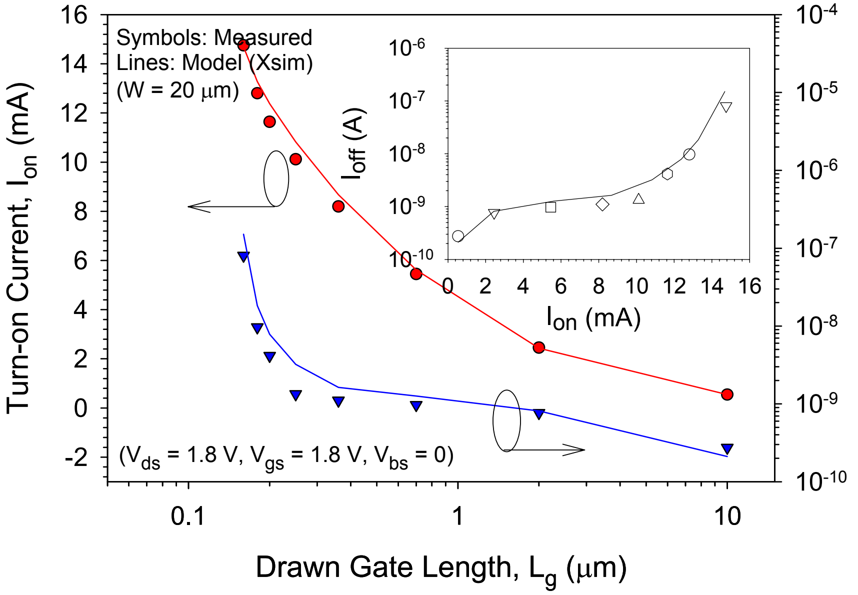
Predicted tranconductance/current ratio at the indicated terminal bias for (*a*) long- (*b*) short-channel devices. The inset shows the same g_m/I_{ds} versus gate-bulk (bottom-left) showing Gummel tree-top test; and g_m/I_{ds} versus drain current (top-right) showing model smoothness.

Gummel Tree-Top Test

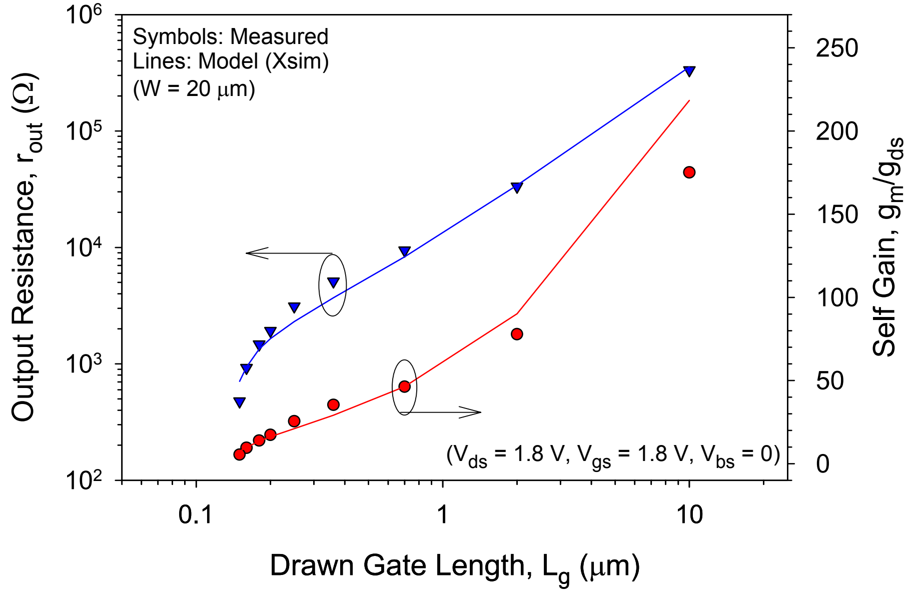


Model Scalability and Predictability

❑ I_{on}/I_{off}, r_{out}, and g_m/g_{ds}



(*a*)



(*b*)

Predicted technology behavior for (*a*) turn-on/turn-off currents and (*b*) the output resistance and the self gain versus drawn gate length at the indicated terminal bias.

Conclusions

❑ Approach

- Our previous source-referenced V_t-based (long-channel) drain current model is revised with bulk reference to preserve the model symmetry.
- The model has been extended to short-channel by adding all important short-channel and reverse short-channel effects.
- Gummel symmetry and tree-top tests are carried out to verify the model symmetry and continuity.

❑ Significance

- Contrary to the general belief, source-extrapolated V_t-based regional model does not necessarily mean asymmetry (i.e., asymmetry is not inherent in V_t-based model).
- Model continuity across regions of operation is an important criterion for analog circuit design, and our unified regional model has demostrated model smoothness with reasonable accuracy as well as symmetry not only for functional behavior but also its higher derivatives (g_m, g_{ds}, g_m', g_{ds}').
- Our unified regional model is calibrated based on "technology characeterization" approach due to being threshold-voltage based, which is "non-binnable" (i.e., binning is *not* an option). This makes the model scalable with reasonable accuracy and predictive for important device parameters such as I_{on}/I_{off} and g_m/g_{ds} over the entire given technology.