Theory and Modeling Techniques Used in PSP Model

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PHILIPS

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PSP Project Overview

- Development of the most advanced surface-potential-based model by merging SP and MM11
- Increasing physical content of the standard MOSFET model by solving several long-standing problems of compact modeling
- Incorporating all or most of the features required and expected by model user community for the next generation of compact models
- Working in close contact with the industry as represented by Compact Model Council
- Whenever possible, incorporating the best features of other compact models

Surface Potential

Considerations

- Surface potential equations (SPE)
- Accuracy of analytical approximation including large forward biases of s/b junction
- Retrograde profiles

Different Forms of SPE

$$(V_{GB} - V_{FB} - \psi_s)^2 = \gamma^2 \phi_T \left\{ e^{-u} + u - 1 + \frac{n_b}{p_b} k_n \left[e^u - u - 1 - \chi(u) \right] \right\}$$

$$u = \psi_s / \phi_T ; \quad k_n = \exp(-V_n / \phi_T)$$

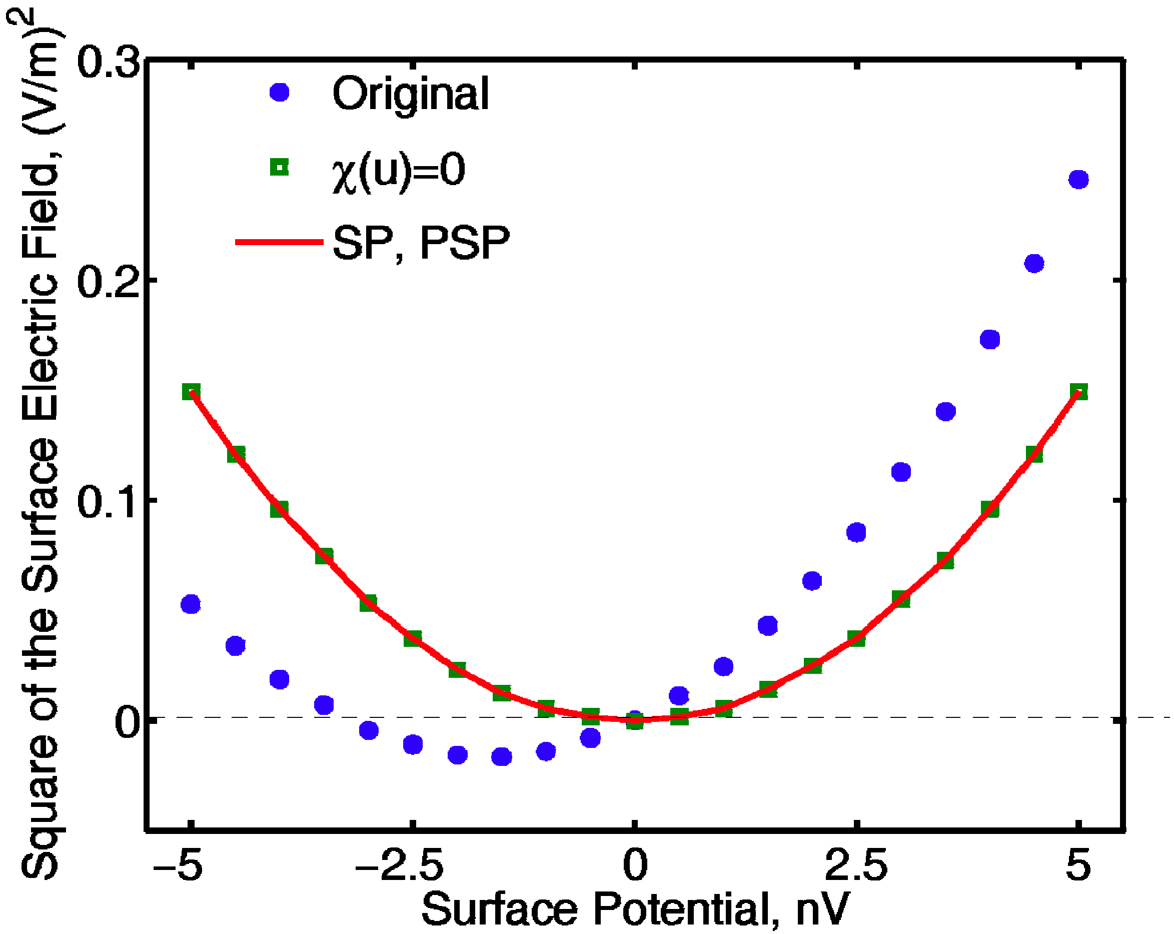
Pao-Sah: $\chi(u) = u(k_n^{-1} - 1)$

McAndrew and Victory, Wu et al.: $\chi(u) = 0$

PSP: $\chi(u) = u^2 / (2 + u^2)$

- All forms of SPE are numerically identical except for
  - narrow regions (nV) near flat-band voltage
  - high forward bias
- This has nothing to do with numerical or analytical calculation of surface potential

Bug that Escaped Detection for 35 years



C. McAndrew and J. Victory, 2002;
W. Wu, T.L. Chen, G. Gildenblat and C. McAndrew, 2004

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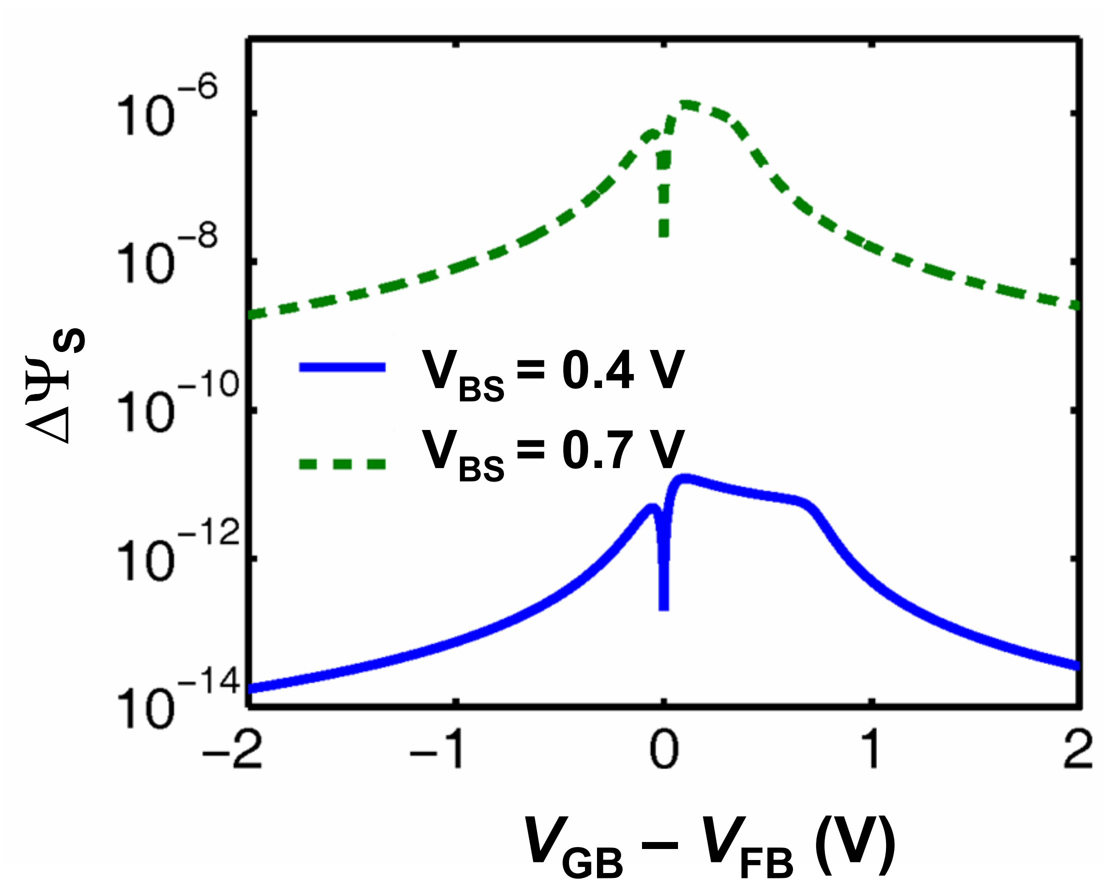
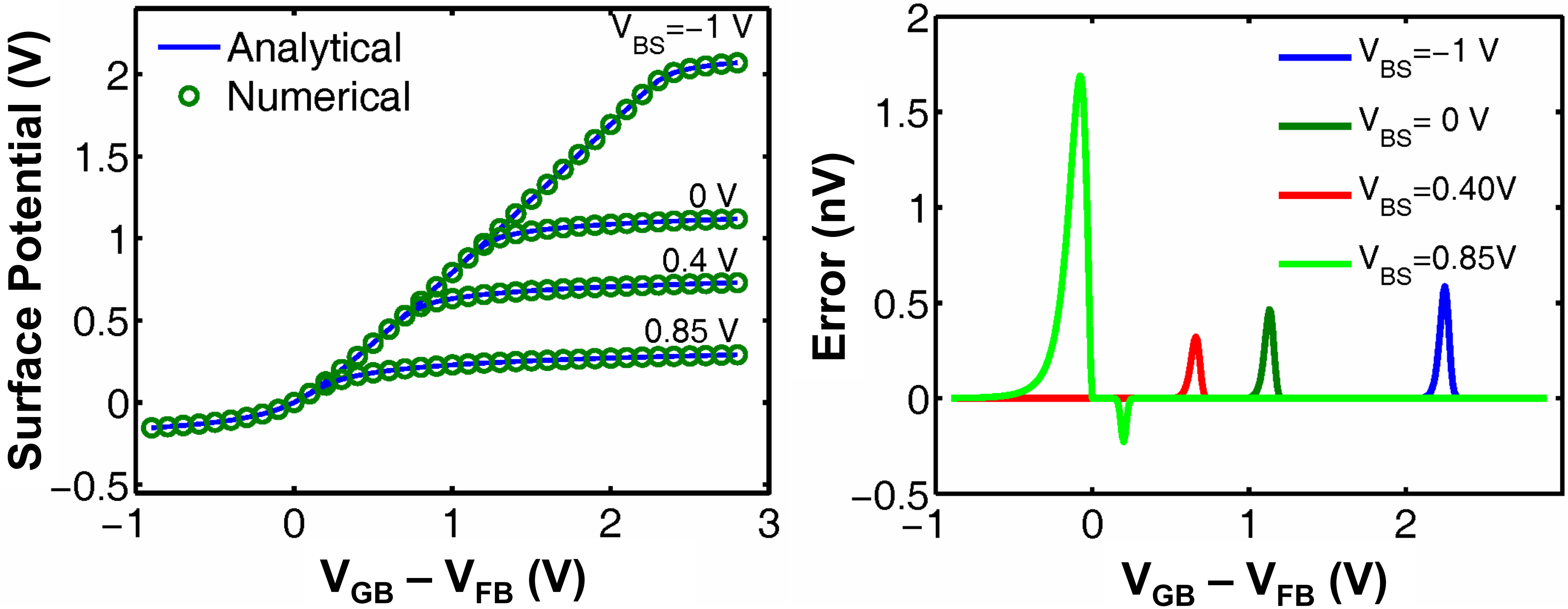
Surface Potential Difference for $\chi(u)=0$ and $\chi(u)=u^2/(2+u^2)$



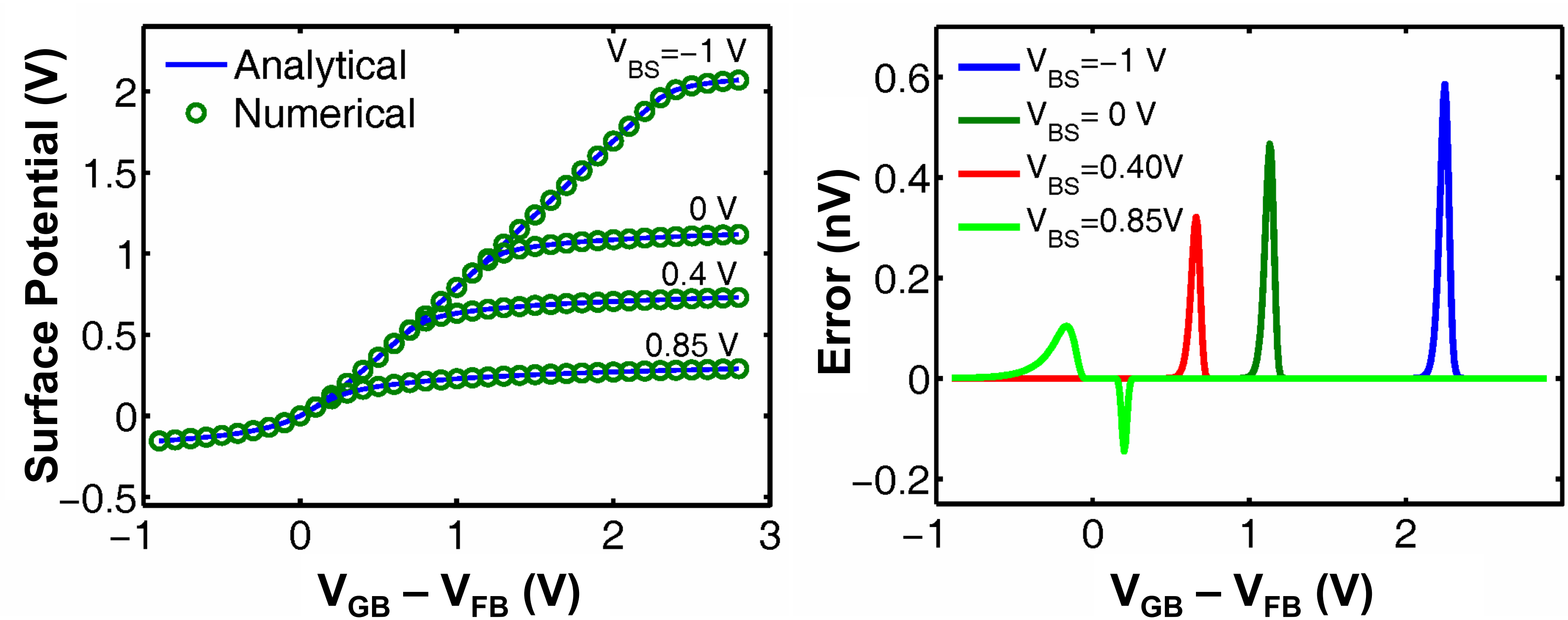
For $V_{BS} \leq 0$ the difference is below 1 fV. $N_{SUB} = 5\times10^{17}cm^{-3}$, T_{ox}= 2nm, V_{FB} = -1V.

Analytical Approximation for Surface Potential, $\chi(u)=0$



$N_{SUB} = 5\times10^{17}cm^{-3}$, T_{ox}= 2nm, V_{FB} = -1V.

Analytical Approximation for Surface Potential, $\chi(u)=u^2/(2+u^2)$



N_{SUB} = 5×10^{17}cm^{-3}, T_{ox}= 2nm, V_{FB} = -1V.

SPE Summary

- Rigorous integration of Boltzmann-Poisson Equation is possible for MOSCAP, impossible for MOSFET (imref splitting is position dependent)
- Pao-Sah approximation of SPE is excellent except within 1-2 nV of flat-band
- Modifications (conditioning) of Pao-Sah SPE are neither less nor more rigorous than original formulation
- Outside of extremely narrow region near flat-band different forms of SPE are numerically indistinguishable

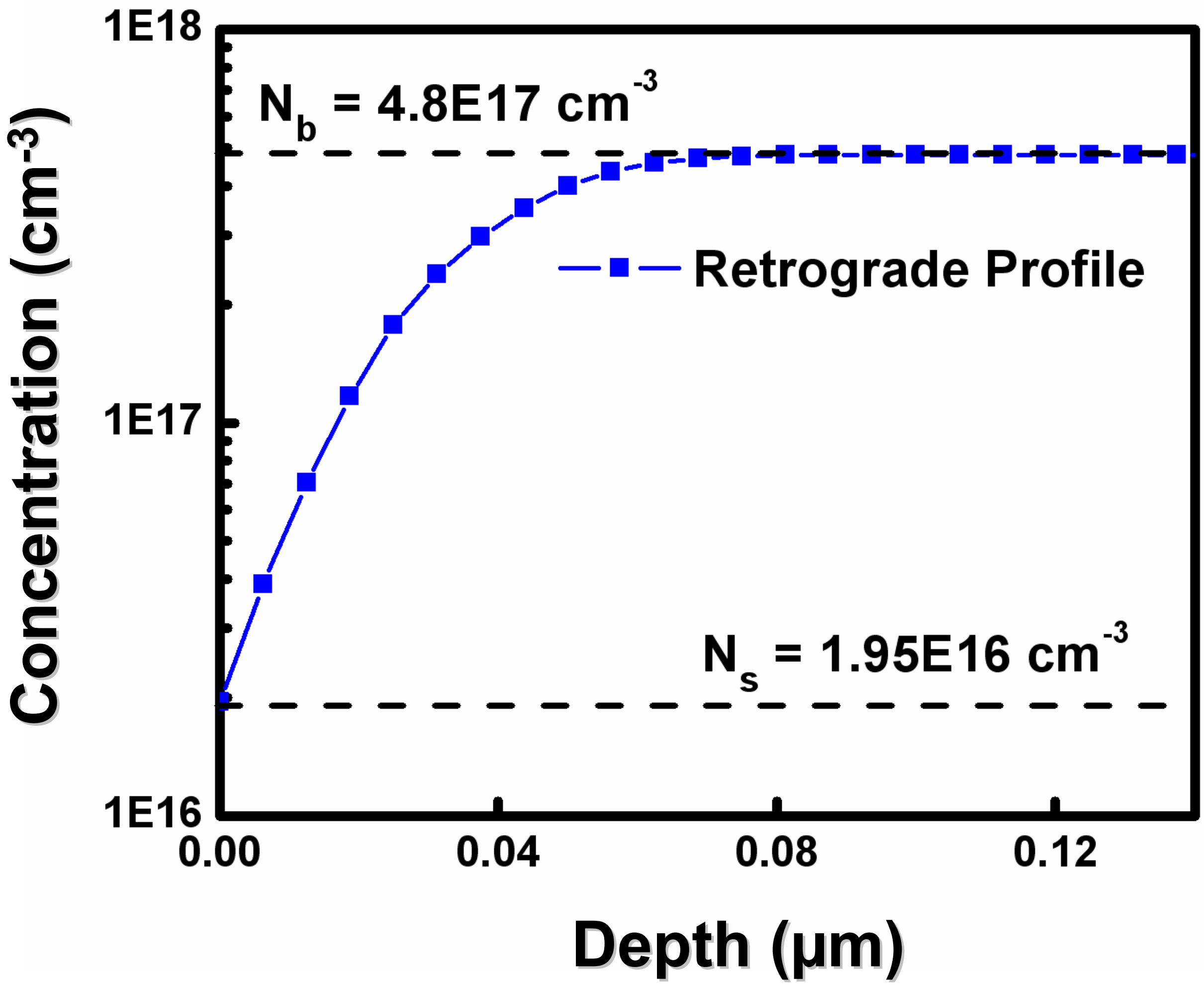
SPE Summary (continued)

- Whatever form of SPE is selected, analytical approximation is perfectly accurate
- Evaluate the accuracy using the same form of SPE for numerical and analytical solutions
- No negative consequences of any kind from using analytical approximation

Retrograde Doping

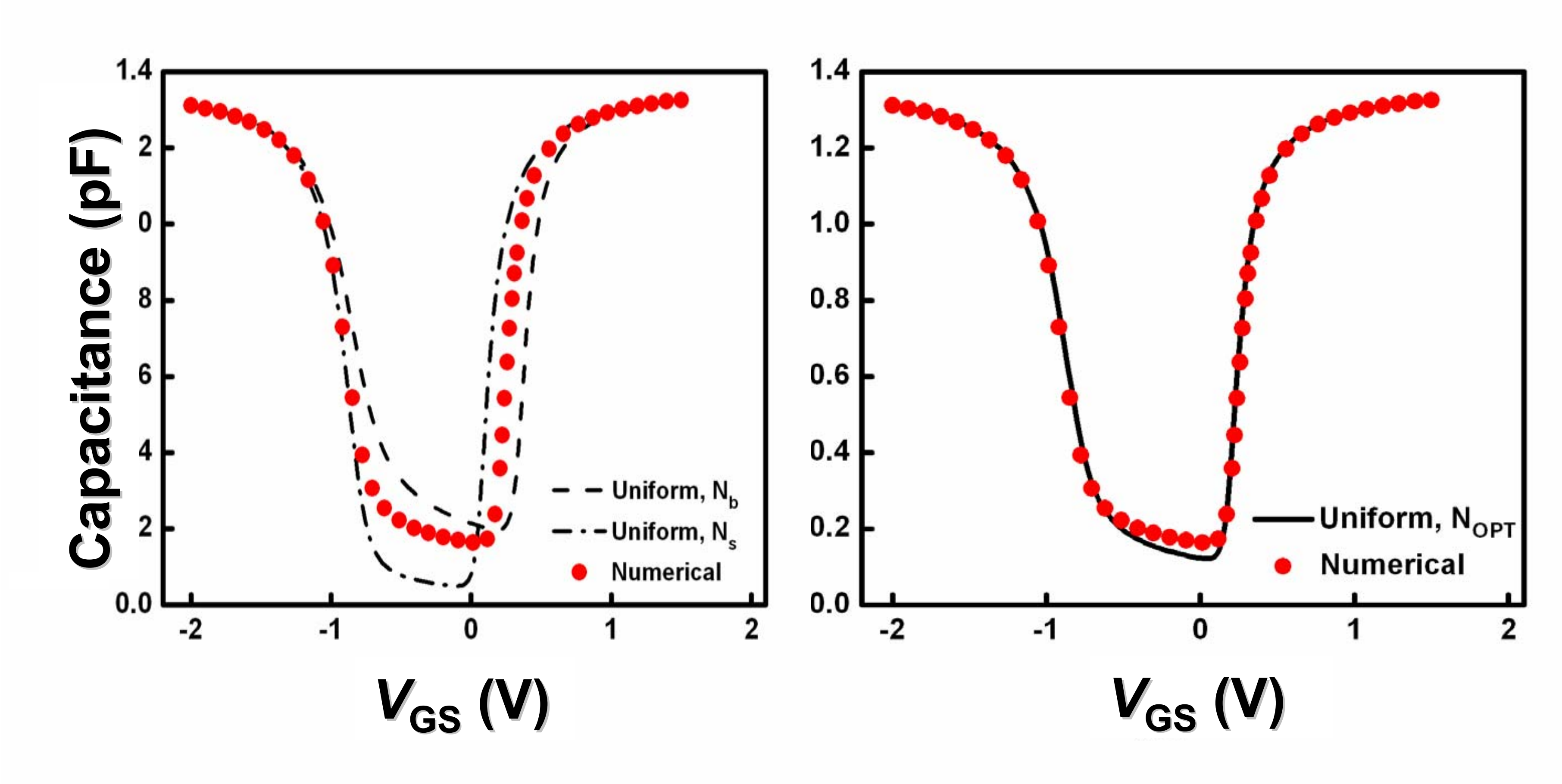
- Device characteristics are not as drastically affected as one may think
- Research in this direction has just begun
- Initial results are promising
- One idea: incremental charge is controlled by the doping at the depletion layer edge, effective doping is bias dependent

Retrograde Doping Profile



From P. Packan, Intel. Presented with permission.

C_{GG}-V_{GS} Plots for Different Substrate Doping Levels



$N_b = 4.8 \times 10^{17} cm^{-3}$ cm^{-3}, $N_s = 1.95 \times 10^{17} cm^{-3}$ cm^{-3}, and $N_{OPT} = 1.5 \times 10^{17} cm^{-3}$ cm^{-3}

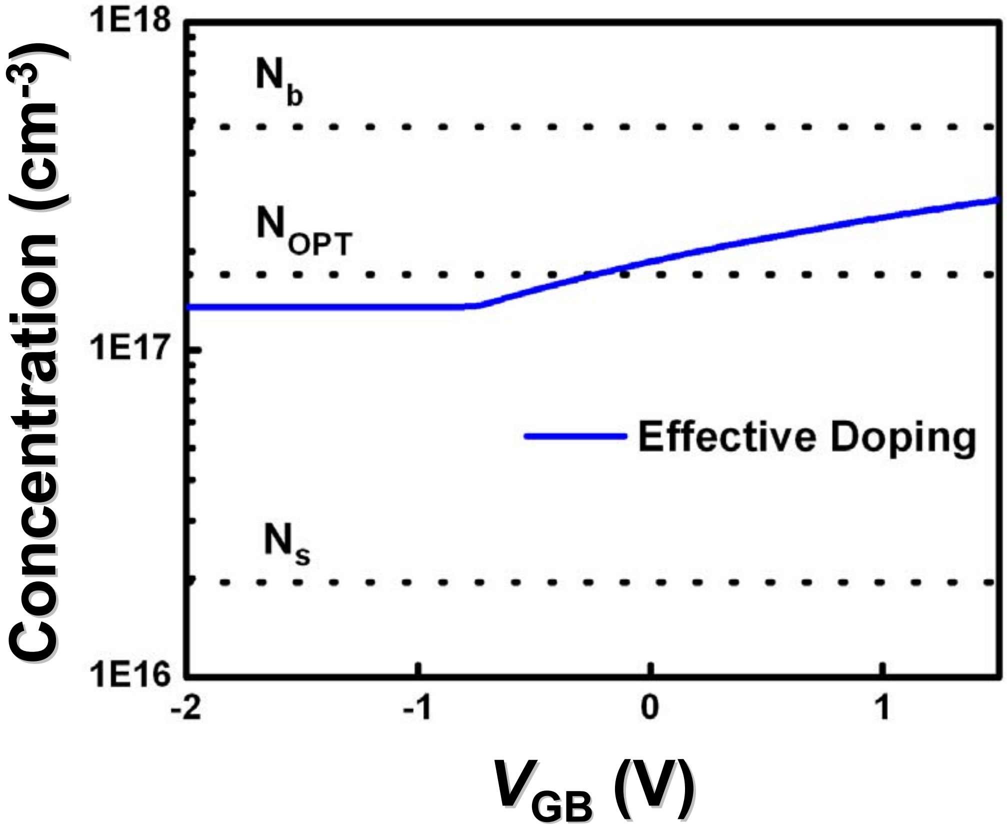
Bias-Dependent Doping

$$\left(V_{GB} - V_{FB} - \psi_s\right)^2 = \gamma^2 \phi_T \left\{ e^{-u} + u - 1 + \frac{n_b}{p_b} k_n \left[e^{u} - u - 1 - \chi(u) \right] \right\}$$

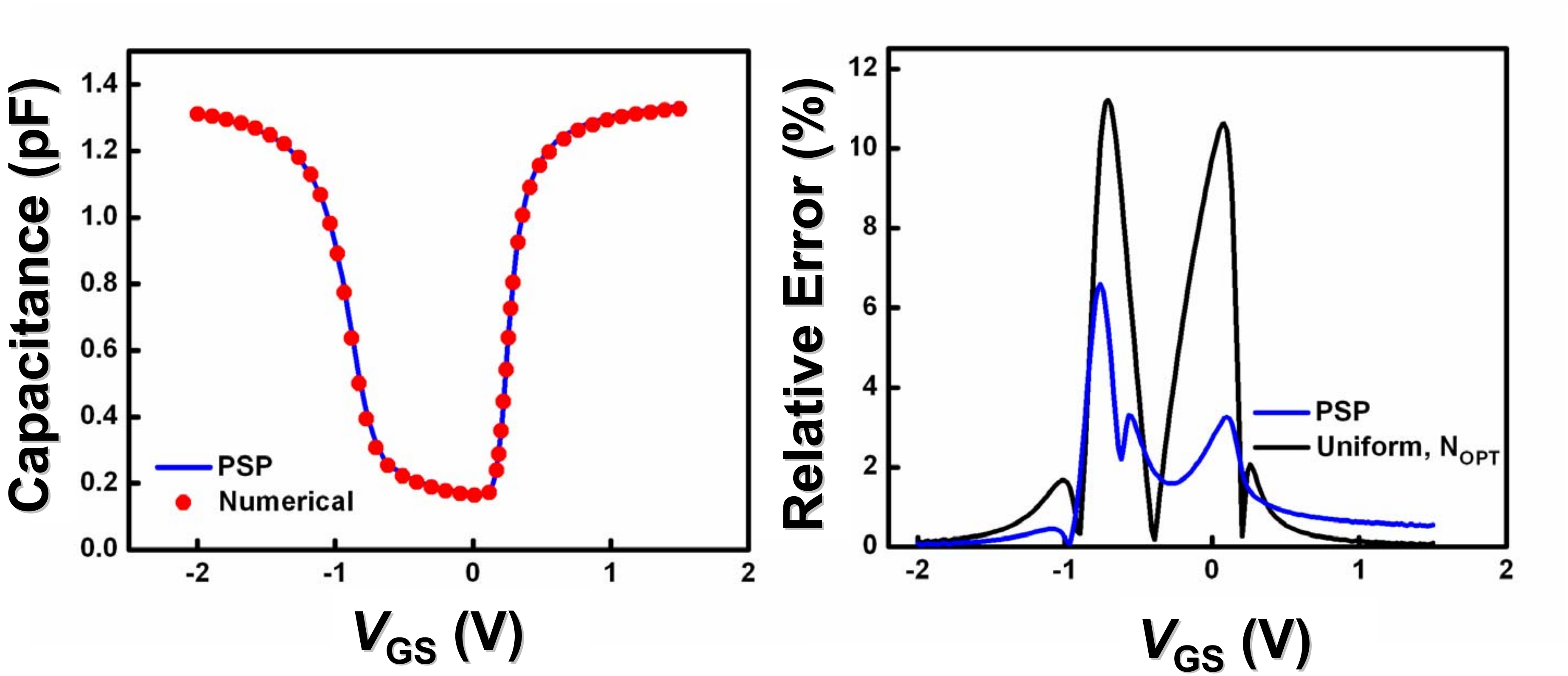
- Arora, 1987: $\gamma = \gamma(\psi_s)$
  - One-step approximation
  - Cannot easily be used in ψ_s- based models
  - SPE functional form changes
- PSP: $\gamma = \gamma(V_{GB})$
  - Same physics, different variable
  - SPE structure remains unchanged
  - Nothing else needs to be modified in the model

Gate Bias Dependence of Effective Doping

$$N = \mathrm{NSUB}\left[1 + \mathrm{DNSUB} \cdot f_s\left(V_g - \mathrm{VNSUB}\right)\right] \qquad f_s(v) = \frac{1}{2}\left(v + \sqrt{v^2 + \mathrm{NSLP}}\right)$$



Retrograde Doping in PSP



NSUB = 1.35×10^{17}cm^{-3} cm^{-3}, DNSUB = 0.5, VNSUB = -0.75, and NSLP = 0.001

Symmetric Linearization

- Objective
  - Simple expressions for drain current and terminal charges
  - Perfect symmetry
  - High accuracy
  - No negatives, no new trade-offs
- Details
  - Insensitivity to the form of the velocity-field relation
  - Higher-order conductances and transconductances
  - Gummel and McAndrew symmetry tests

Symmetric Linearization and Velocity Saturation

$$q_{i} = q_{im} - \alpha(\psi_{s} - \psi_{m}); \quad \psi_{m} = (\psi_{ss} + \psi_{sd})/2$$

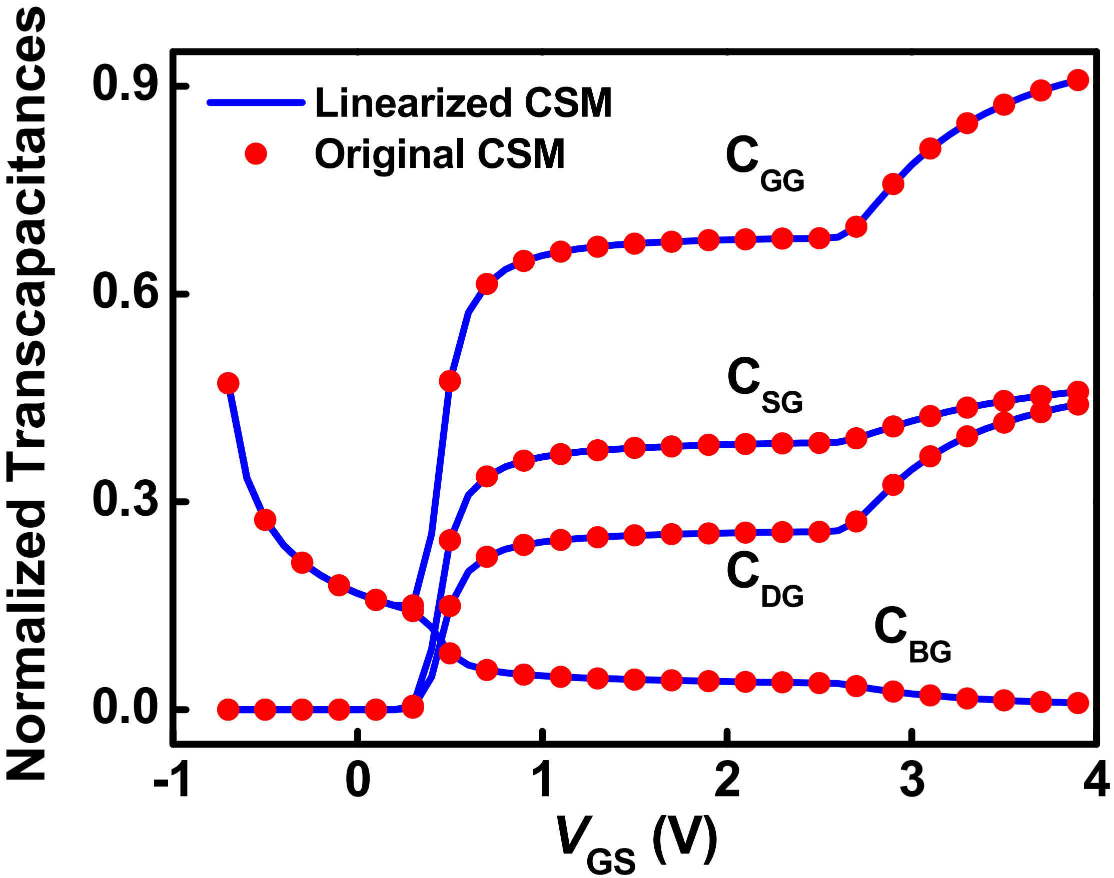
$$I_{DS} = \frac{\mu_{eff} W q_{im}^{*}}{\sqrt{1+(E_{y}/E_{c})^{2}}} \cdot \frac{d\psi_{s}}{dy}; \quad q_{im}^{*} = q_{im} + \alpha\phi_{T}$$

$$I_{DS} = \frac{\mu_{eff}}{G_{vsat}} \cdot \frac{W}{L} \cdot q_{im}^{*} \cdot \Delta\psi; \quad \Delta\psi = \psi_{sd} - \psi_{ss}$$

$$G_{vsat} = \frac{1}{2}\left[1 + \sqrt{1 + 2(\theta_{sat}\Delta\psi)^{2}}\right]; \quad \theta_{sat} = \mu_{eff}\Big/(v_{sat} \cdot L)$$

- ❑ Simple expressions for charges, noise, gate current, etc.
- ❑ All benchmark tests are satisfied.

Verification of Symmetric Linearization

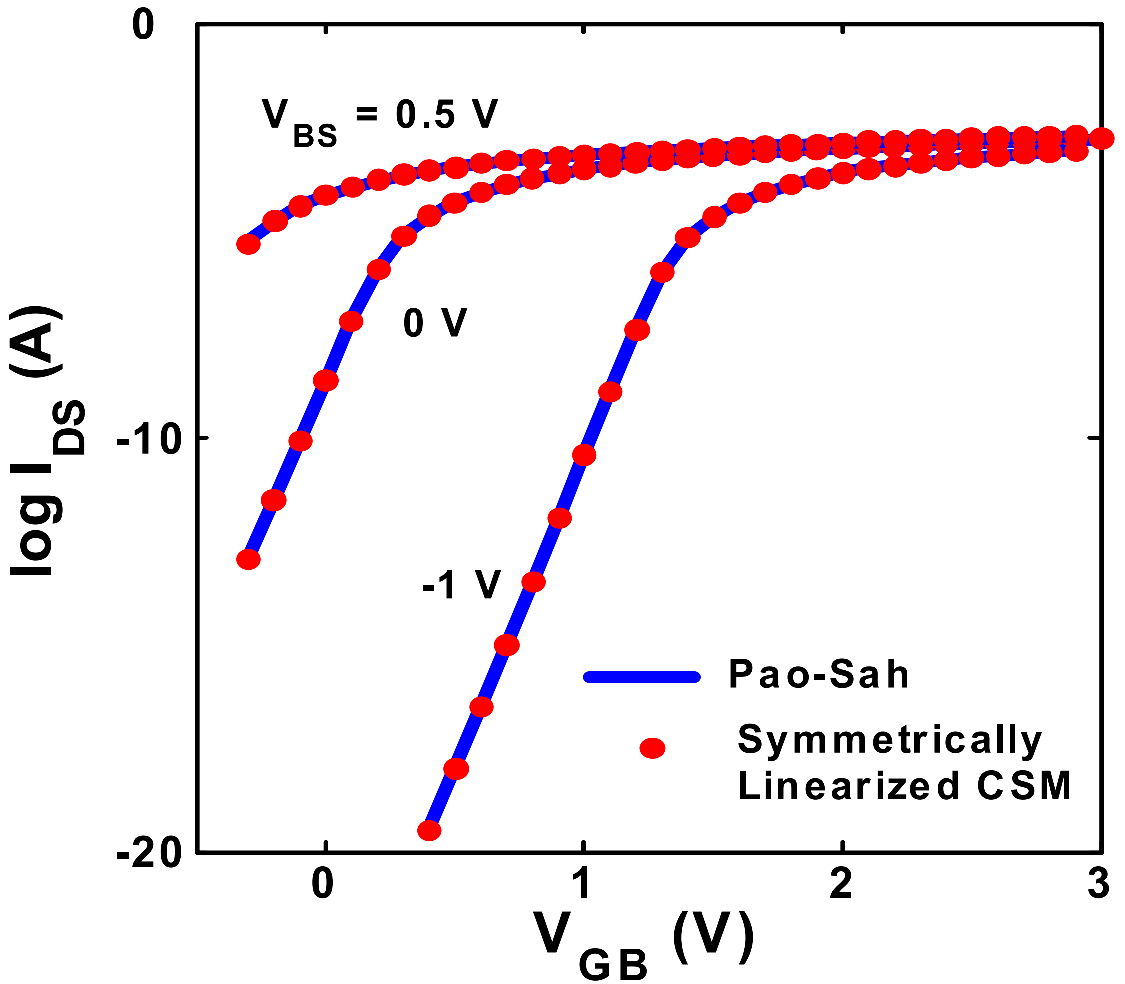


V_{DS} = 2V, V_{BS} = 0 V, V_{FB} = -1V

Comparison with Pao-Sah Model

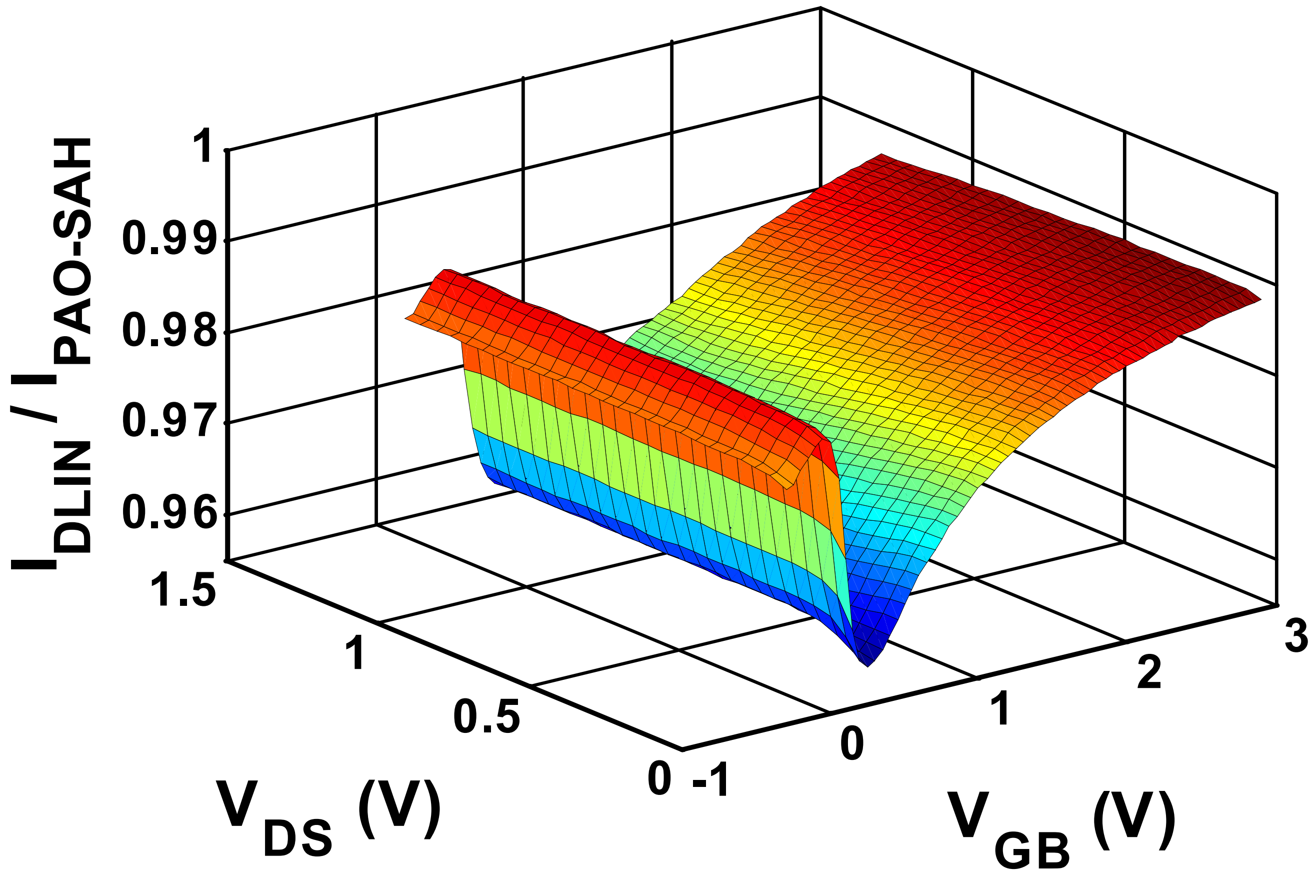
- Recent claims of 10% inaccuracy of CSM are inaccurate
- Direct comparison of symmetrically linearized CSM with Pao-Sah model validates symmetric linearization
- Accuracy is within 4% (usually better), totally adequate for compact modeling, other factors dominate

Comparison of Symmetrically Linearized CSM and Pao-Sah Models



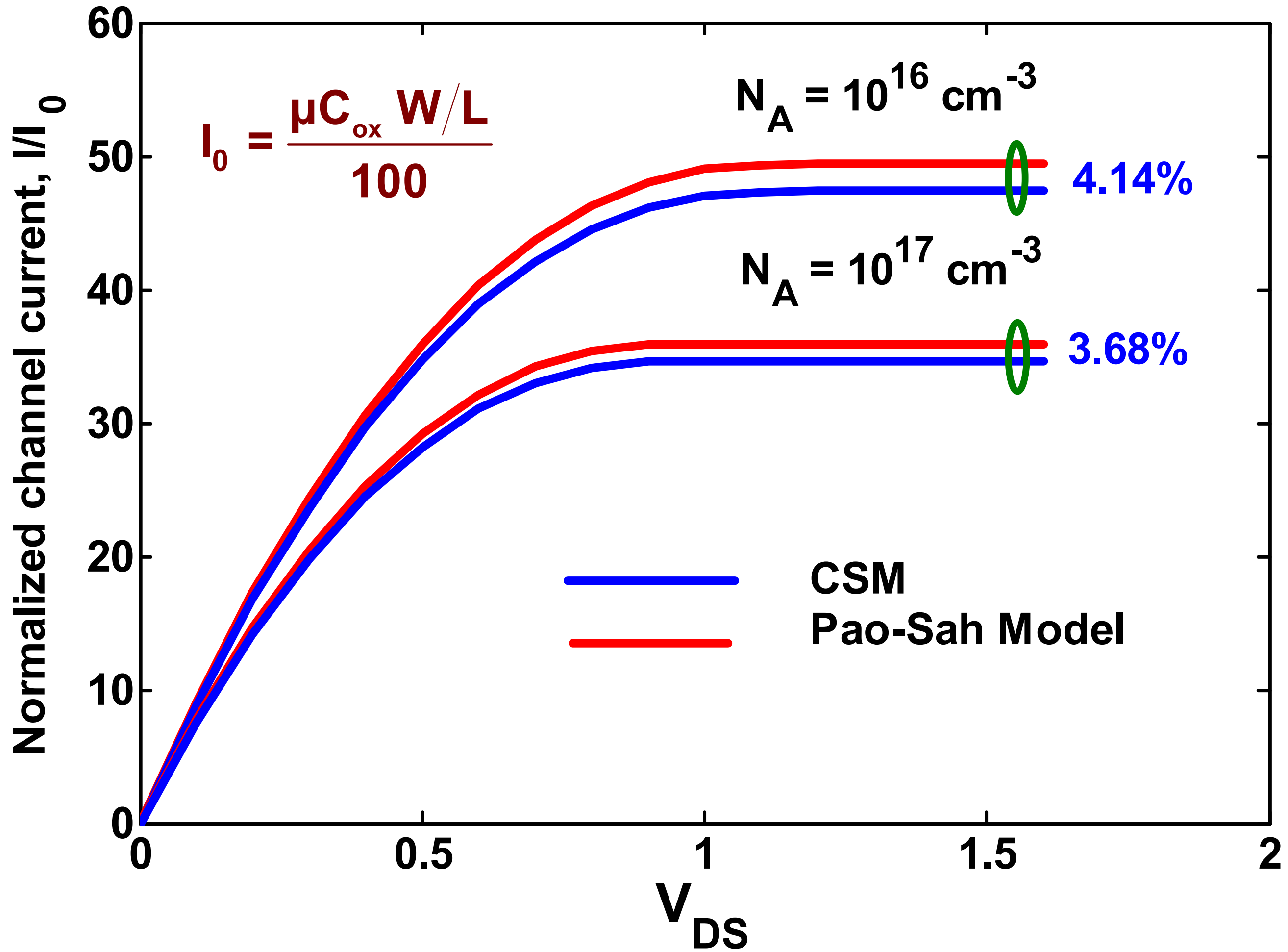
T= 27^{0}C, W/L= 2, T_{ox}= 2 nm, NSUB = 5×10^{17}cm^{-3}, μ= 400 cm^2/Vs, V_{DS}= 0.5V, V_{FB}= -1 V

Comparison of Symmetrically Linearized CSM and Pao-Sah Models



T = 27^{0}C, W/L = 2, T_{ox}= 2 nm, NSUB = 5×10^{17}cm^{-3}, μ = 400 cm^2/Vs, V_{FB}= -1 V, V_{BS} = 0 V

Comparison of Charge-Sheet and Pao-Sah Models (Revisited)



$T = 27^0C$, W/L =10/10μm, V_{FB}= -0.95 V, μ = 500 cm^2/Vs, V_{GS} = 1V, T_{OX} = 2nm

Recent Analysis of CSMs
He et al. SSE, vol. 50, p. 263 (2006)

- Accuracy of CSM relative to Pao-Sah is 10%.
  Actually, 4% - see previous slide for the same parameter values as in the cited paper
- Original SPE is “exact”
  Not really, see above
- SP, MM11, PSP do not include accumulation region in SPE
  They do, see code, results
- Symmetric linearization is “semi-empirical”
  Reality: nothing empirical, no new parameters

  Incorrect analysis: differences between CSM and symmetrically linearized CSM are reported for V_{DS}=0 (Fig. 4) where there is nothing to linearize.

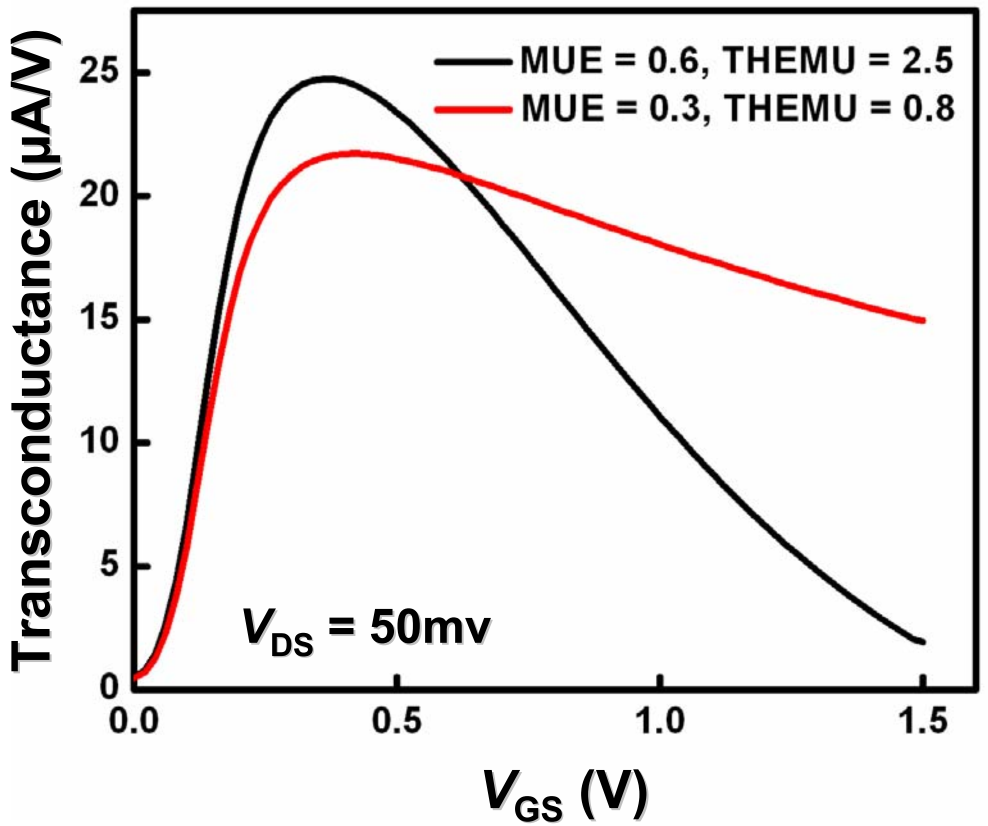
Mobility Model

- User side
  - Scalability
  - All features that proved to be useful over the years
  - Higher-order transconductances

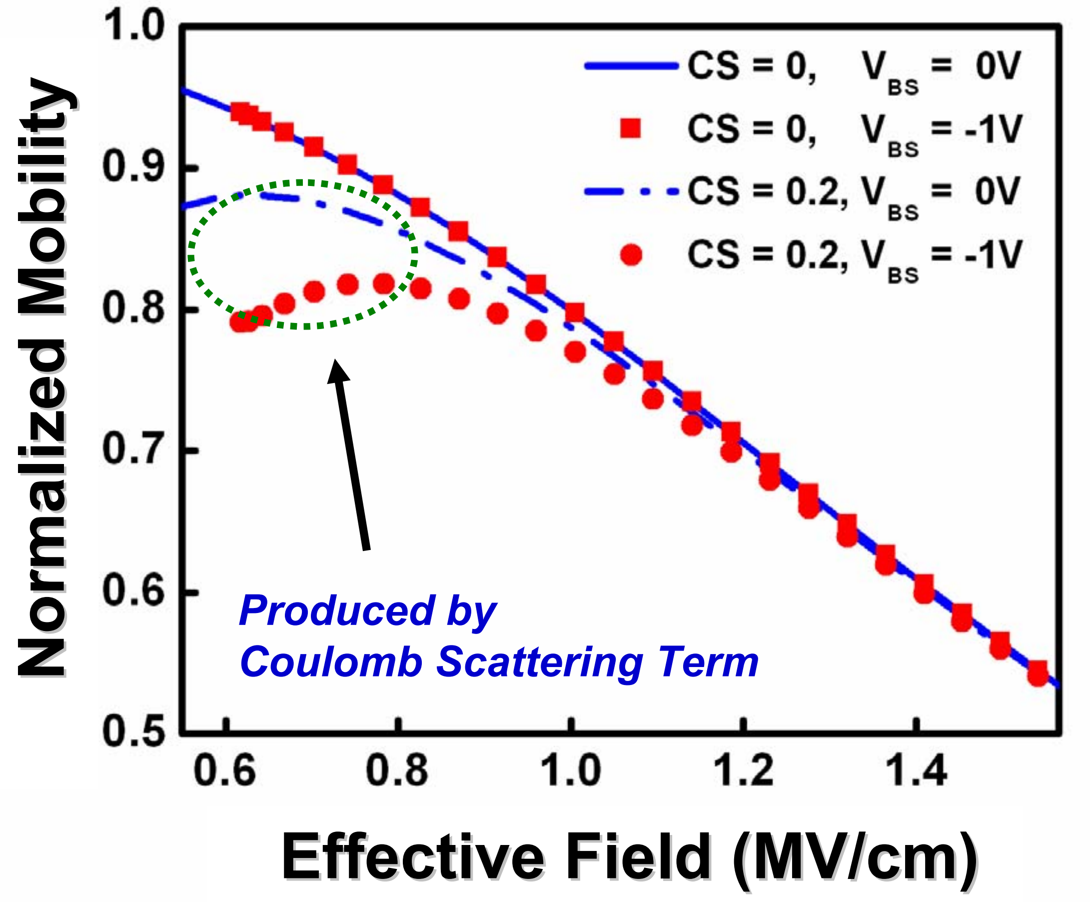
- Physics
  - Universal dependence on effective vertical field
  - Deviations from universality, Coulomb scattering

Mobility Model

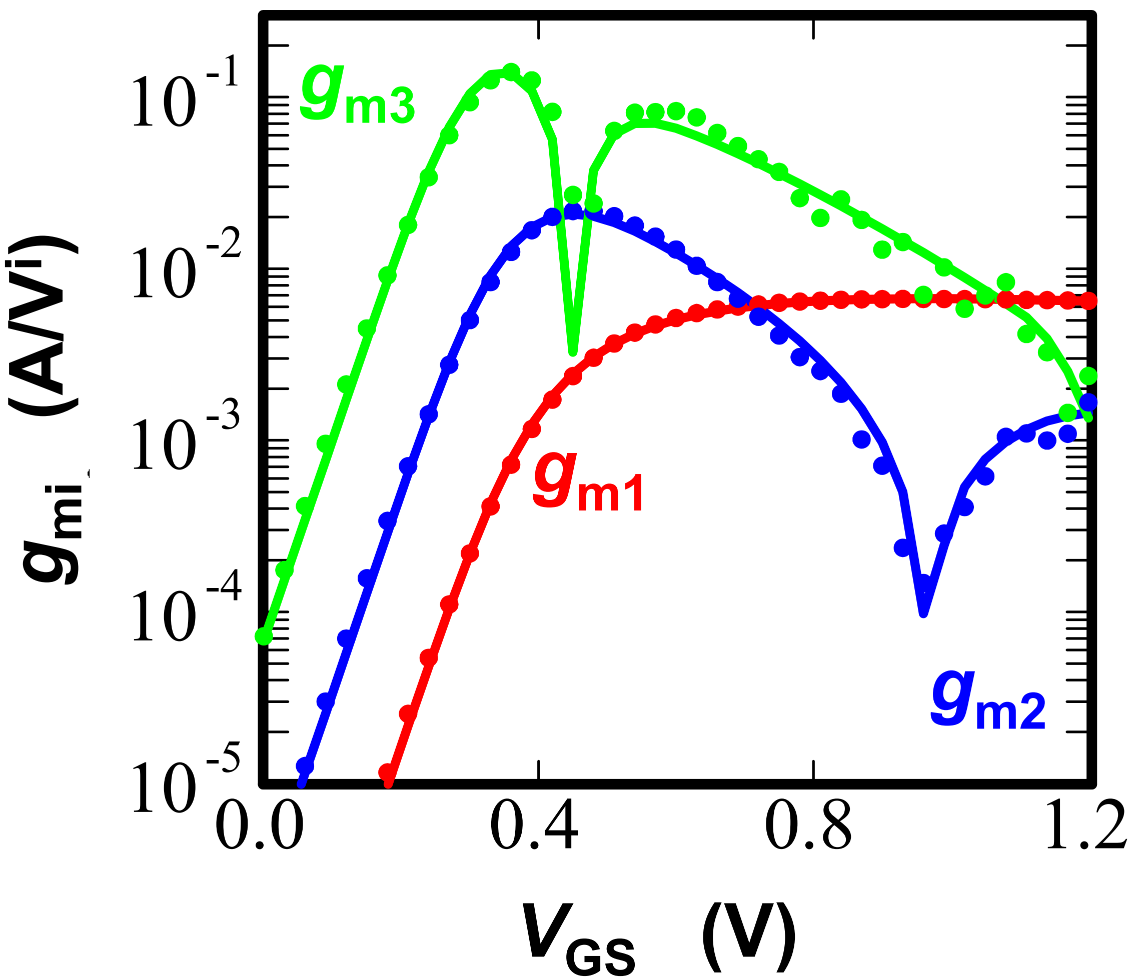
$$\mu_{eff} = \frac{MU0 \cdot \mu_x}{1 + (MUE \cdot E_{eff})^{THEMU} + CS \cdot \left(\frac{q_{bm}}{q_{bm} + q_{im}} \right)^2 + G_R}$$



Non-Universality of the Effective Mobility Produced by the Coulomb Scattering

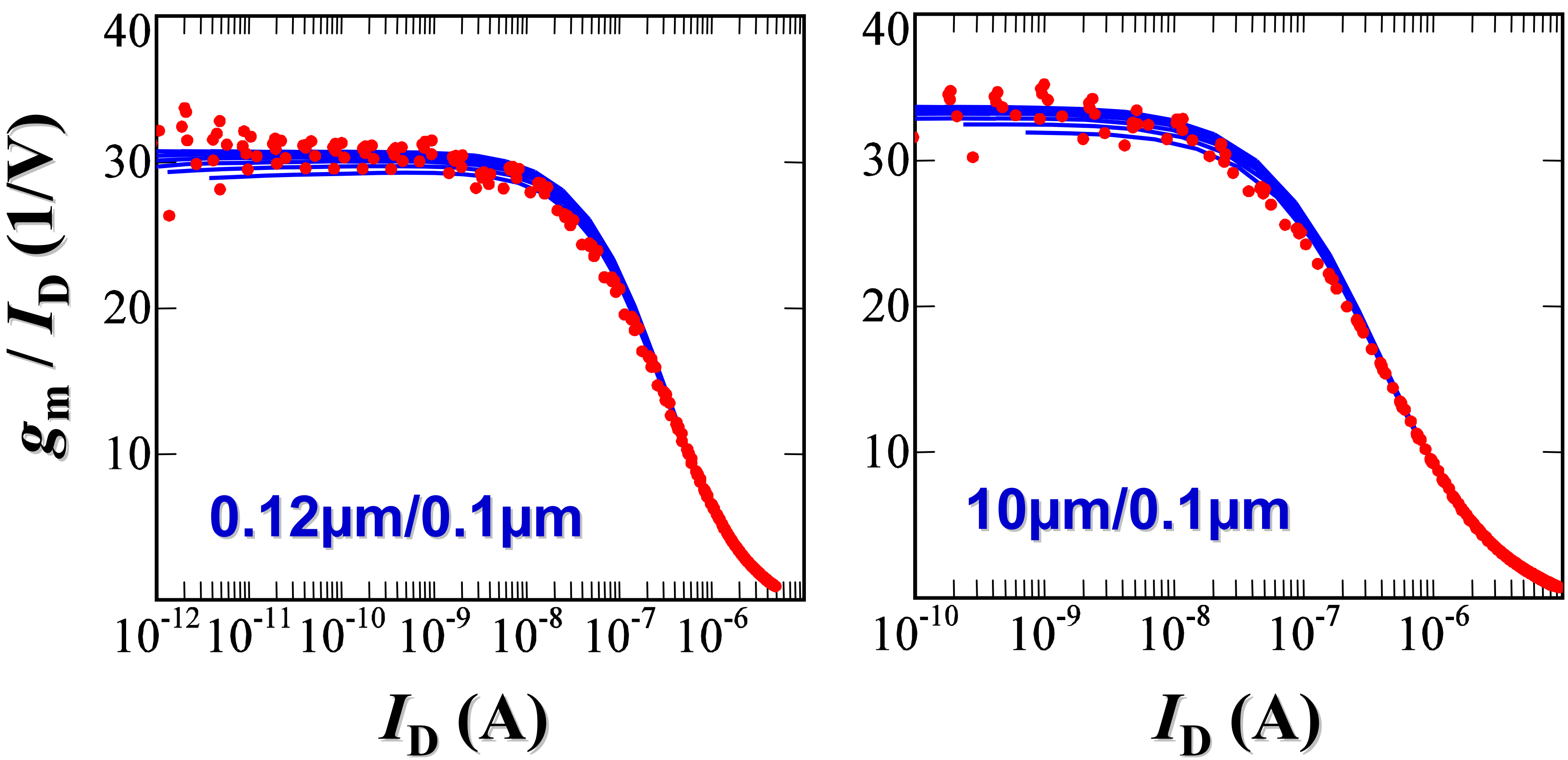


Higher Order Transconductances



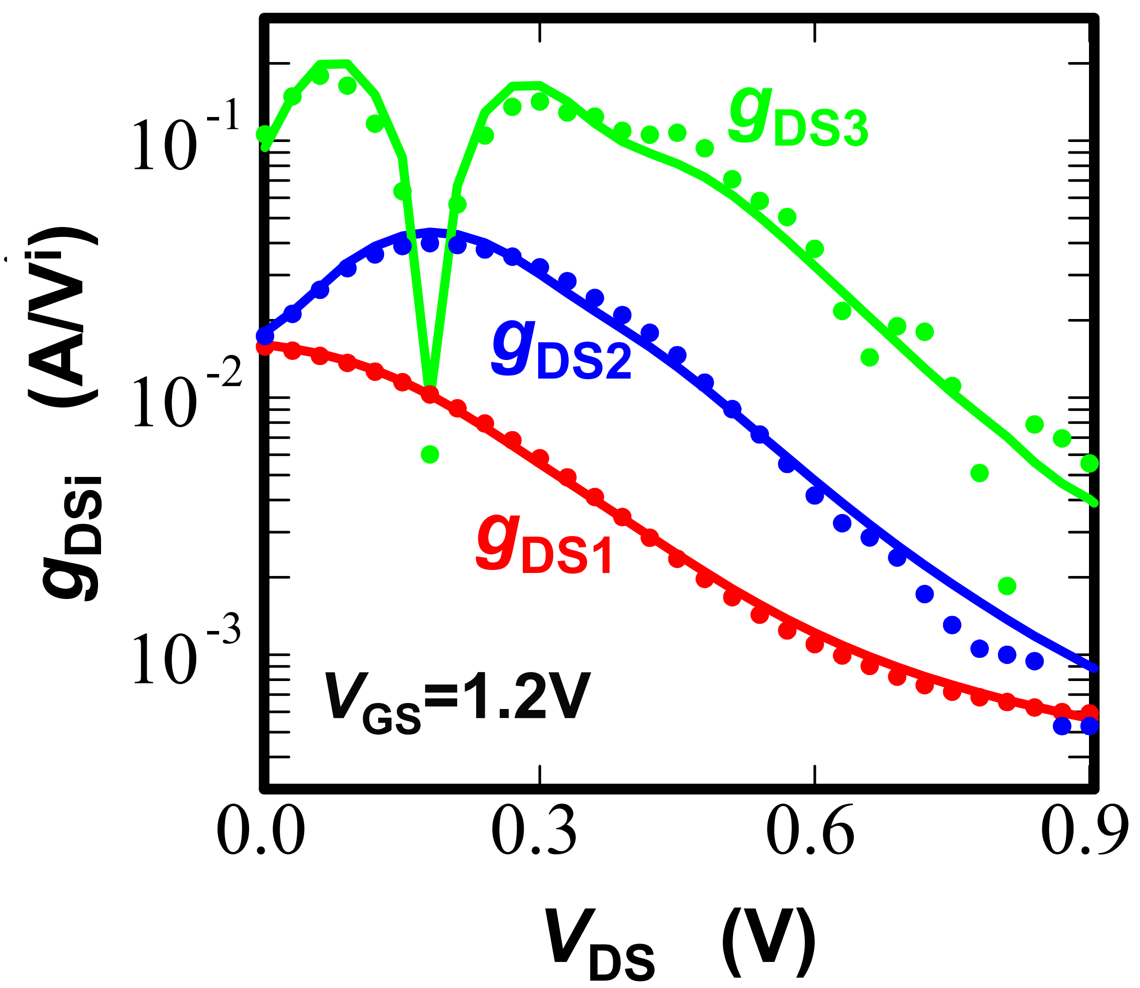
$g_{mi} = \partial^i I_D / \partial V^i_{GS}$ NMOS, W/L = 10 μm/0.12 μm, V_{DS} = 1.2 V, V_{BS} = 0 V

g_m/I_D for Two Corners of 90nm Process



V_{DS} = 0.025V, V_{SB} = 0 to -1.2V, and V_{GS} = 0 to 1.2V.

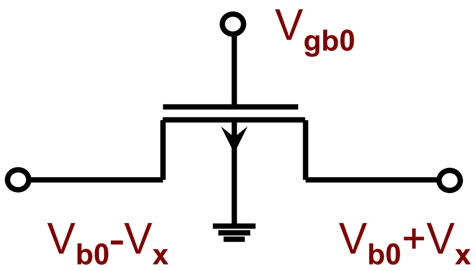
Higher Order Conductances



$g_{mi} = \partial^i I_D / \partial V^i_{GS}$ NMOS, W/L = 10 µm/0.12 µm

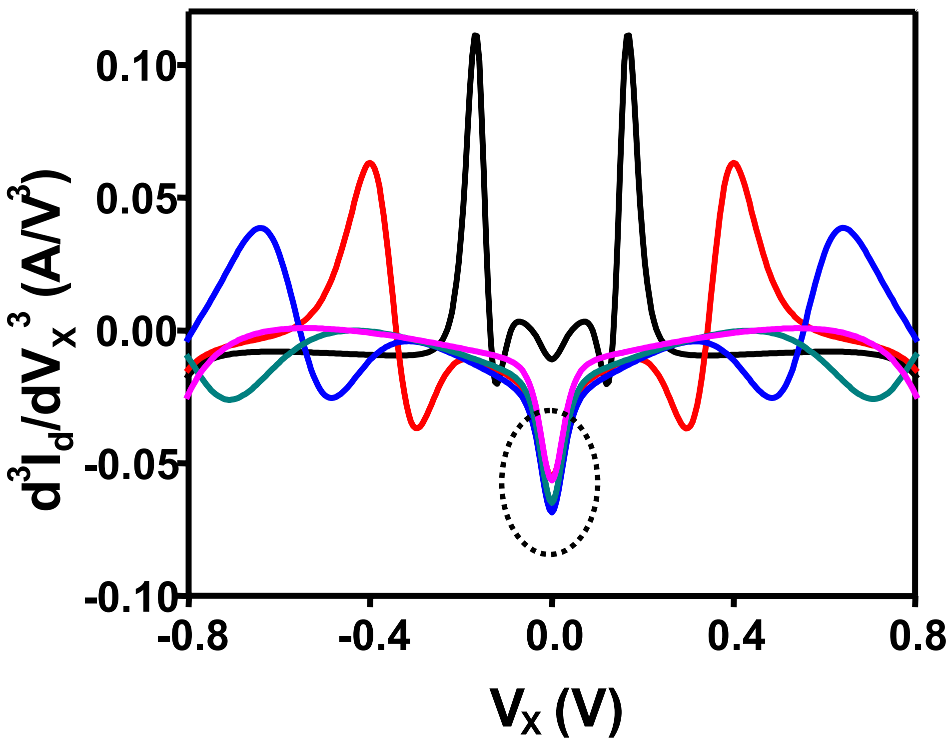
Symmetry

- Essential for RF applications
- New developments, better understanding
- Gummel Symmetry Test

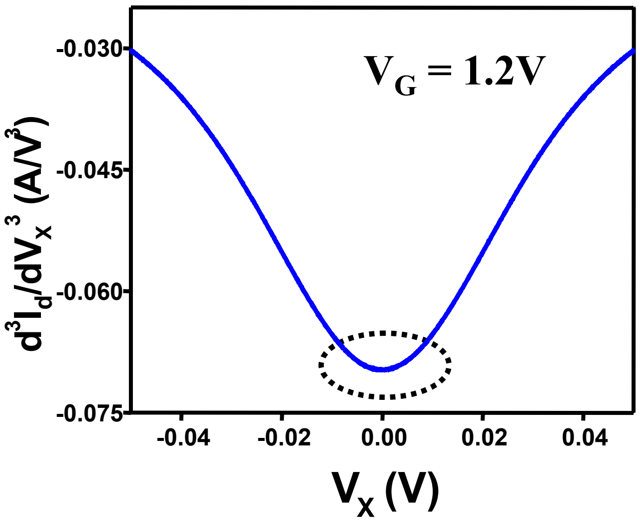


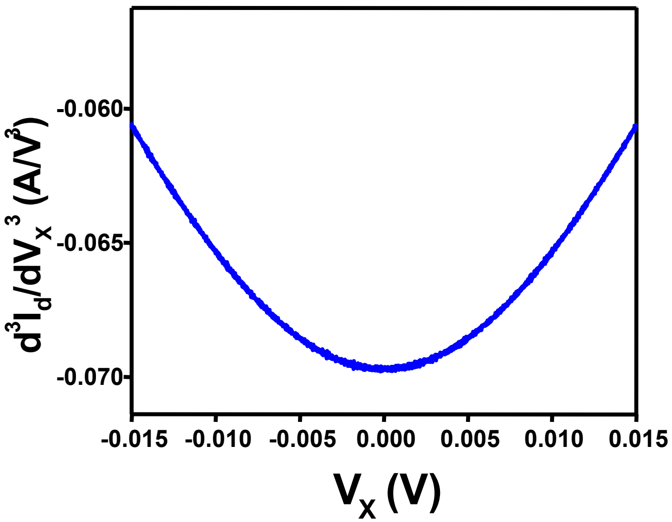
- Third derivatives are now routinely required by the industry
- McAndrew Symmetry Test

Gummel Symmetry Test
3rd Order Derivative of I_d

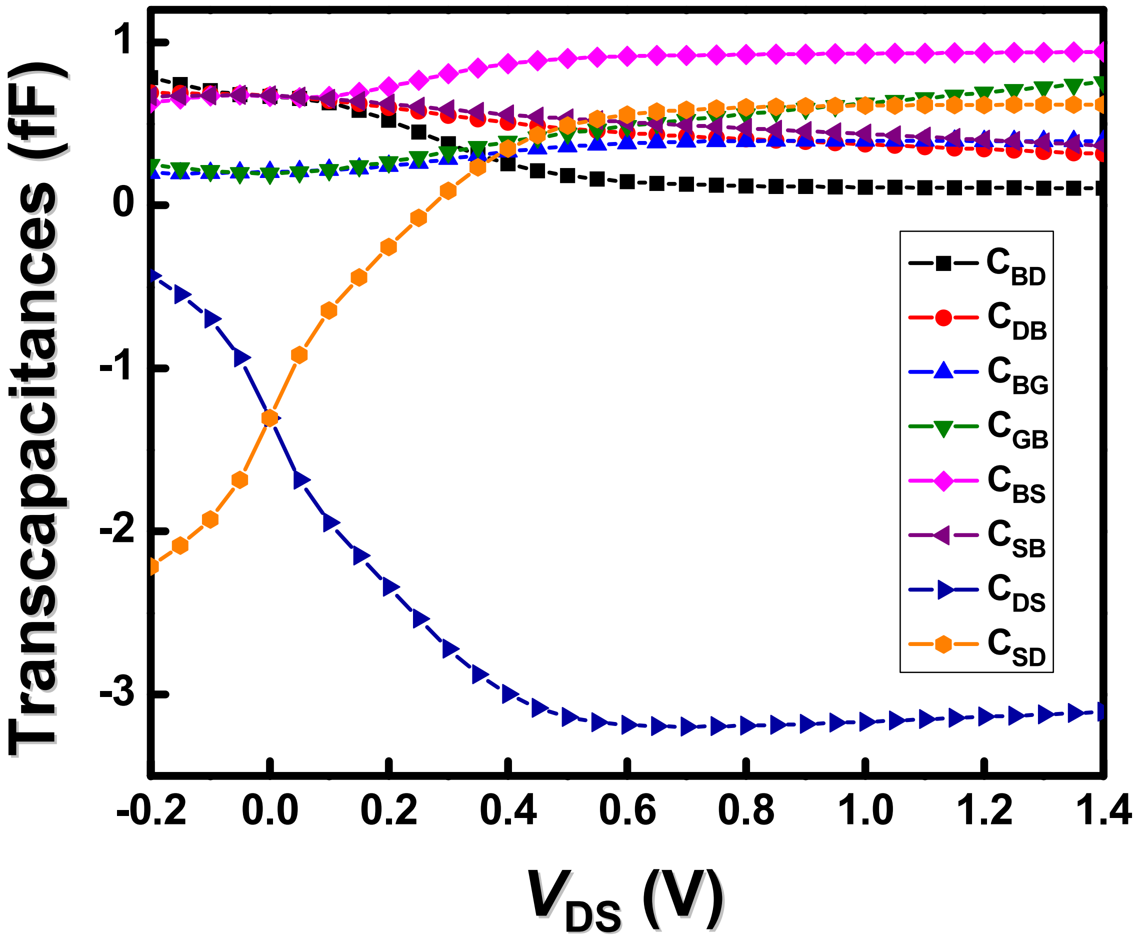


PSP 101.0



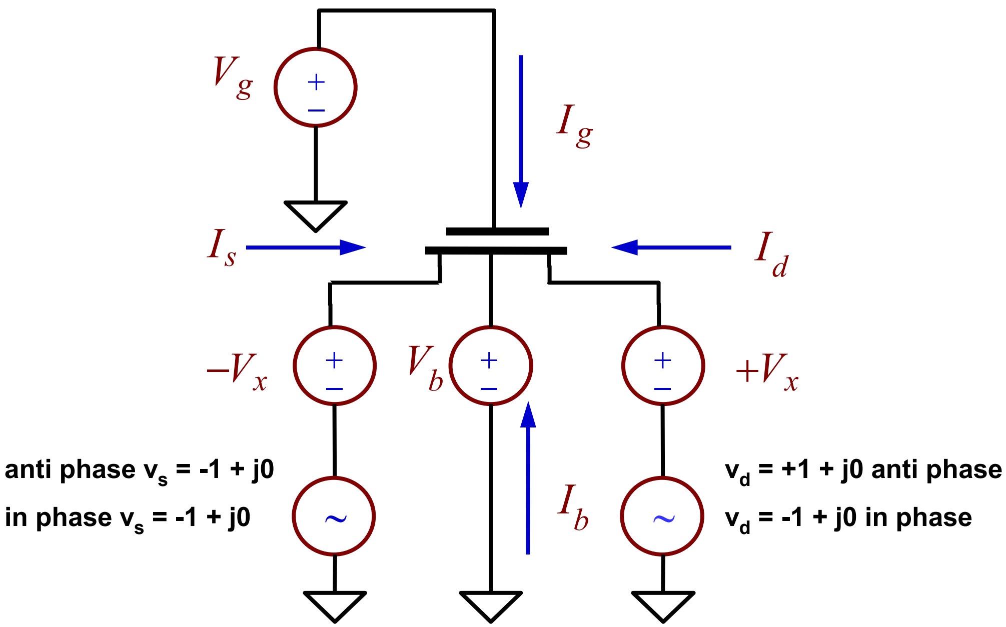


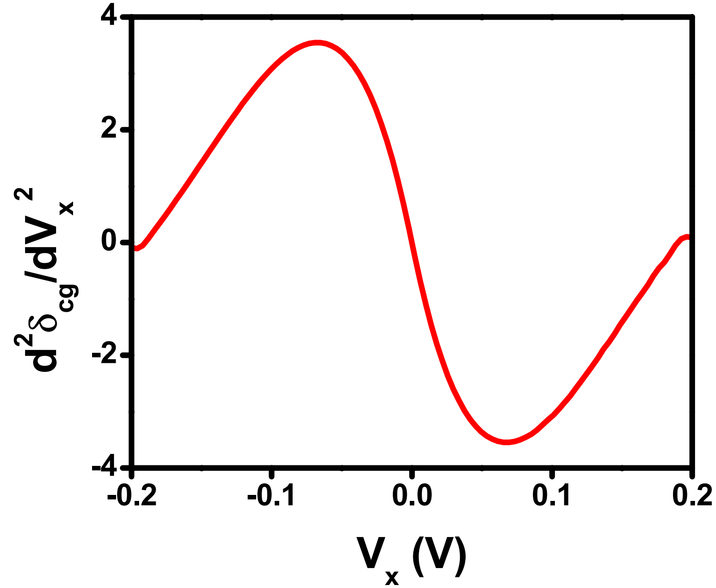
Transcapacitances



W/L=10/0.08µm, V_{BS}=-0.1V, V_{GS}=1.2V

McAndrew Symmetry Test AC version





$$\delta_{cg} = \frac{i_{g^-}}{i_{g^+}} = \frac{C_{gs} - C_{gd}}{C_{gs} + C_{gd}}; \quad \delta_{cb} = \frac{i_{b^-}}{i_{b^+}} = \frac{C_{bs} - C_{bd}}{C_{bs} + C_{bd}}$$

$$\delta_{csd} = \frac{\left(i_{s^-} + i_{d^-}\right) + \left(i_{s^+} - i_{d^+}\right)}{\left(i_{s^-} - i_{d^-}\right) + \left(i_{s^+} + i_{d^+}\right)} = \frac{C_{ss} - C_{dd}}{C_{ss} + C_{dd}}$$

PSP 101.0

W/L=10/0.08µm

$$i_{g^+} = \mathrm{Im}\left(I_g\left[\text{in phase}\right]\right)$$

$$i_{g^-} = \mathrm{Im}\left(I_g\left[\text{anti phase}\right]\right)$$

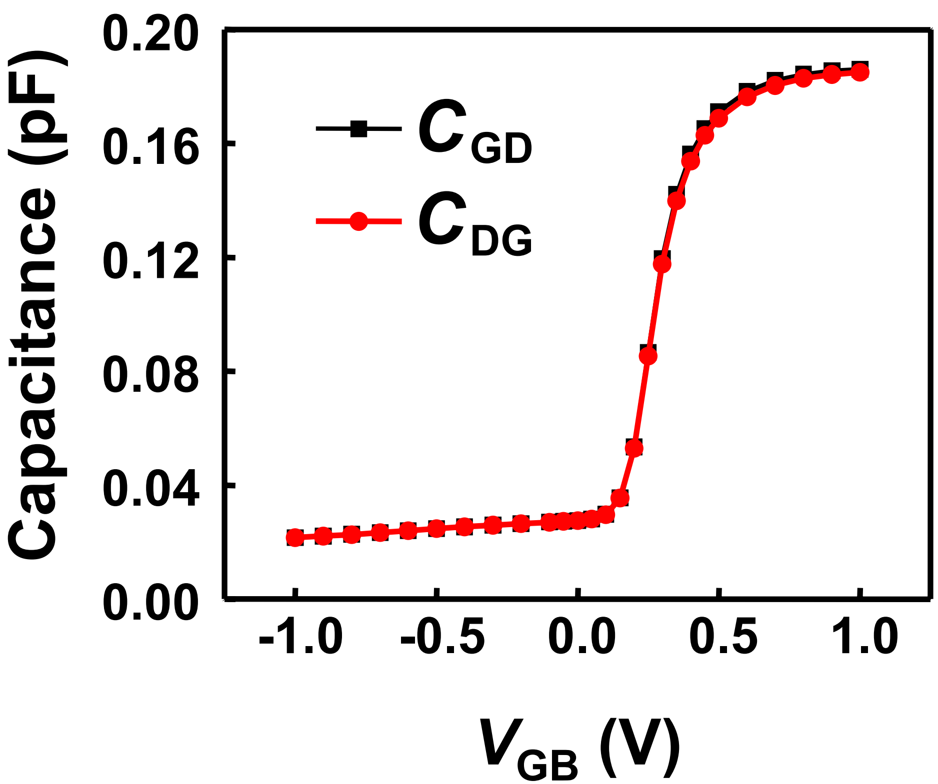
Reciprocity Requirement

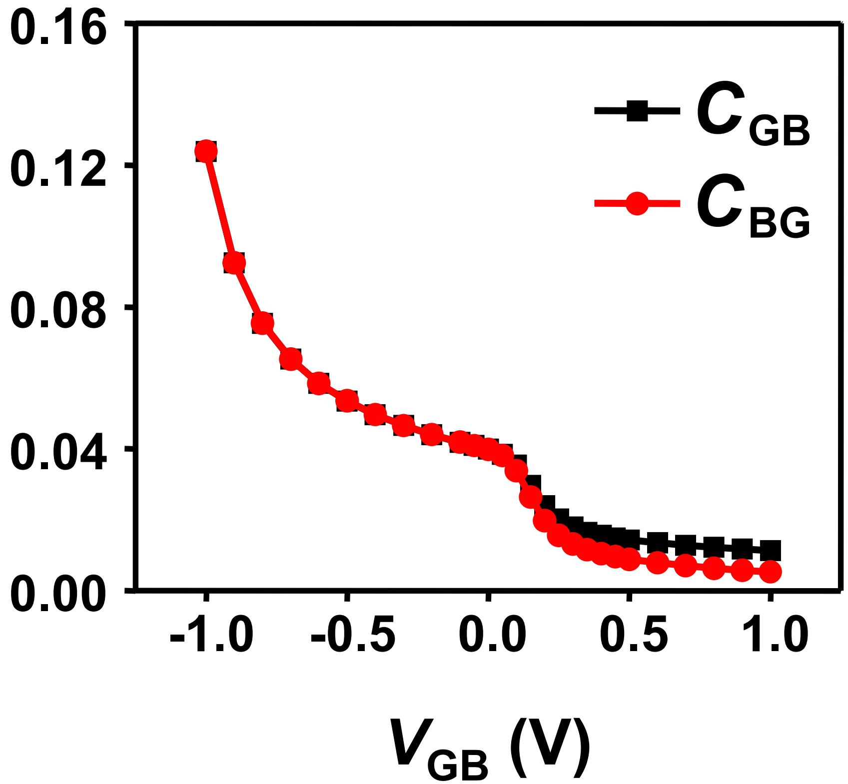
- General speaking, $C_{ij} \neq C_{ji}$. But for the special case of V_{DS}=0, $C_{ij} = C_{ji}$. For example, $C_{GD} = C_{DG}$ and $C_{GB} = C_{BG}$

  This requirement is rather subtle (violated in most models) Satisfied in PSP 101.0 to the extend allowed by the charge-sheet approximation (1% of C_{ox} or better)

- Complete symmetry of PSP implies that for V_{DS}=0, C_{SD}=C_{DS} exactly

Reciprocity of Transcapacitances for $V_{DS} = 0$





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- PSP development at PSU was supported in part by SRC, LSI Logic, Freescale Semiconductor, IBM and by simulation tools provided by Freescale Semiconductor, Mentor Graphics and Agilent

- Evaluation of PSP100.1 by CMC member companies resulted in significant improvements of the model reflected in PSP101.0 – new industry standard

Conclusions (I)

- The results of surface potential calculations in PSP are indistinguishable from the numerical solutions for all bias conditions
- Symmetric linearization method is not limited to any particular velocity-field relation
- Saturation region modeling in PSP is highly accurate including higher order output conductances

Conclusions (II)

- Mobility models in advanced compact models must include Coulomb scattering. “Universal” models no longer suffice. Higher order transcondactances are well reproduced in PSP
- Retrograde doping is included
- PSP satisfies the reciprocity requirement at zero drain bias
- PSP has been tested down to 65nm nodes
- PSP passes both the old and the new symmetry tests