A Unified View of Drain Current Models for Undoped Double-Gate SOI MOSFETs

Adelmo Ortiz-Conde, Francisco J. García Sánchez, and Juan Muci

Solid State Electronics Laboratory
Universidad Simón Bolívar
Caracas, Venezuela

E-mail addresses: {ortizc, fgarcia}@ieee.org, jmuci@usb.ve
URL: http://pancho.labc.usb.ve

The Sixth Workshop on Compact Modeling at the Tenth International Conference on Modeling and Simulation of Microsystems, NSTI Nanotech 2007
Santa Clara, California, USA, May 20-24, 2007
http://www.nsti.org/Nanotech2007/WCM2007/

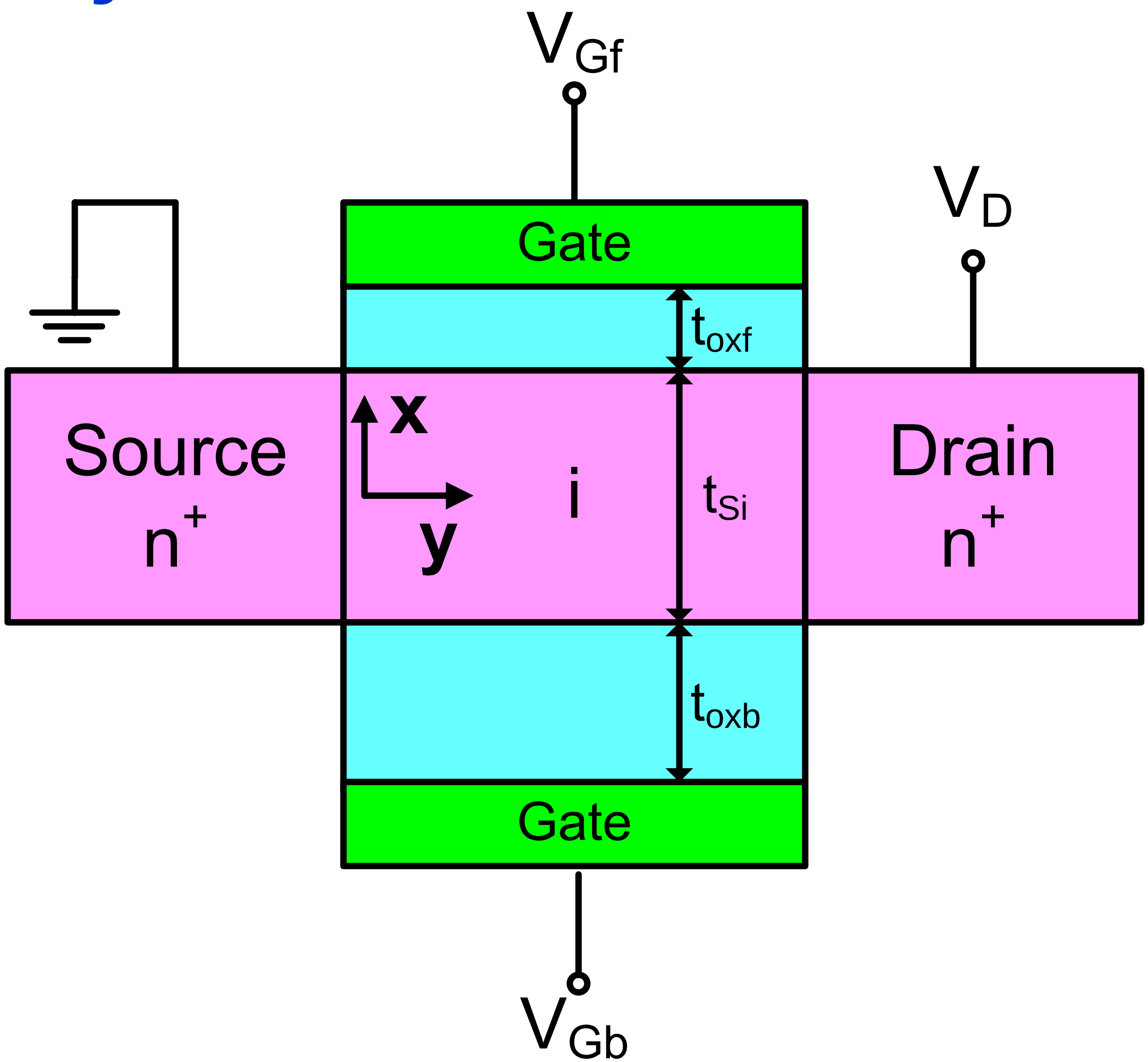
Motivation:

- **It is important to model both symmetric and asymmetric DG MOSFETs in a unified manner.**
- **Model must be valid for different front- and back-oxide thicknesses and for arbitrary front- and back-gate biases.**
- **Generalization may be achieved by noting that a 1-D solution of surface potential in the silicon, for given voltage along the channel, is valid for linear combinations of front- and back-gate biases and front- and back-oxide thicknesses.**

Contents:

- We will present a unified classical physics core model for the drain current of asymmetric and symmetric DG undoped-body MOSFETs. The model is valid even when the electric field does vanish inside the semiconductor body.
- The potential-based drain current model is rigorously transformed into a charge-based equation or into a mixed charge- and surface potential-based formulation.
- The mixed charge and surface potential formulation does not explicitly contain the front and back flatband voltages, oxide thicknesses, or gate biases, and therefore it is a description of the behavior inside the silicon body by itself.
- The drain current and transconductance formulations are continuously valid for all bias conditions, from subthreshold to strong inversion and from linear to saturation operation.

Asymmetric DG n-MOSFET



Drain current for Asymmetric DG n-MOSFET [1,2]:

$$I_D = \mu \frac{W}{L}\left(C_f + C_b + C_\alpha \right)$$

where:

$$C_f \equiv C_{of}\left[\left(V_{Gf} + \frac{2}{\beta}\right)\left(\psi_{sfL} - \psi_{Sf0}\right) - \frac{1}{2}\left(\psi_{sfL}^2 - \psi_{Sf0}^2\right)\right]$$

$$C_b \equiv C_{ob}\left[\left(V_{Gb} + \frac{2}{\beta}\right)\left(\psi_{sbL} - \psi_{sb0}\right) - \frac{1}{2}\left(\psi_{sbL}^2 - \psi_{sb0}^2\right)\right]$$

$$C_\alpha \equiv \frac{\varepsilon_s t_{Si}}{2}\left(\alpha_0 - \alpha_L\right)$$

and α is the charge coupling parameter [1,2].

This equation was originally obtained assuming that the electric field does not vanish inside the semiconductor body. We will prove that this is valid in general.

[1] A. Ortiz-Conde et al, "Drain Current and Transconductance Model for the Undoped Body Asymmetric Double-Gate MOSFET", ICSICT, Shanghai, China, pp. 1239-1242, Oct. 2006.

[2] A. Ortiz-Conde et al, "A Review of Core Compact Models for Undoped Double-Gate SOI MOSFETs", IEEE Trans. Electron Device, 54, pp. 131-140, Jan. 2007.

Previous potential equation can be rigorously transformed into a charge-based equation [1] :

$$I_D = \mu \frac{W}{L} \left\{ C_\alpha + \left[2v_t \left(Q_{sf0} - Q_{sfL} \right) - \frac{1}{2} \left(\frac{Q_{sfL}^2}{C_{of}} - \frac{Q_{sf0}^2}{C_{of}} \right) \right] + \left[2v_t \left(-Q_{sb0} + Q_{sbL} \right) - \frac{1}{2} \left(\frac{Q_{sbL}^2}{C_{ob}} - \frac{Q_{sb0}^2}{C_{ob}} \right) \right] \right\}$$

where

$$Q_{sf} \equiv + \varepsilon_s F_{sf} = + C_{of} \left(V_{Gf} - \psi_{sf} \right)$$

$$Q_{sb} \equiv + \varepsilon_s F_{sb} = - C_{ob} \left(V_{Gb} - \psi_{sb} \right)$$

$$v_t \equiv \frac{kT}{q}$$

[1] A. Ortiz-Conde et al, “Unification of Asymmetric DG, Symmetric DG and Bulk Undoped-body MOSFET Drain Current”, Solid-State Electronics, Vol. 50, pp. 1796–1800, November 2006.

Previous equation can also be rigorously transformed into a mixed charge- and surface potential-based formulation [1]:

$$I_D = \mu \frac{W}{L}\left\{ C_\alpha + \left[2v_t\left(Q_{sf0} - Q_{sfL}\right) + \frac{1}{2}\left(\psi_{sfL} - \psi_{sf0}\right)\left(Q_{sfL} + Q_{sf0}\right)\right] - \left[2v_t\left(Q_{sb0} - Q_{sbL}\right) + \frac{1}{2}\left(\psi_{sbL} - \psi_{sb0}\right)\left(Q_{sbL} + Q_{sb0}\right)\right] \right\}$$

Above expression is based only on the silicon body. It is convenient for studying different geometries and different operating conditions.

[1] A. Ortiz-Conde et al, “Unification of Asymmetric DG, Symmetric DG and Bulk Undoped-body MOSFET Drain Current”, Solid-State Electronics, Vol. 50, pp. 1796–1800, November 2006.

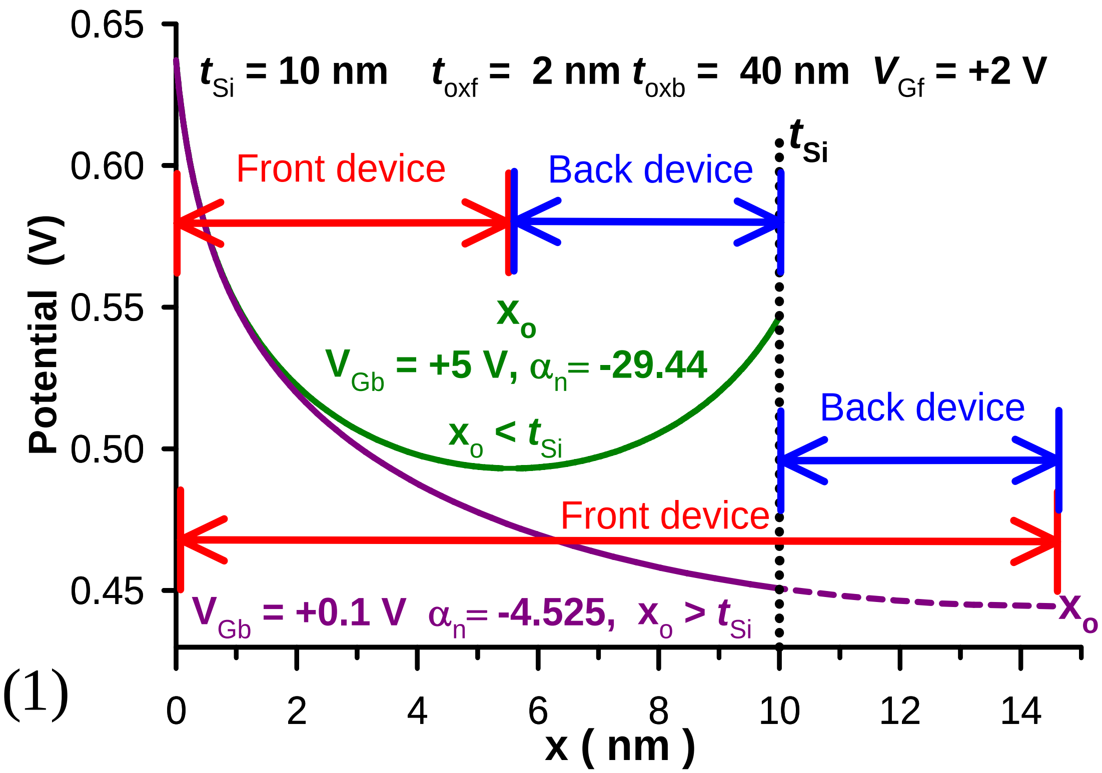
Analysis of a generic Asymmetric DG MOSFET

$$I_D = \mu \frac{W}{L} \int_0^{V_{DS}} Q_I \, dV$$

where

$$Q_I = \varepsilon_S \left(F_{sf} - F_{sb} \right) = \left(Q_{sf} - Q_{sb} \right)$$

$$I_D = \mu \frac{W}{L} \left(\int_0^{V_{DS}} Q_{sf} \, dV - \int_0^{V_{DS}} Q_{sb} \, dV \right) \quad (1)$$



The first term represents half the current of a symmetrical device from the front surface to 2 x_o (a silicon thickness of 2 x_o), that is:

$$\int_0^{V_{DS}} Q_{sf} \, dV = + \frac{\varepsilon_s}{4} \left(\alpha_0 - \alpha_L \right) \left(2 x_o \right) + 2 v_t \left(Q_{sf0} - Q_{sfL} \right) + \frac{1}{2} \left(\psi_{sfL} - \psi_{sf0} \right) \left(Q_{sfL} + Q_{sf0} \right) \qquad (2)$$

The second term represents half the current of a symmetrical device from the back surface to x_o (a silicon thickness of 2 (x_o - t_{Si})), that is:

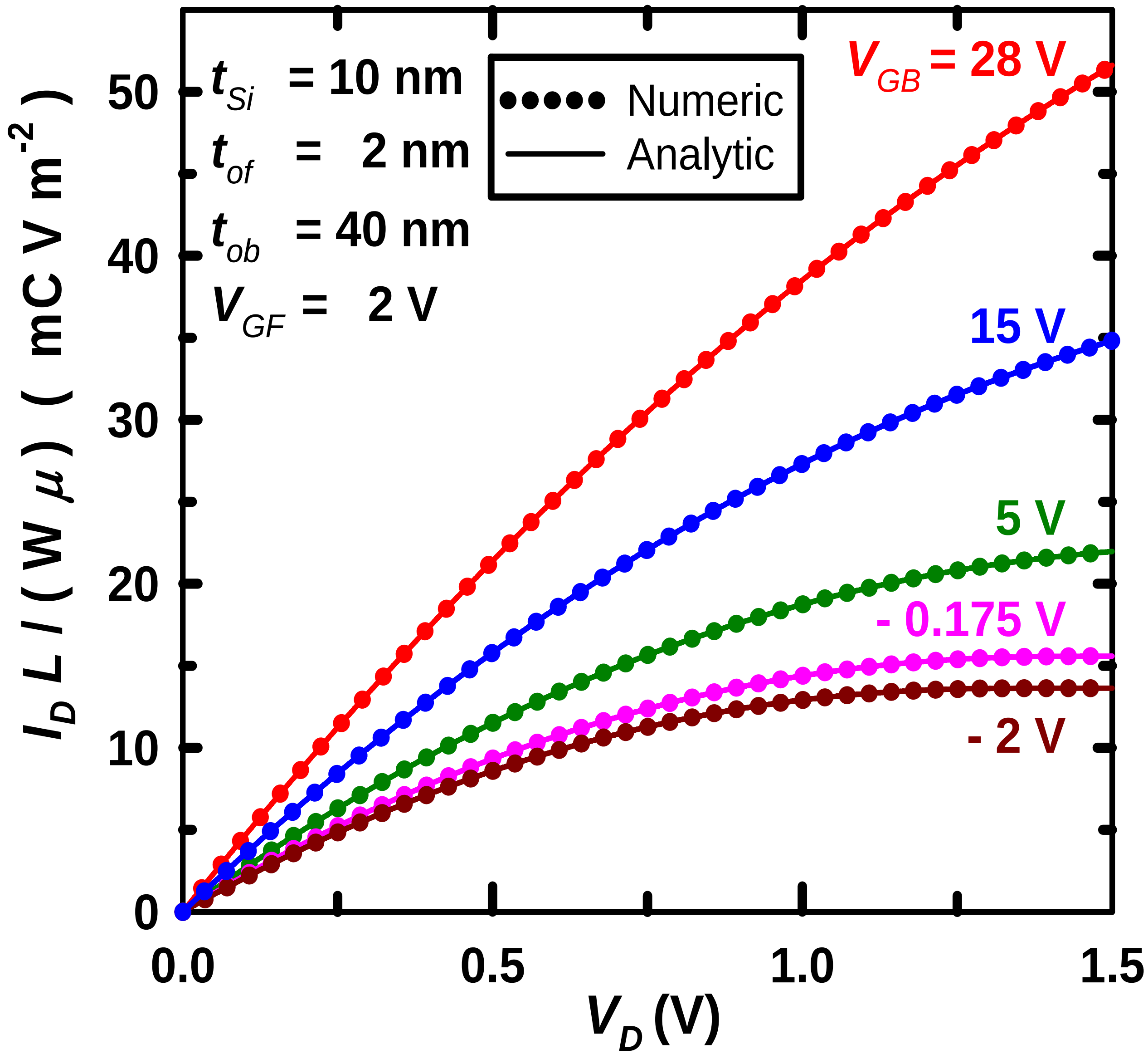
$$\int_0^{V_{DS}} Q_{sb} \, dV = + \frac{\varepsilon_s}{4} \left(\alpha_0 - \alpha_L \right) \left[2 \left(x_o - t_{SI} \right) \right] + 2 v_t \left(Q_{sb0} - Q_{sbL} \right) + \frac{1}{2} \left(\psi_{sbL} - \psi_{sb0} \right) \left(Q_{sbL} + Q_{sb0} \right) \qquad (3)$$

Substituting (2) and (3) into (1) we obtain our previous mixed charge- and surface potential-based formulation:

$$I_{\mathrm{D}} = \mu \frac{W}{L} \left\{ C_{\alpha} + \left[2v_{\mathrm{t}} \left(Q_{\mathrm{sf0}} - Q_{\mathrm{sfL}} \right) + \frac{1}{2} \left(\psi_{\mathrm{sfL}} - \psi_{\mathrm{sf0}} \right) \left(Q_{\mathrm{sfL}} + Q_{\mathrm{sf0}} \right) \right] - \left[2v_{\mathrm{t}} \left(Q_{\mathrm{sb0}} - Q_{\mathrm{sbL}} \right) + \frac{1}{2} \left(\psi_{\mathrm{sbL}} - \psi_{\mathrm{sb0}} \right) \left(Q_{\mathrm{sbL}} + Q_{\mathrm{sb0}} \right) \right] \right\}$$

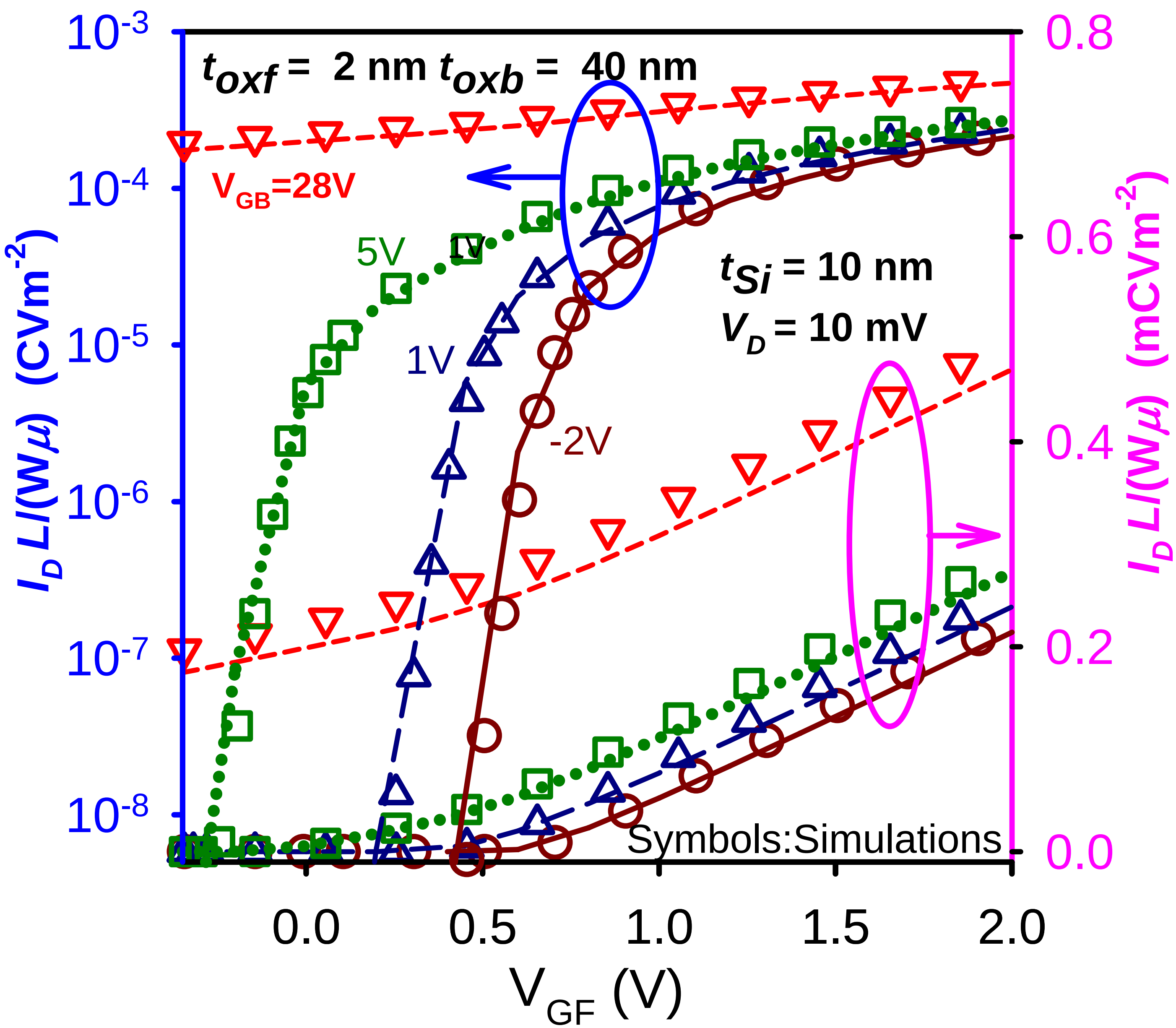
- **This expression is valid even if the electric field does vanish inside the semiconductor body.**
- **It is also valid for a symmetric device.**
- **It is completely equivalent to both the charge-based and the surface potential-based formulations previously presented.**

Comparison:
Normalized drain current as a function of drain voltage



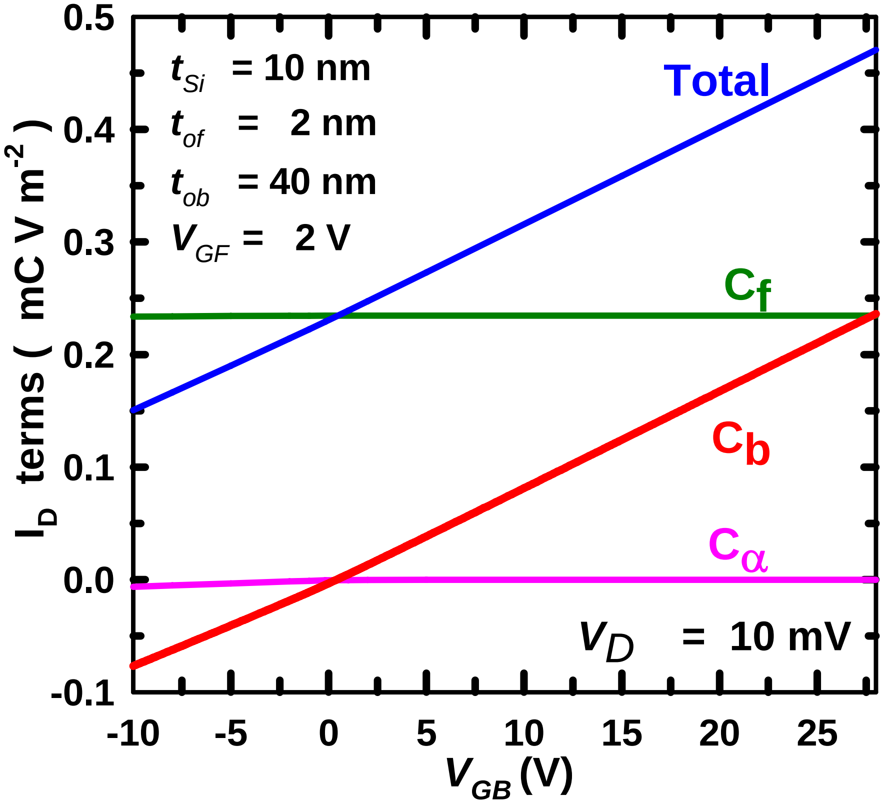
Workshop on Compact Modeling 2007, "A Unified View of Drain Current Models ...", A. Ortiz-Conde et al.

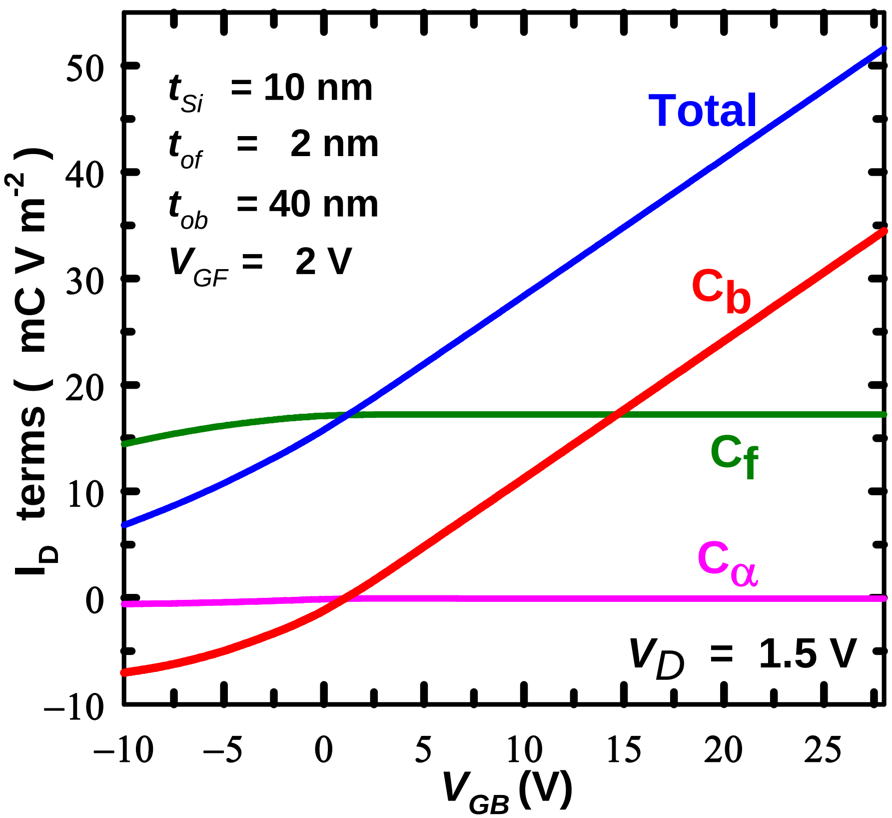
Effect of back gate bias on the transfer characteristics



Components of the drain current versus back gate bias

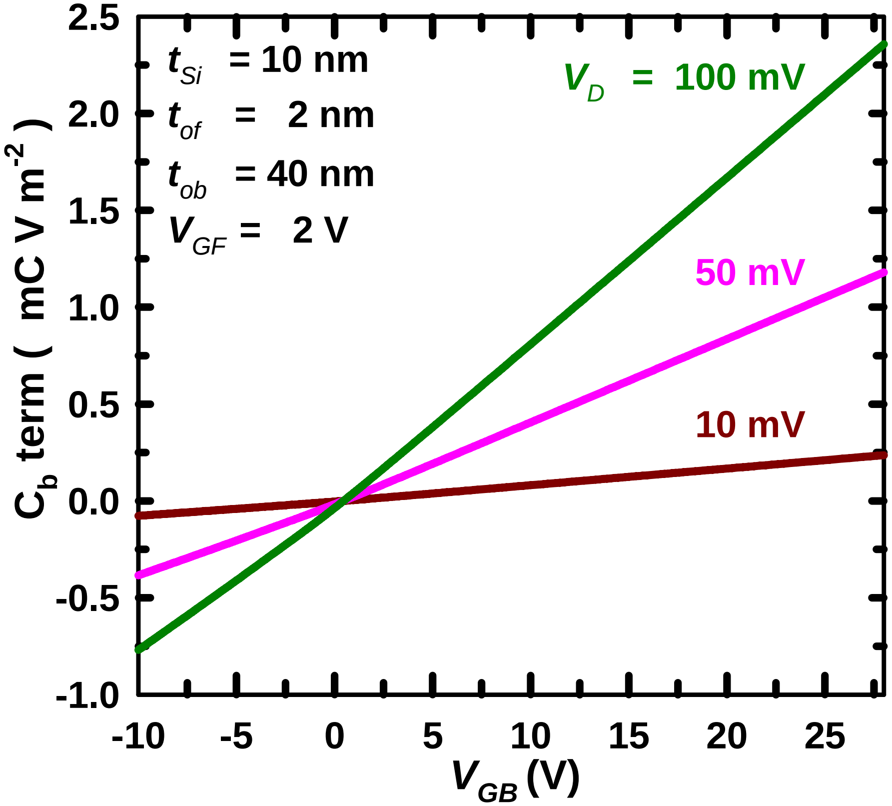
$$I_D = \mu \frac{W}{L}\left(C_f + C_b + C_\alpha \right)$$

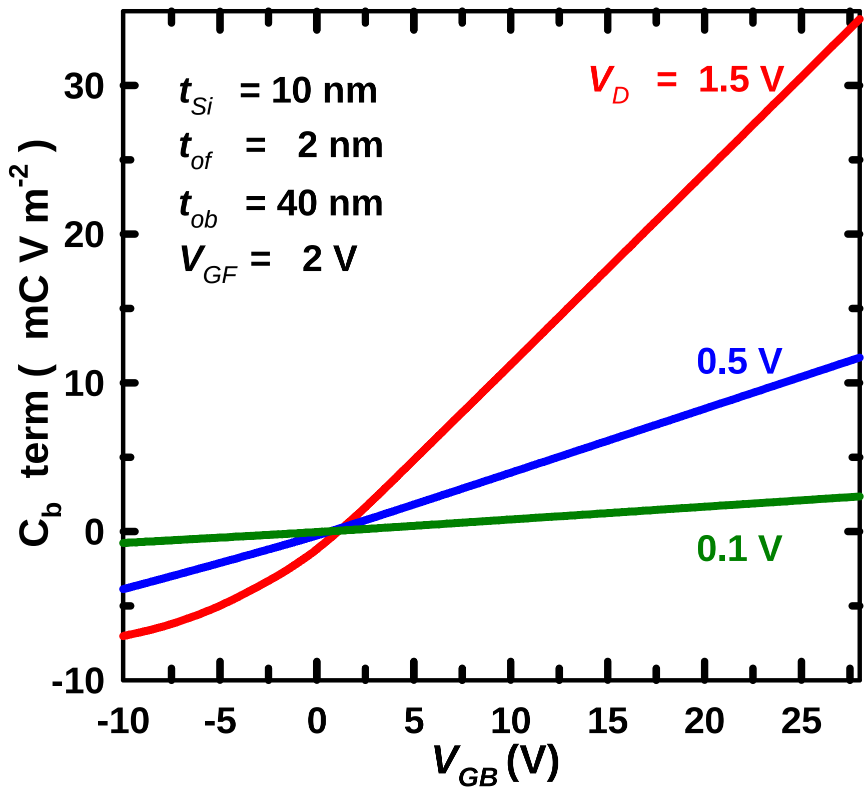




C_f is insensitive to V_{GB} because V_{GF} is above threshold.
C_b < 0 for values of V_{GB} corresponding to the condition $x_o > t_{Si}$ and C_b > 0 for $x_o < t_{Si}$.
C_α is negligible .
The device behaves as a symmetric device when $C_f = C_b$.

Back side component of the drain current versus the back gate bias



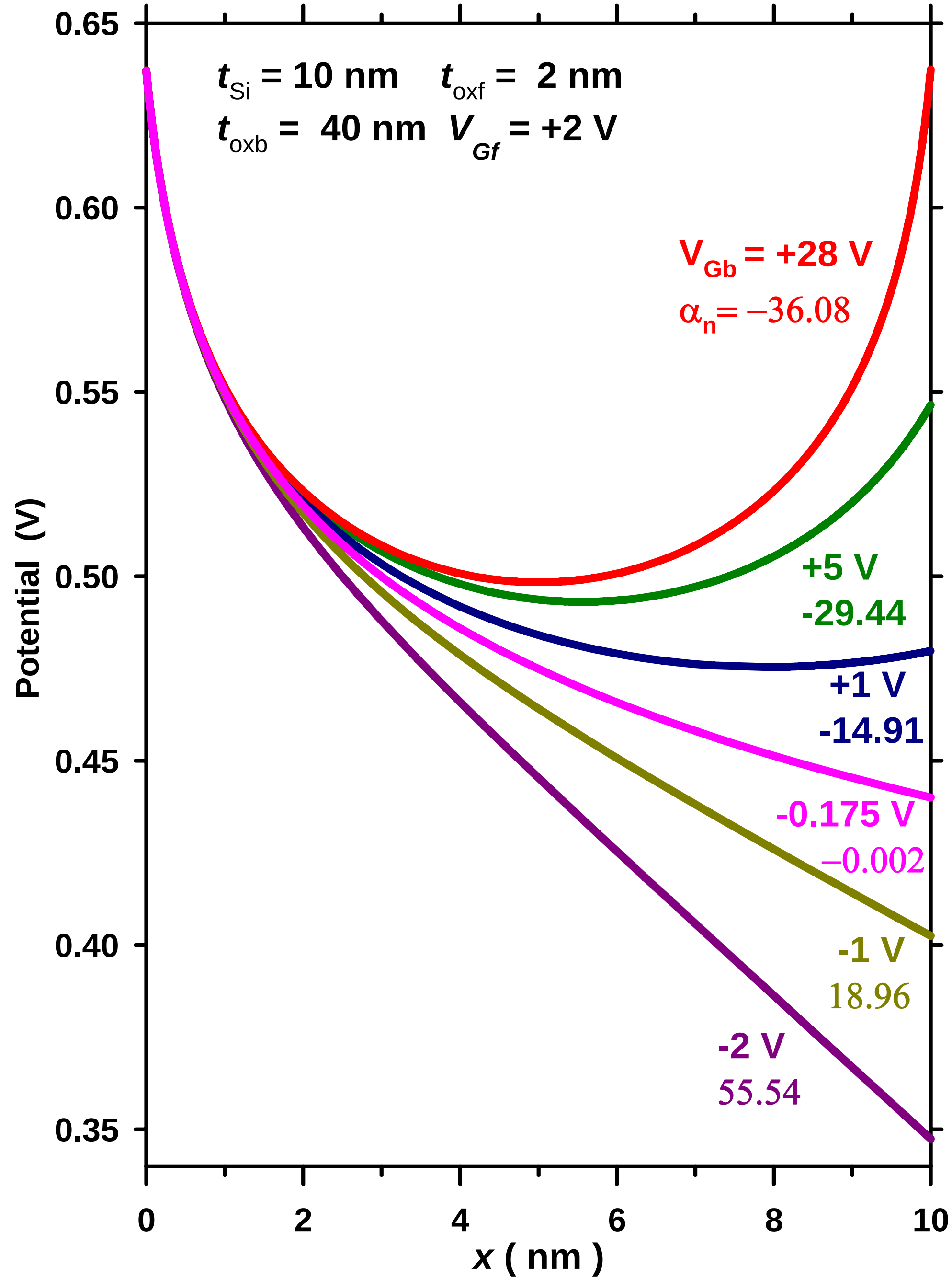


C_b is approximately proportional to V_{GB} for V_{GB} >> 0.

Potential distribution in the semiconductor body for various back-gate bias.

The resulting negative and positive values of α are indicated in each case.

For α>0 x_o is not real



Front and back transconductance equation for doped SOI MOSFET from 1993 [1]:

$$g_{mf} \equiv \frac{\partial I_{\mathrm{D}}}{\partial V_{\mathrm{Gf}}} = \frac{W}{L}\mu\, C_{\mathrm{of}}\left(\psi_{\mathrm{sfL}} - \psi_{\mathrm{sf0}}\right)$$

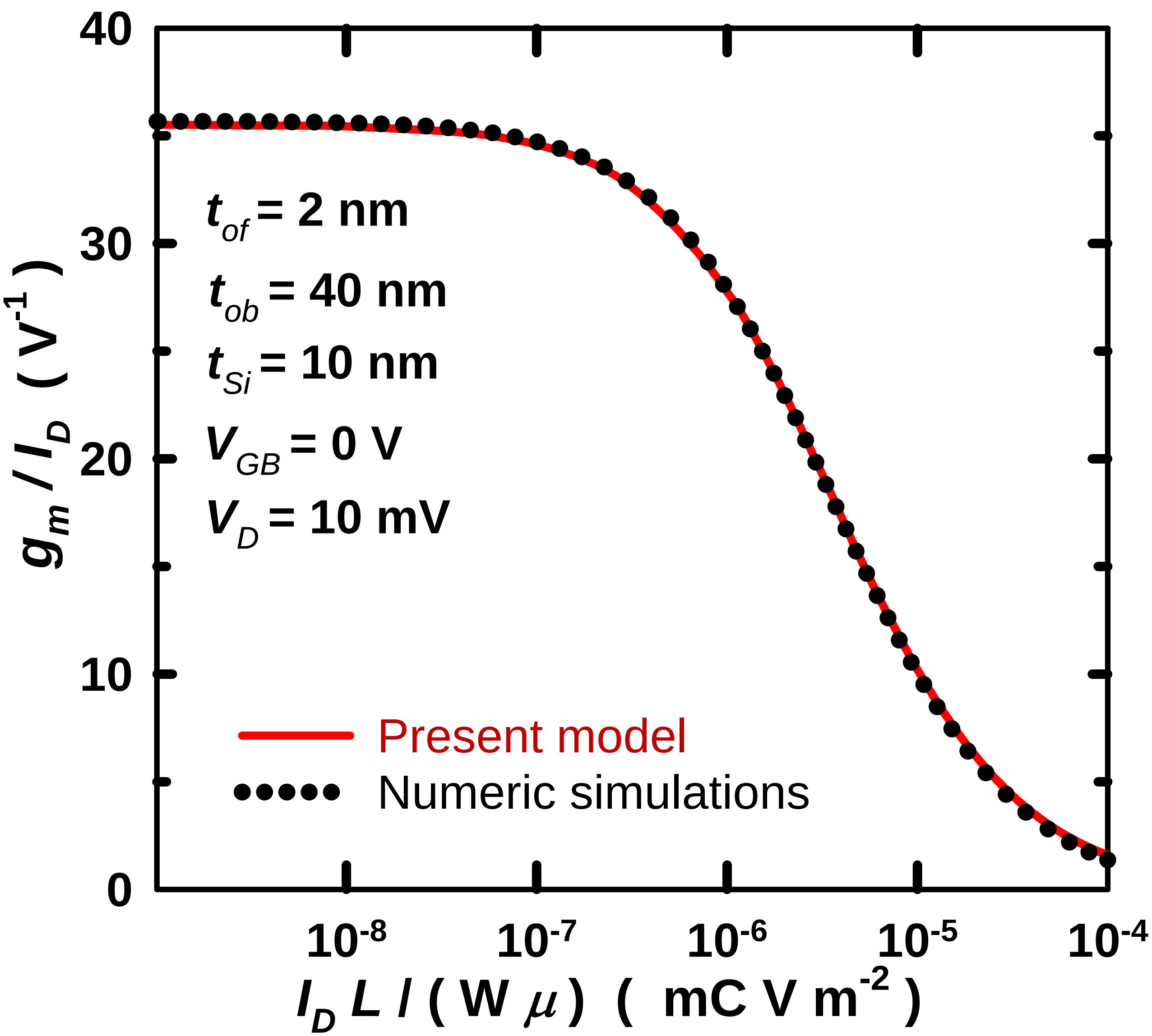
$$g_{mb} \equiv \frac{\partial I_{\mathrm{D}}}{\partial V_{\mathrm{Gb}}} = \frac{W}{L}\mu\, C_{\mathrm{ob}}\left(\psi_{\mathrm{sbL}} - \psi_{\mathrm{sb0}}\right)$$

where the subscripts “0” and “L” indicate evaluated at the “source” and “drain” respectively. These two equations are also valid [2] for undoped Asymmetric DG MOSFET.

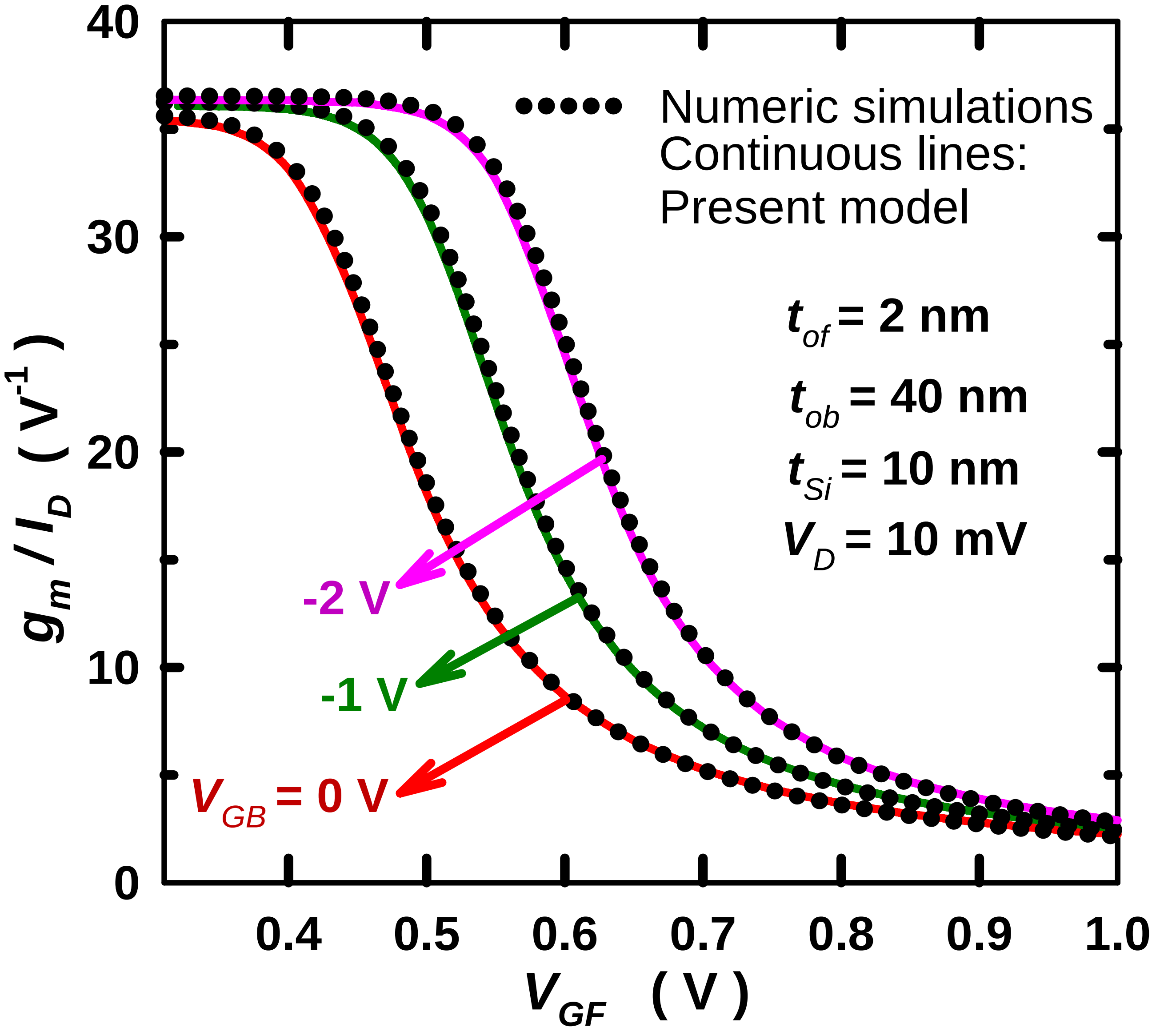
[1] A. Ortiz-Conde, F.J. García Sánchez, P.E. Schmidt, J. Andrian, and E. Paris, "Transconductances of the long-channel silicon-on-insulator MOSFET", Solid-State Electronics, vol. 36, pp. 631-637, April 1993.

[2] A. Ortiz-Conde et al, "Drain Current and Transconductance Model for the Undoped Body Asymmetric Double-Gate MOSFET“, ICSICT, Shanghai, China, pp. 1239-1242, Oct. 2006.

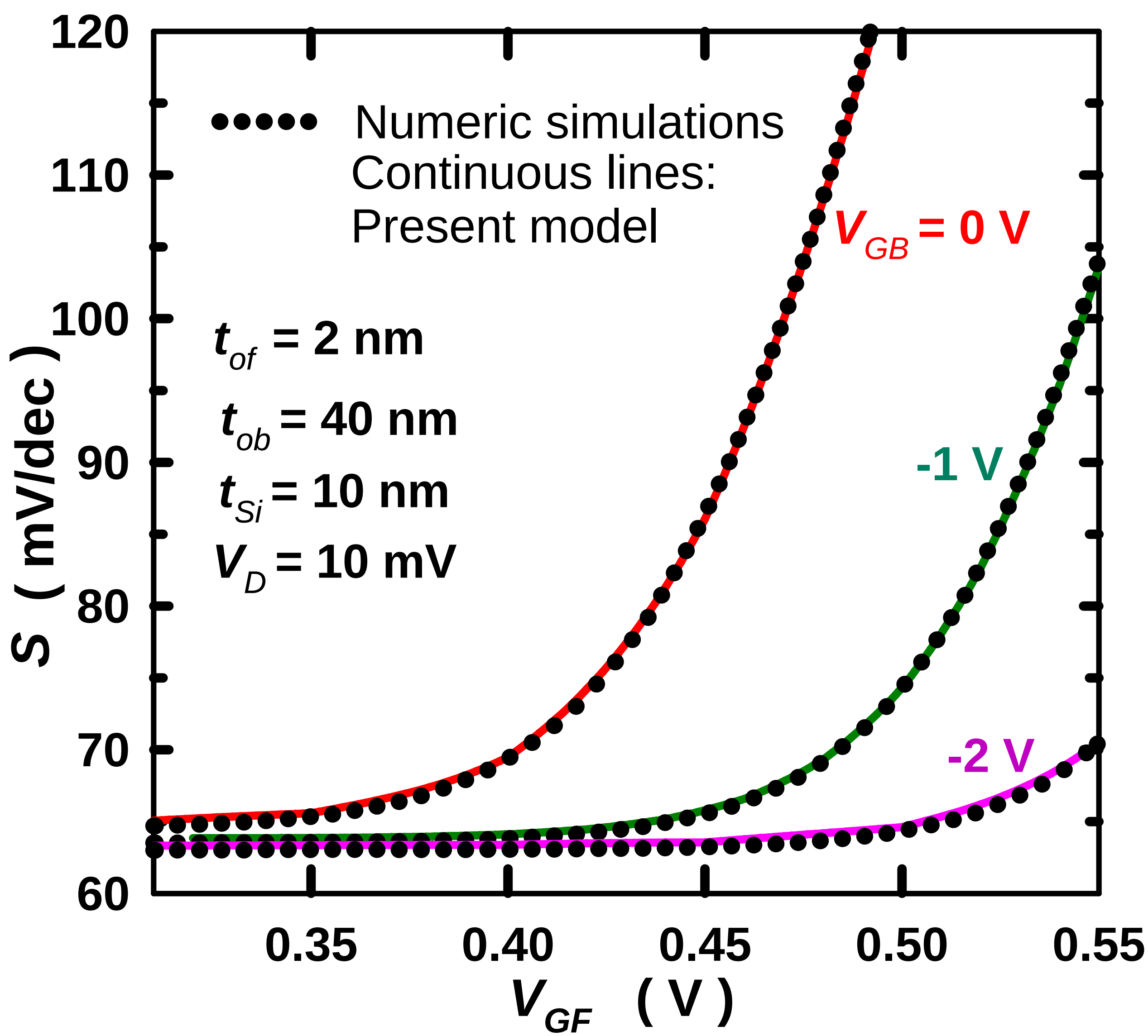
Comparison:
Front transconductance to current ratio



Front transconductance to current ratio for three back gate voltages



Subthreshold slope factor and back gate voltage



Conclusions :

- Our recent analytic potential-based drain current classical physics model for undoped-body asymmetric DG MOSFETs was originally obtained by assuming that the electric field does not vanish inside the semiconductor body.
- We have now proved that this model is also valid even when the electric field does vanish inside the semiconductor body. Therefore, the original assumption has been removed.
- The potential-based drain current model can be rigorously transformed into:

  a charge-based equation or into

  a mixed charge- and surface potential-based formulation.
- The mixed charge- and surface potential-based formulation is based only on the silicon body and it is convenient for studying different geometries and different operating conditions.
- The drain current and transconductance formulations are continuously valid for all bias conditions, from subthreshold to strong inversion and from linear to saturation operation.

END of presentation

Thank you for your attention

Solid State Electronics Laboratory
Universidad Simón Bolívar
Caracas, Venezuela