

# Advanced Compact Models for MOSFETs

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# Outline

## Simulation Needs

## Approaches to MOSFET Compact Modeling

### Charge-Based Models

- ACM
- EKV
- BSIM5

### Surface-Potential Based Models

- Source-side only
- HiSIM
- MM11
- SP

# MOSFET Modeling Needs

## Accurate representation of

- standard DC and AC ( $g_{ij}$  and  $C_{ij}$ ) and S-parameter characteristics
- NQS effects
- noise (including induced correlated gate noise)
- statistics

## Over

- bias
- geometry (all layout configurations, including parasitics and substrate connections, proximity effects, short- and narrow-channel effects)
- temperature (potentially including self-heating)
- device types (bulk, SOI, MG, LDMOS, ...)

## Key circuit metrics

- “standard” FoMs: speed, leakage,  $f_T$ , power, etc.
- “RF” FoMs: phase noise/BER, linearity/ $IM_3$ ,  $NF_{min}$ , etc.

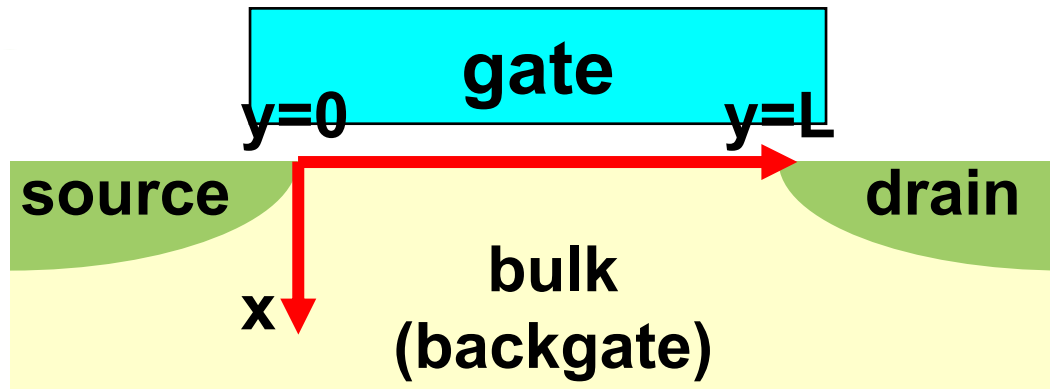
# MOSFET Modeling Needs

**but all of these need to be ...**

**... based on a core model formulation**

# Basic MOSFET Operation

## 2-dimensional problem

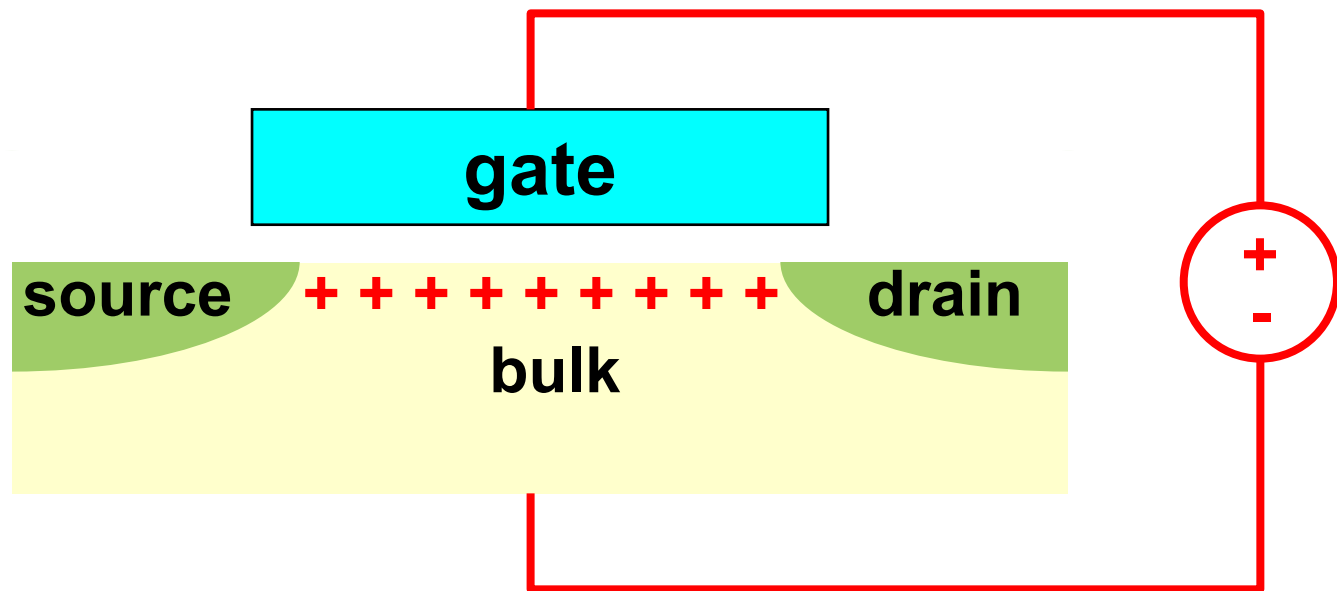


# Basic MOSFET Operation

## 2-dimensional problem

Approached by separating into 2 1-dimensional problems

- vertical 1-D field electrostatics control conduction charge

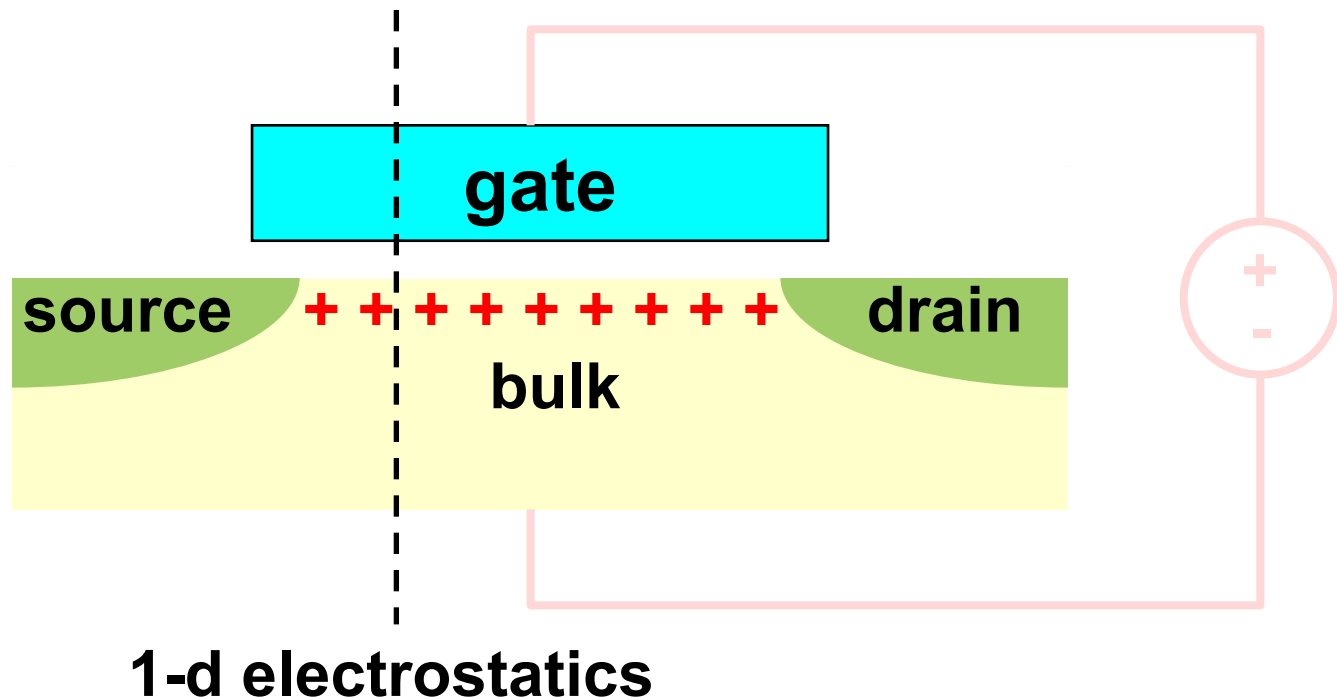


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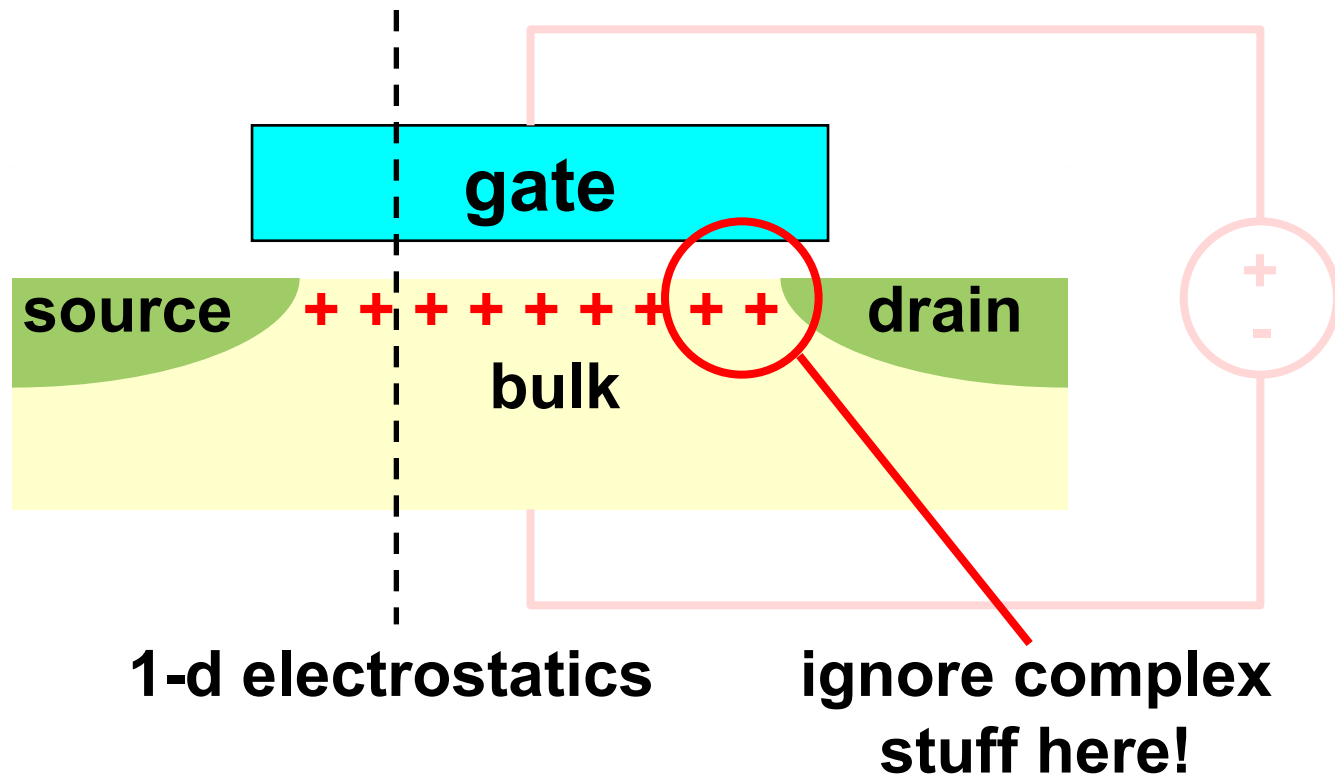


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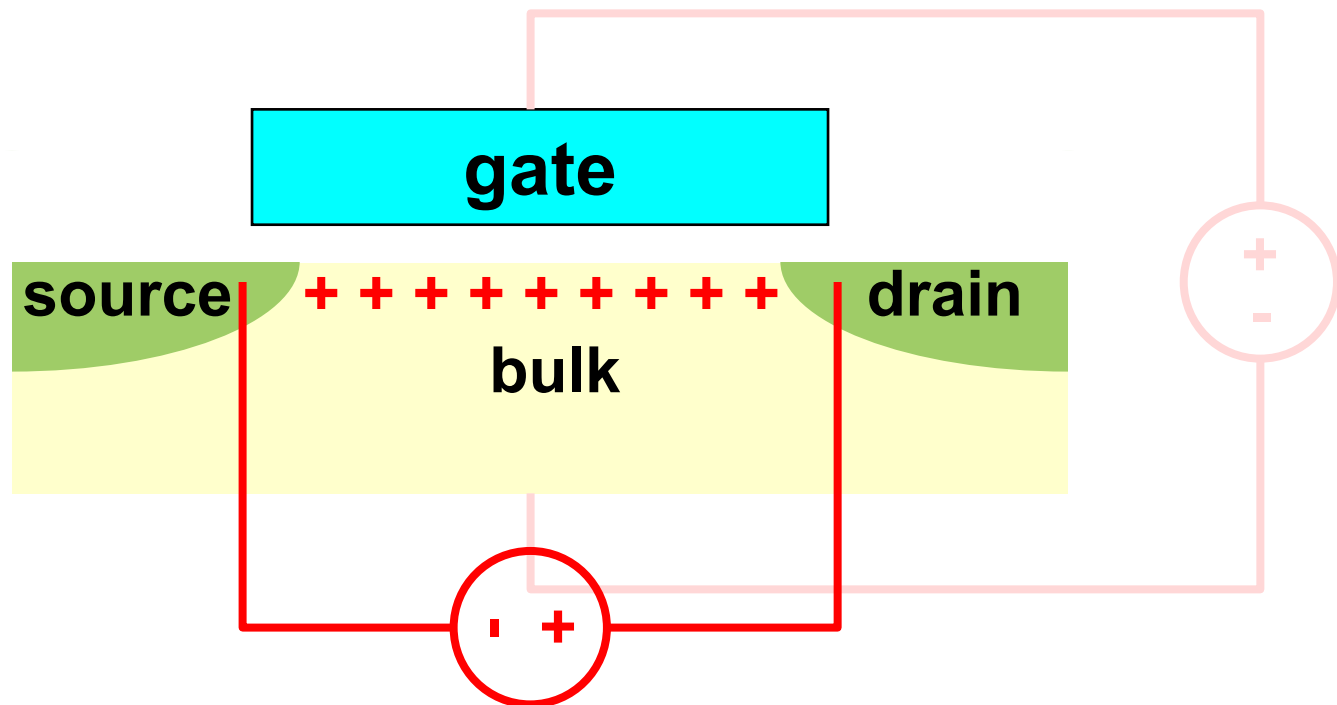


# Basic MOSFET Operation

## 2-dimensional problem

### Approached by separating into 2 1-dimensional problems

- vertical 1-D field electrostatics control conduction charge
- longitudinal 1-D field controls current flow



# Pao-Sah Model – The “Golden” Reference

$$\begin{aligned} I(y) &= W \int J(x, y) dx \\ &= -q\mu \frac{\partial \phi_e}{\partial y} W \int n(x, y) dx \end{aligned}$$

**assume  $I$  is independent of  $y$ , integrate along channel**

$$I_{ds} = \frac{q\mu W}{L} \int_{V_{sb}}^{V_{db}} \int_{\psi_{bulk}}^{\psi_s} \frac{n(x, y)}{-\partial \psi / \partial x} d\psi dV$$

# Pao-Sah Model – The “Golden” Reference

**Electrostatics:**

$$\frac{E^2}{2qN/\epsilon_s} = \varphi_t \left( e^{-\psi/\varphi_t} - 1 \right) + \psi + e^{-(2\varphi_F + V_{cb})/\varphi_t} \left( \varphi_t \left( e^{\psi/\varphi_t} - 1 \right) - \psi \right)$$

$$I_{ds} = \frac{q\mu NW}{L} \int_{V_{sb}}^{V_{db}} \int_{\psi_{bulk}}^{\psi_s} \frac{e^{(\psi - 2\varphi_F - V)/\varphi_t}}{E(\psi)} d\psi dV$$

# Charge-Sheet Model (CSM) Formulation

**Inversion charge density  $Q_i'$  is basic variable**

**Leads to implicit equation for the surface potential  $\psi_s$**

- a function of gate bias and quasi-Fermi level splitting  $V$

**Current is then derived from**

$$I_{ds} = \frac{\mu W}{L} \int_{\psi_{s0}}^{\psi_{sL}} \left( -Q_i'(\psi_s) \right) \frac{\partial V}{\partial \psi_s} d\psi_s$$

# MOSFET Models

**Historically the Pao-Sah and CSM formulations were considered too computationally burdensome**

**The solution adopted was the threshold voltage based MOSFET model formulation**

- **early models were piecewise formulations, with separate equations used to model different regions of operation**
- **later models used mathematical techniques to make the models single-piece and a single set of model equations was applicable to all regions of operation**
- **not discussed: table models, tanh models**

**Advanced MOSFET models being developed today**

- **charge based models**
- **surface potential based models**

# Other Issues

**Complex doping profiles**

**Short and narrow channel effects**

**Accurate mobility modeling**

**Polysilicon depletion**

**Quantum effects**

**Velocity saturation and drain saturation voltage**

**Operation in accumulation**

**Parasitics**

**Gate and substrate currents**

**Device structure (SOI, MG, ...)**

**Only core model formulation will be reviewed here**

# Charge Based Models

**Initial formulation in terms of charges by Maher and Mead, 1987**

**Charge expression (for HFETs) and current formulation (for MOSFETs) from Shur's group, 1990 & 1991**

**EKV model July 1995**

**ACM model November 1995**

**Gummel 2001**

**UCB group (genesis of BSIM5) 2003**

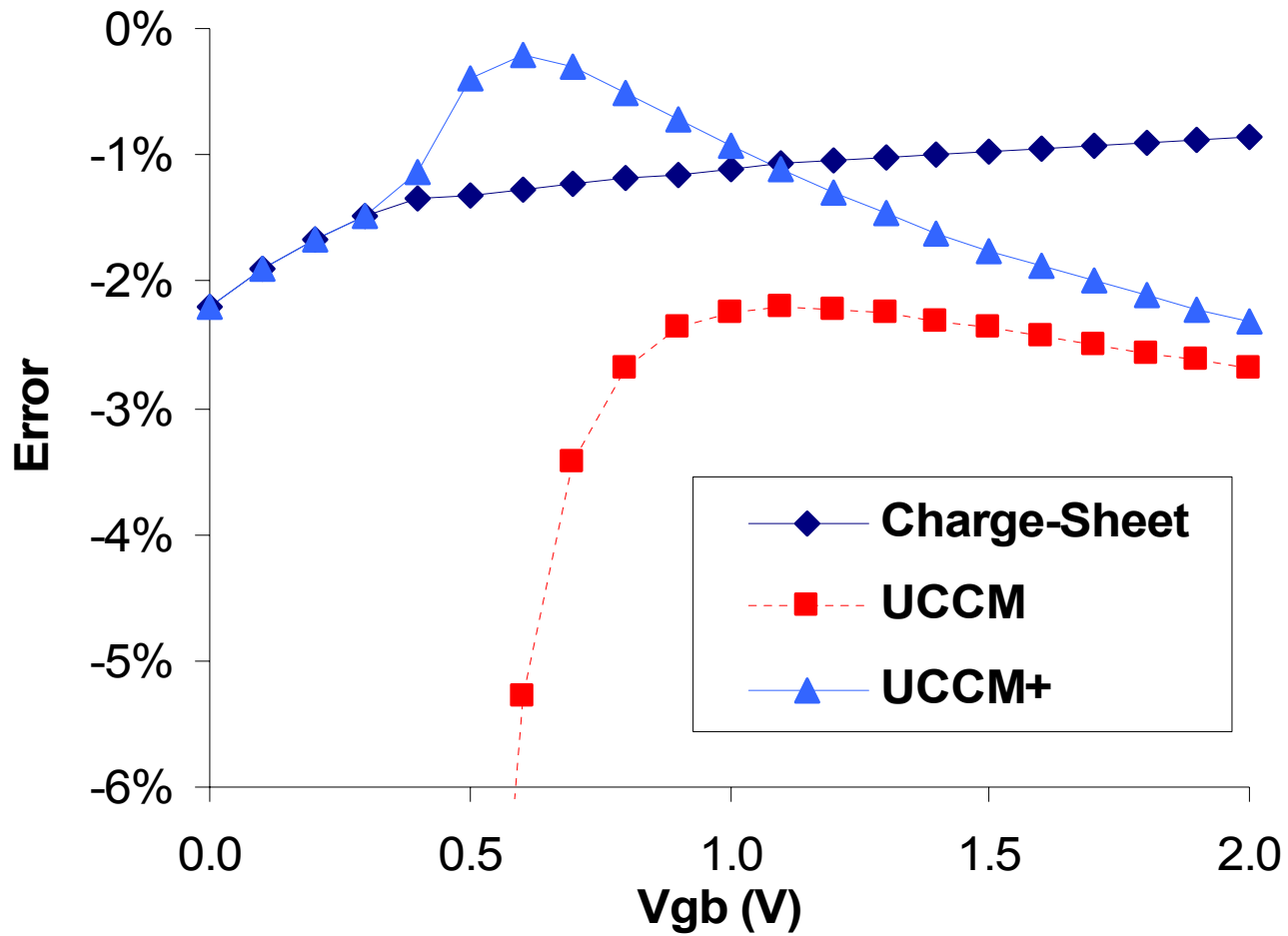
**ACM = “Advanced Compact MOSFET” model**

**Development began in late 1980’s**

**Driving need was for MOS varactors, then developed for MOSFETs**

**Pinch-off voltage and charge density**

$$Q'_{ip} = -nC'_{OX} \varphi_t, \quad dQ'_i \left( \frac{1}{nC'_{OX}} - \frac{\varphi_t}{Q'_i} \right) = dV_{cb}$$
$$\frac{Q'_{ip} - Q'_i}{nC'_{OX}} + \varphi_t \ln \left( \frac{Q'_i}{Q'_{ip}} \right) = V_p - V_{cb}$$



# EKV – Introduction

**Driven by needs of very low power analog design**

**Weak and moderate inversion very important**

- conventional models unphysical in this region, depend only on the numerical tricks used to make the models continuous

**Symmetric formulation**

**Initial emphasis was  $g_m/I_d$ , did use linearized inversion charge**

**Later moved to physical formulation, like Maher, that unifies weak to strong inversion**

**Conductance and capacitance coefficients follow simply from modeled charges**

# EKV – Foundations

## Basic relation

$$V_p - V_{sb} = 2q_s + \ln(q_s)$$

**Inversion charge linearization gives direct relation to surface potential**

$$\psi_s = V_p + 2\phi_F + m\phi_t - (-Q'_i)/nC_{OX}$$

**Direct link from charge based to surface potential based models**

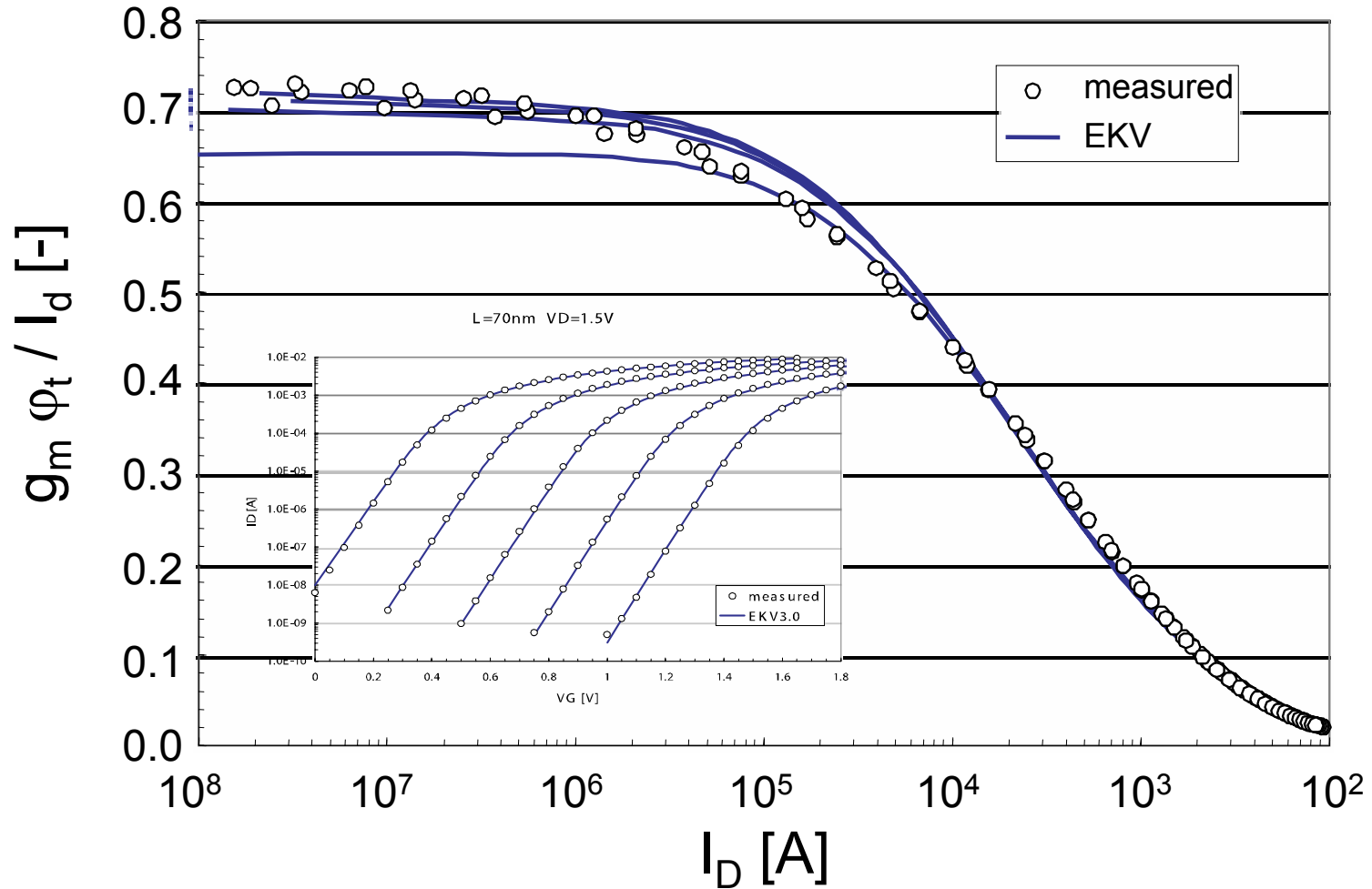
**Drain current given by**

$$\frac{I_{ds}}{I_{spec}} = i_f - i_r = \underbrace{(q_s^2 + q_s)}_{=i_f} - \underbrace{(q_d^2 + q_d)}_{=i_r}$$

$$I_{spec} = 2n\mu C_{OX} \frac{W}{L} \phi_t^2$$

# EKV – $g_m/I_d$ Characteristics

$L = 70 \text{ nm}$   $V_{ds} = 1.5 \text{ V}$



**Single set of equations used to calculate charges in all regions of operation**

- continuous and symmetric

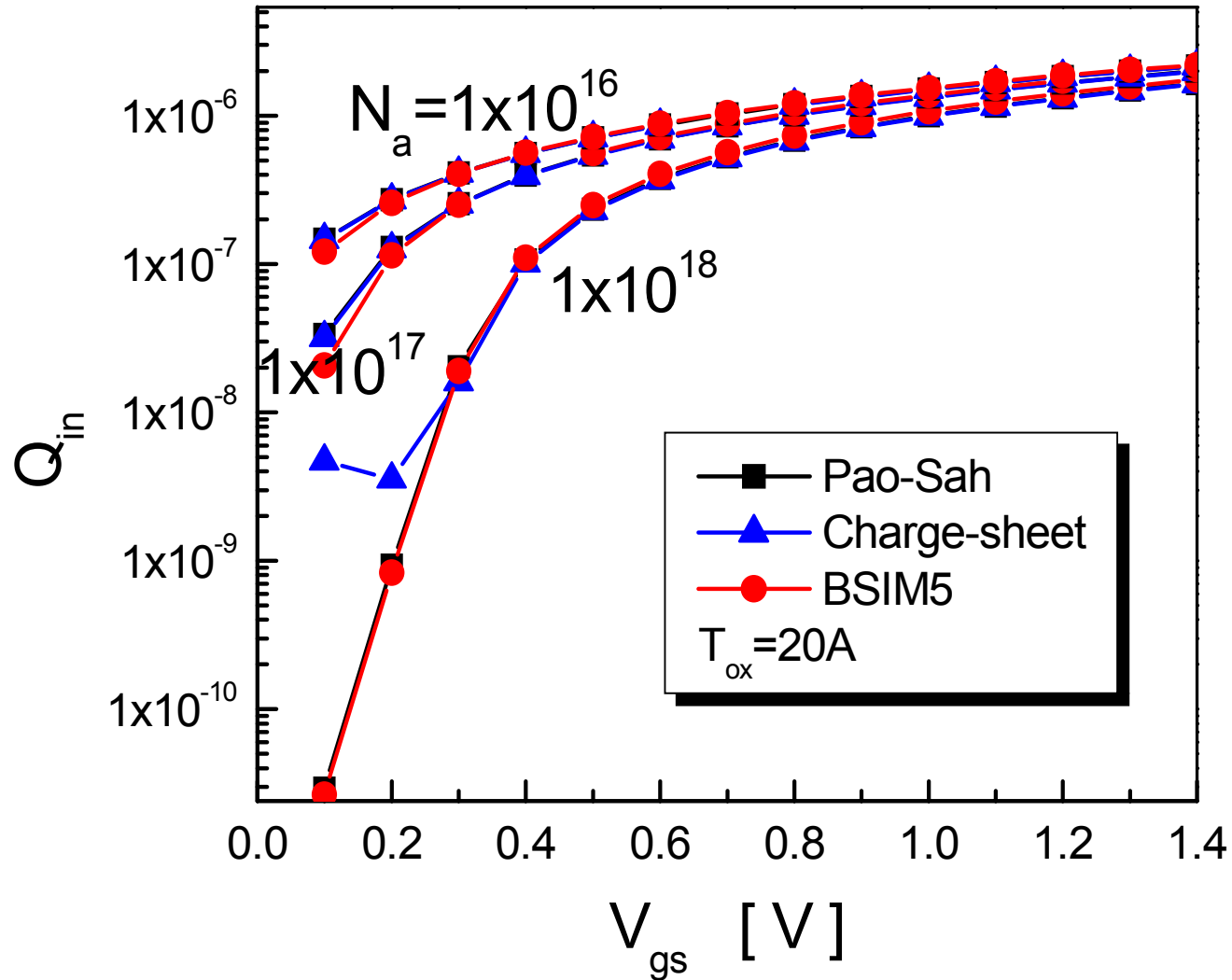
**Inversion charge density solution**

$$\ln\left(\frac{q_i}{n}\right) + \frac{q_i}{n} = \frac{V_{gb} - V_{FB}}{n\varphi_t} - \varphi_B - \frac{V_{cb}}{\varphi_t} - n \ln\left(\frac{n}{n-1}\right)$$

**Drain current**

$$I_{ds} = \frac{\mu C_{OX} W}{L} \varphi_t^2 \left( \frac{q_s^2 - q_d^2}{2n} + q_s - q_d \right)$$

# BSIM5



# Surface Potential Based Models

**Origin is generally considered to be Brews (1978)**

**HiSIM 1989 (DC), 1994 (AC)**

**MISNAN in 1991**

**DEC source-side model 1995**

**MM11 1998**

**SP 1998**

# Source-Side Model

**Developed for DEC's Alpha chip design**

**Only requires solution for  $\psi_s$  at the source**

$$q_g = C_{OX} (V_{gb} - V_{FB} - \psi_s)$$

$$q_b = \pm \gamma \sqrt{\psi_s + \phi_t (e^{-\psi_s/\phi_t} - 1)}$$

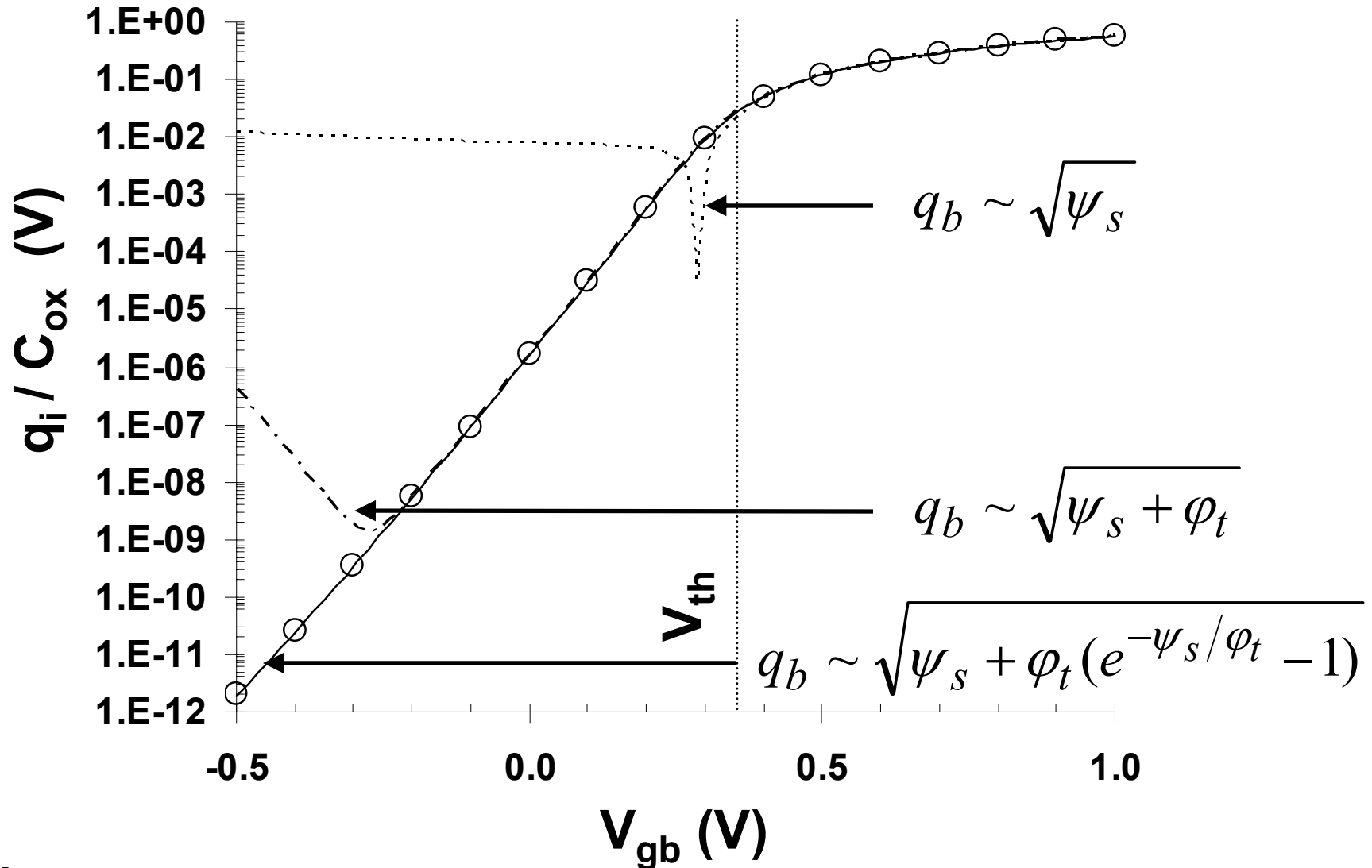
**$q_b$  is linearized w.r.t. source and drain end points**

- preserves source/drain symmetry

**Drain saturation corrected to maintain correct behavior for small  $V_{ds}$**

$$V_{dsx} = g_0 V_{ds} / (1 + (g_0 V_{ds} / V_{dsat})^m)^{1/m}$$

# Source-Side Model



**Development began in late 1980's**

**Iterative solution for  $\psi_s$**

- accurate solution needed for conductance and capacitance

**Physical handling of lateral doping profiles (halo)**

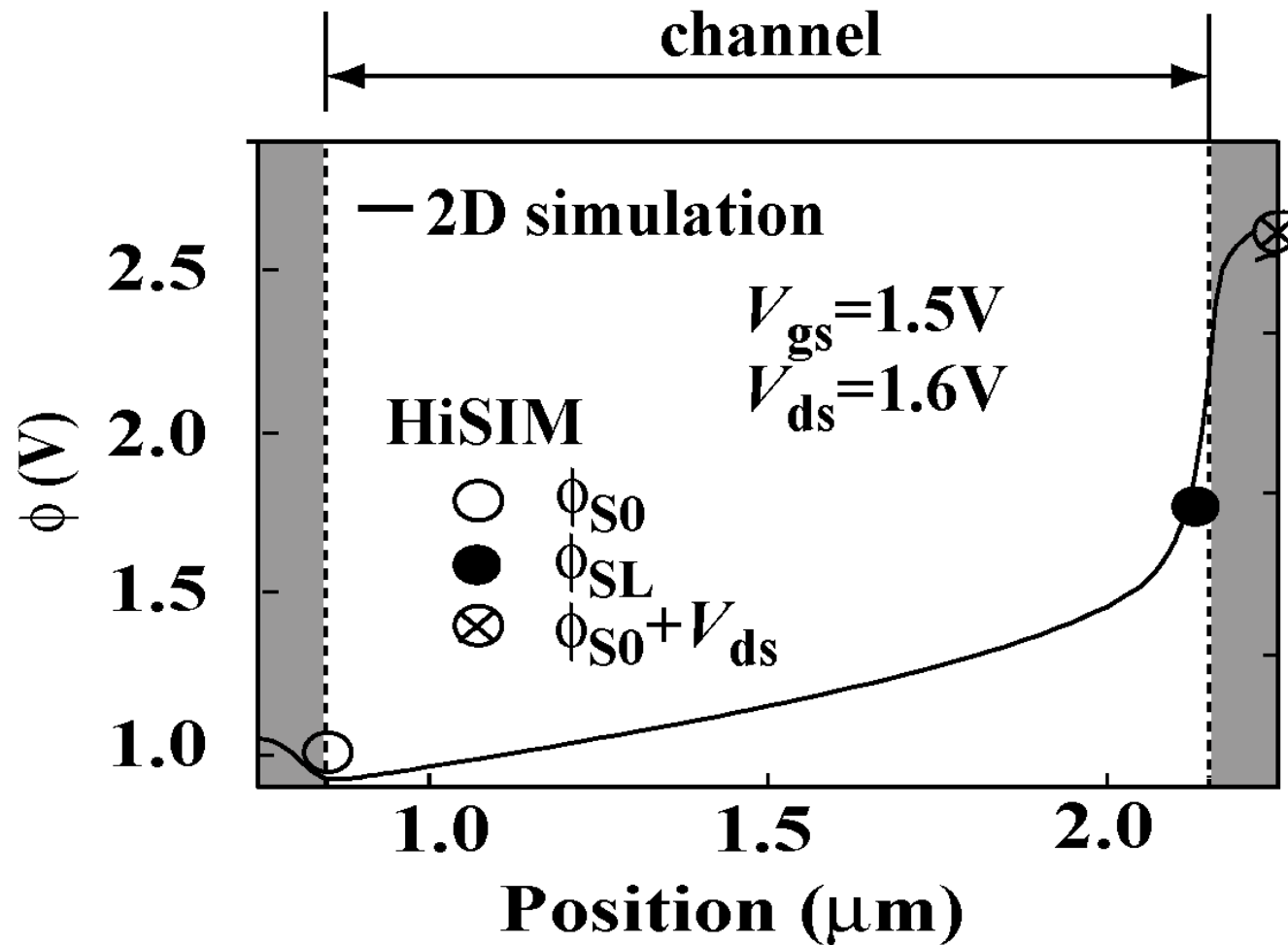
**Consistent, simple formulation with a small number of physical parameters**

**GCA plus lateral field gradient are maintained in “intrinsic” device**

- self-consistent solution maintained from pinch-off point to drain

**Simulation time comparable with BSIM3v3**

# HiSIM



**Development started in 1994, emphasis was analog and RF modeling**

- mobility model targeted distortion
- accurate noise modeling
- proper symmetry
- of course, it works for digital too!

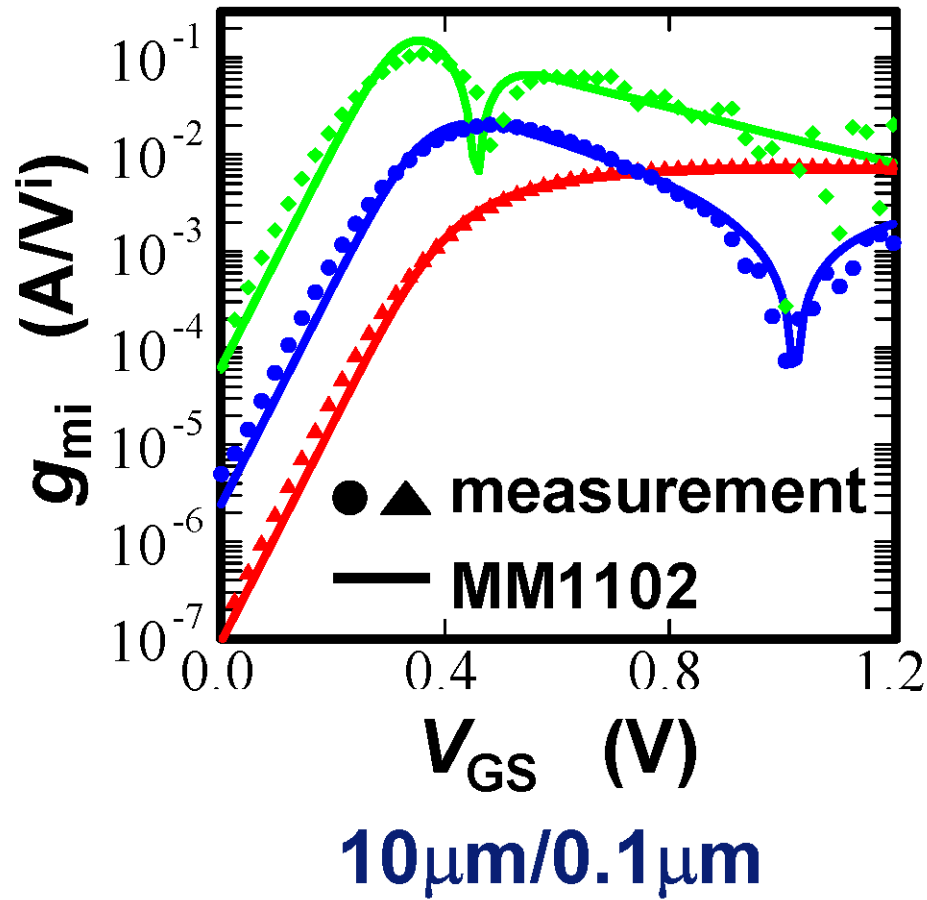
**Model structure includes local (miniset, per geometry) and global (maxiset, over geometry) parameters**

- some parameters are common to both sets
- simplifies parameter extraction and geometry modeling

**Linearization is done around mid-point potential,  
 $0.5(\psi_{s0} + \psi_{sL})$**

**Original non-iterative  $\psi_s$  solution, iterative procedure used since MM1102**

# MM11



## Accurate non-iterative solution for $\psi_s$

- extreme accuracy required for accurate modeling of conductance and capacitance coefficients
- modified form also applicable for overlap capacitance modeling

## Symmetric linearization gave very compact, highly accurate modeling equations

- substantially simpler than “classic” CSM expressions
- linearization is about mid-point potential,  $0.5(\psi_{s0} + \psi_{sL})$

## Velocity saturation model used has no singularity at $V_{ds}=0$ so symmetry is preserved

## Many bias and geometry dependent effects implemented via lateral gradient factor

## Spline-collocation-based NQS model

