

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.

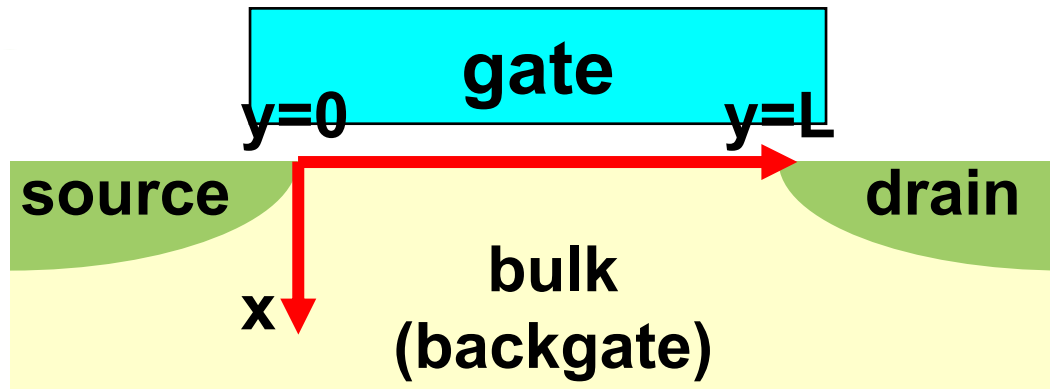
MOSFET Modeling Needs

but all of these need to be ...

... based on a core model formulation

Basic MOSFET Operation

2-dimensional problem

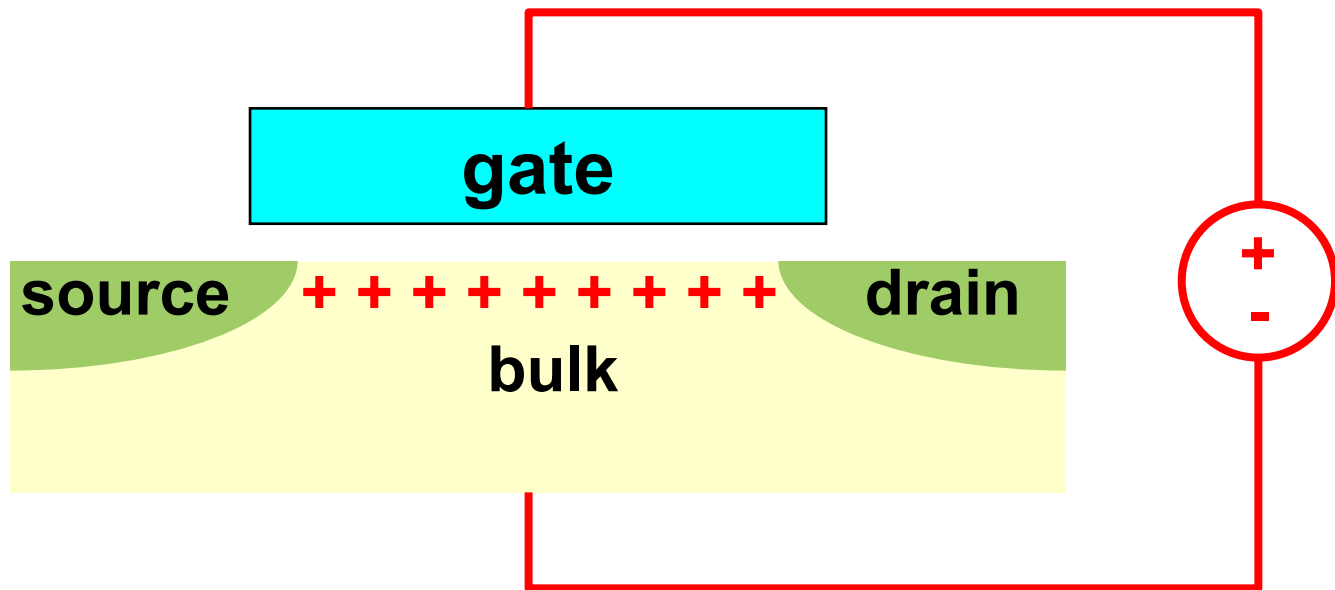


Basic MOSFET Operation

2-dimensional problem

Approached by separating into 2 1-dimensional problems

- vertical 1-D field electrostatics control conduction charge

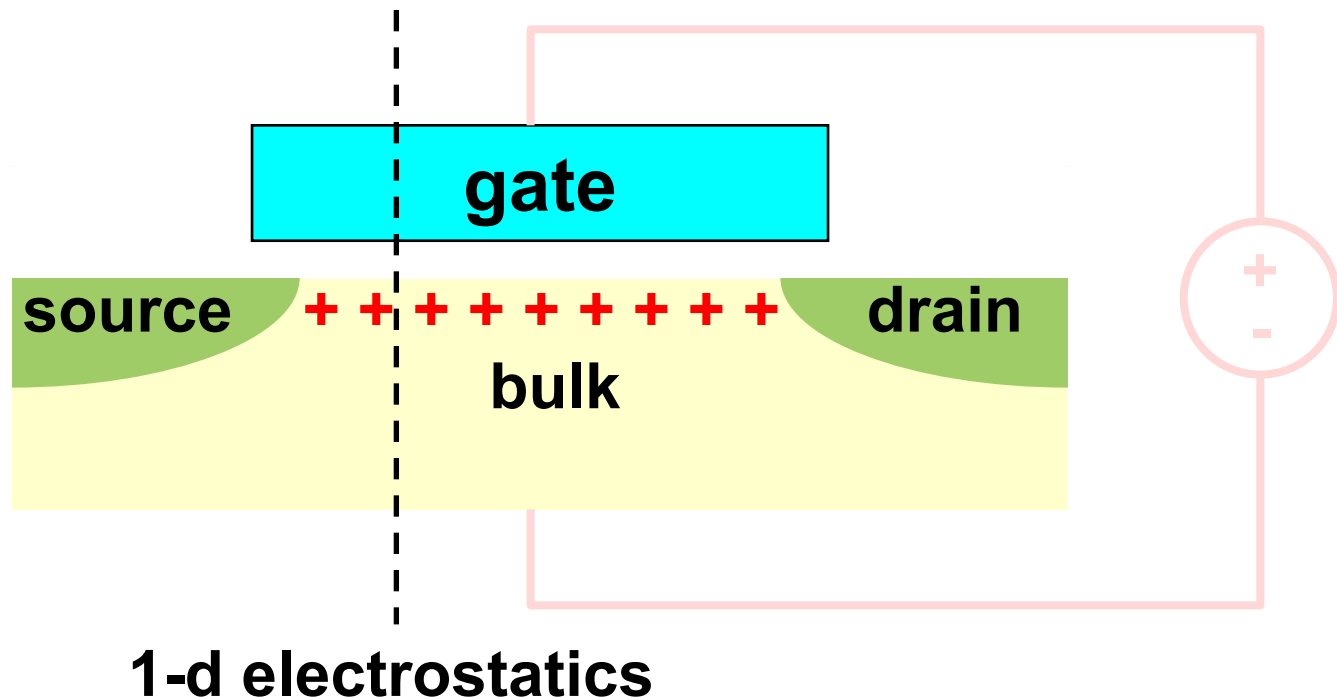


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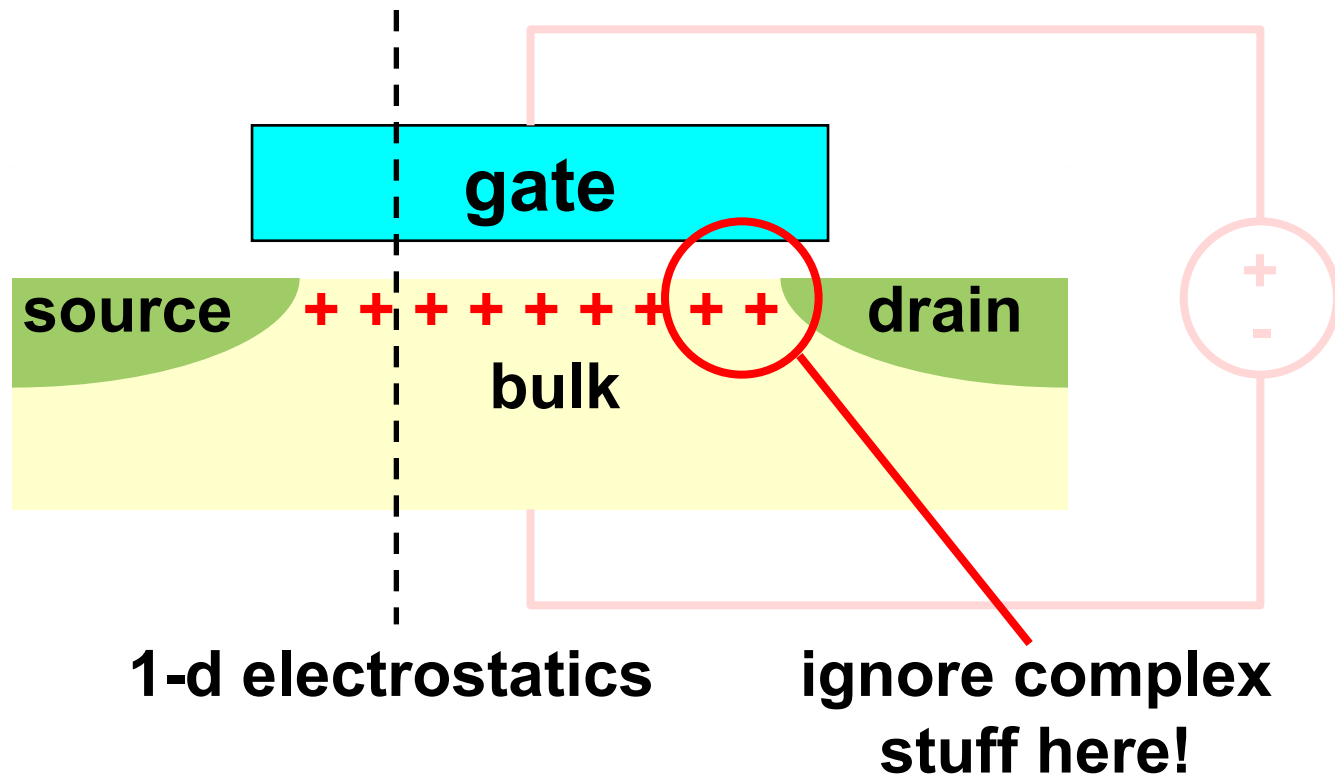


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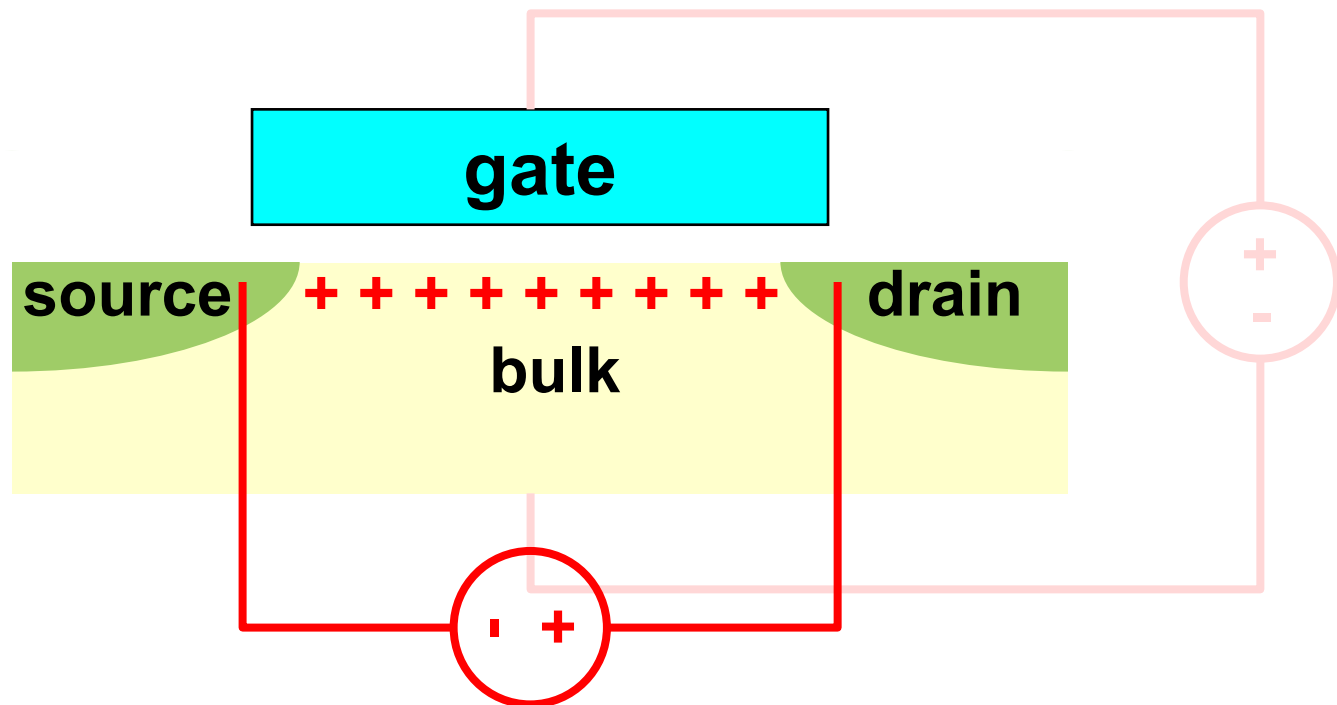


Basic MOSFET Operation

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 ψ_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

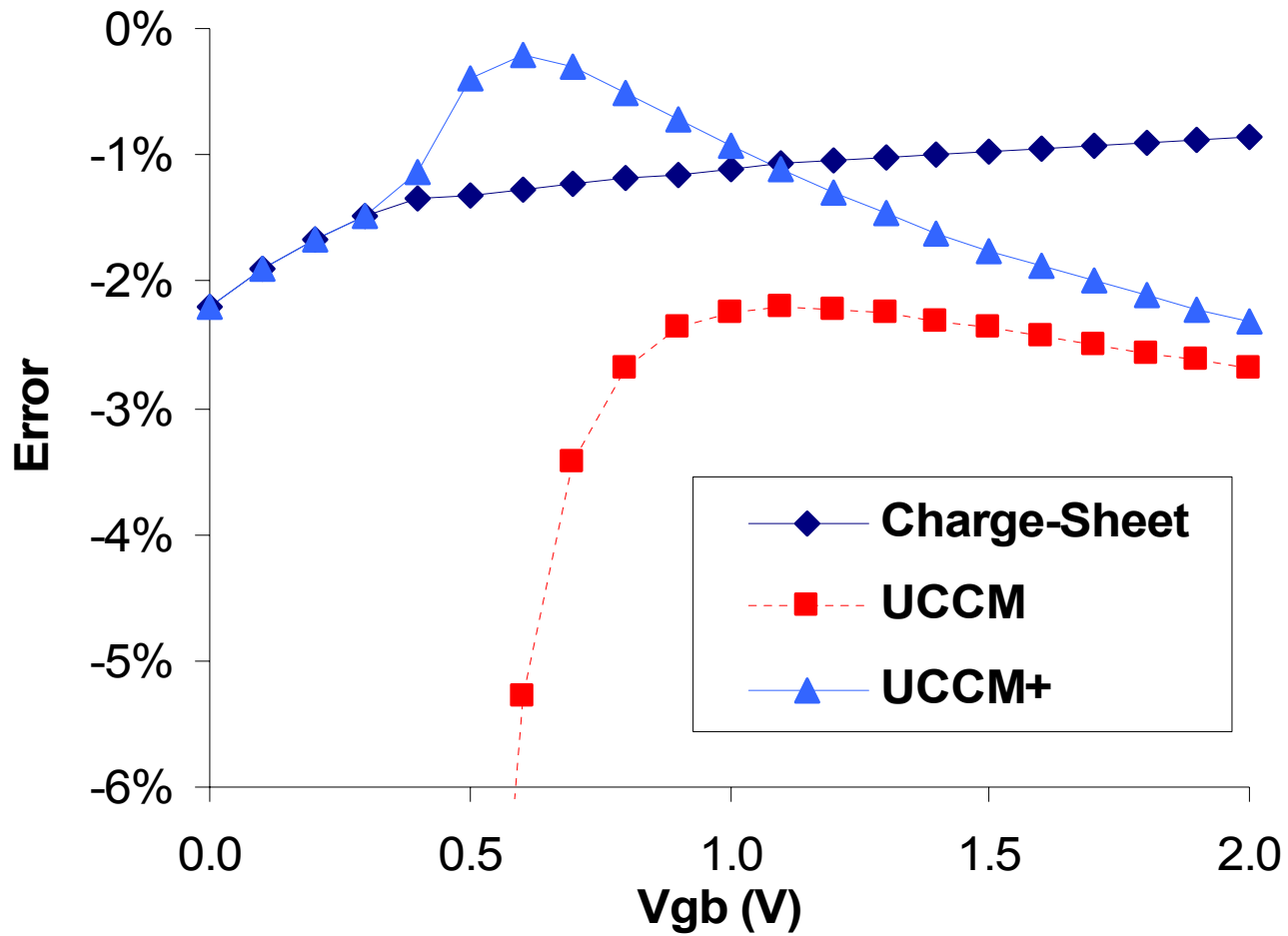
ACM = “Advanced Compact MOSFET” model

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

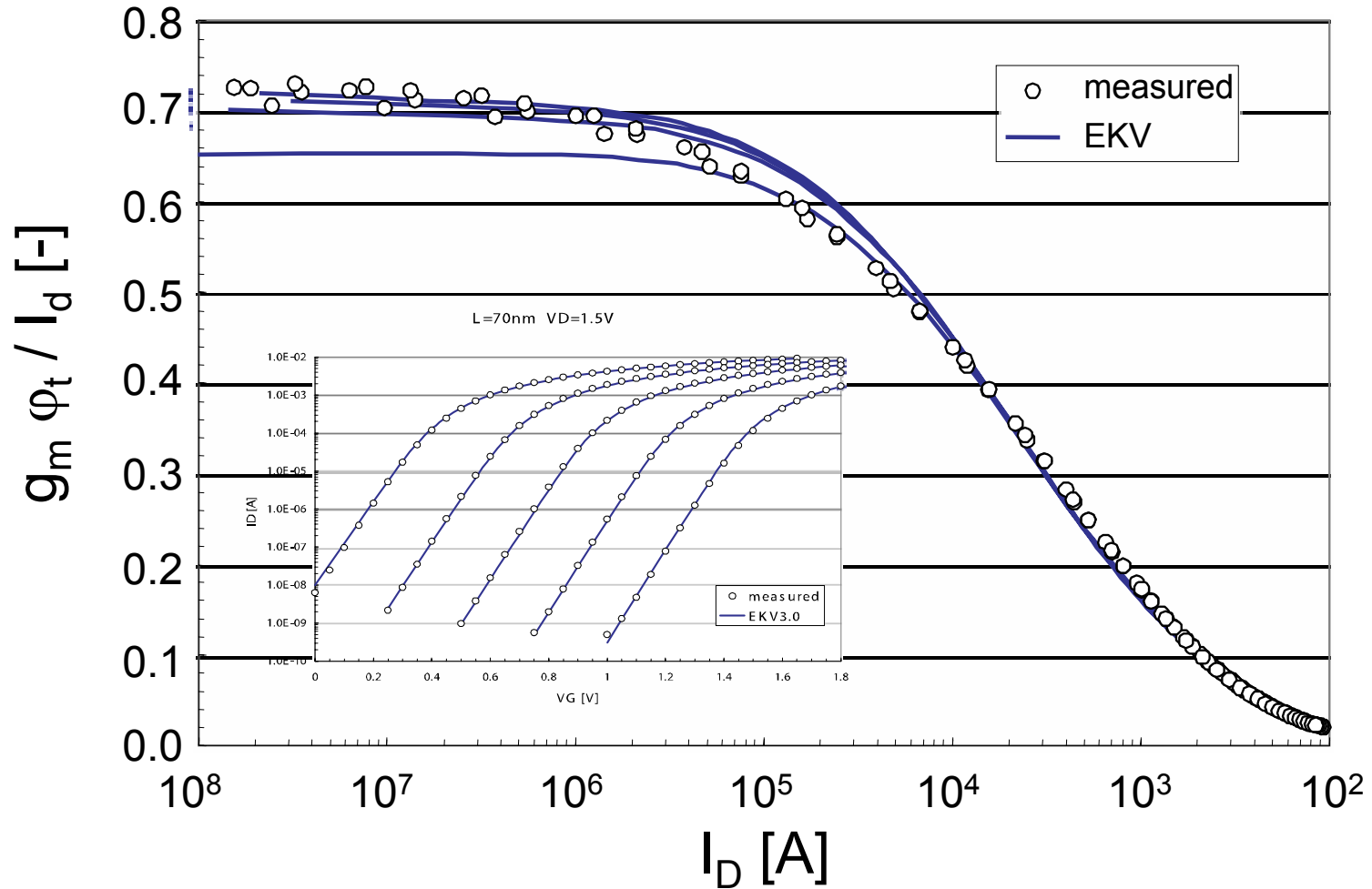
Drain current given by

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

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

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

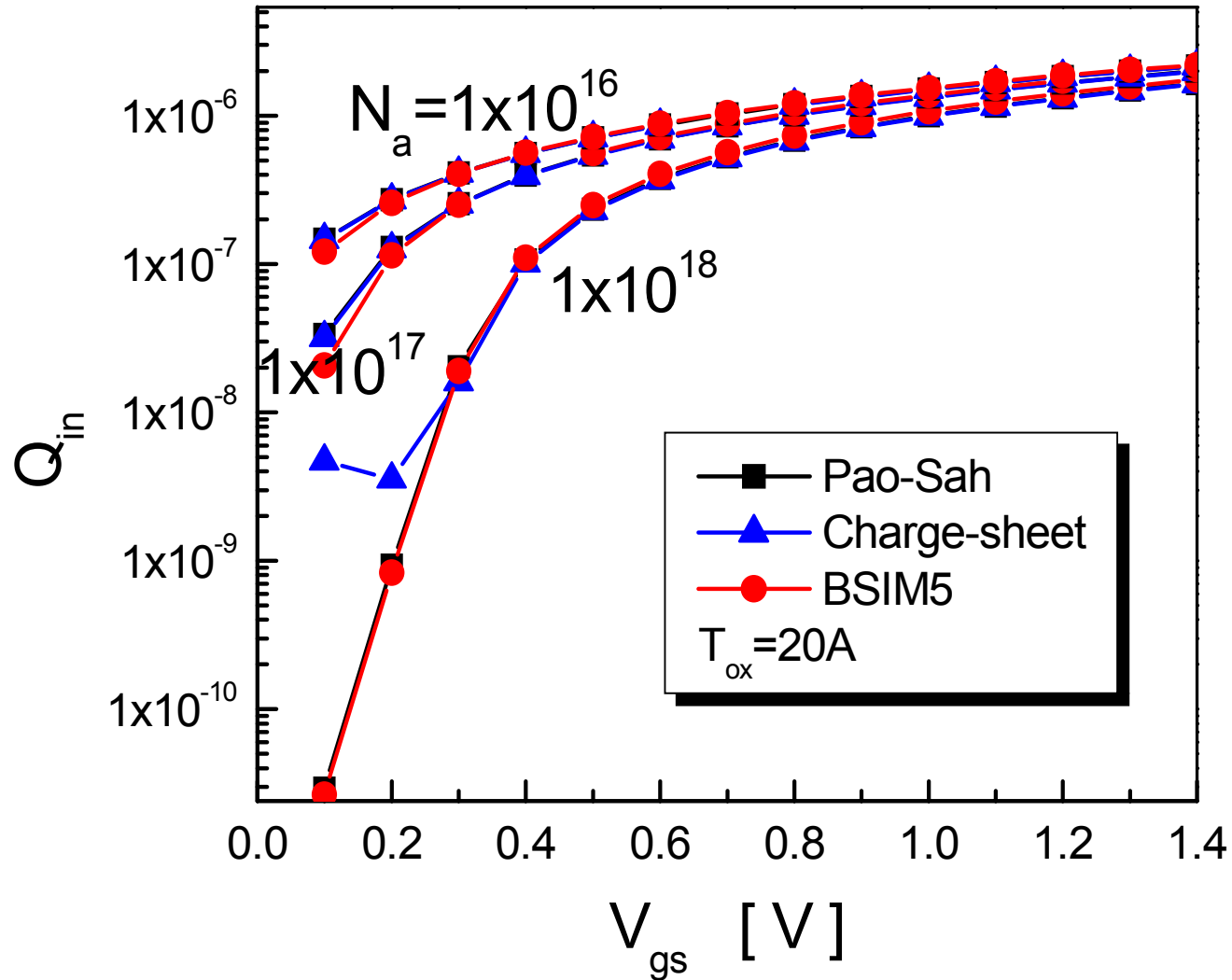
Inversion charge density solution

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

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 ψ_s at the source

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

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

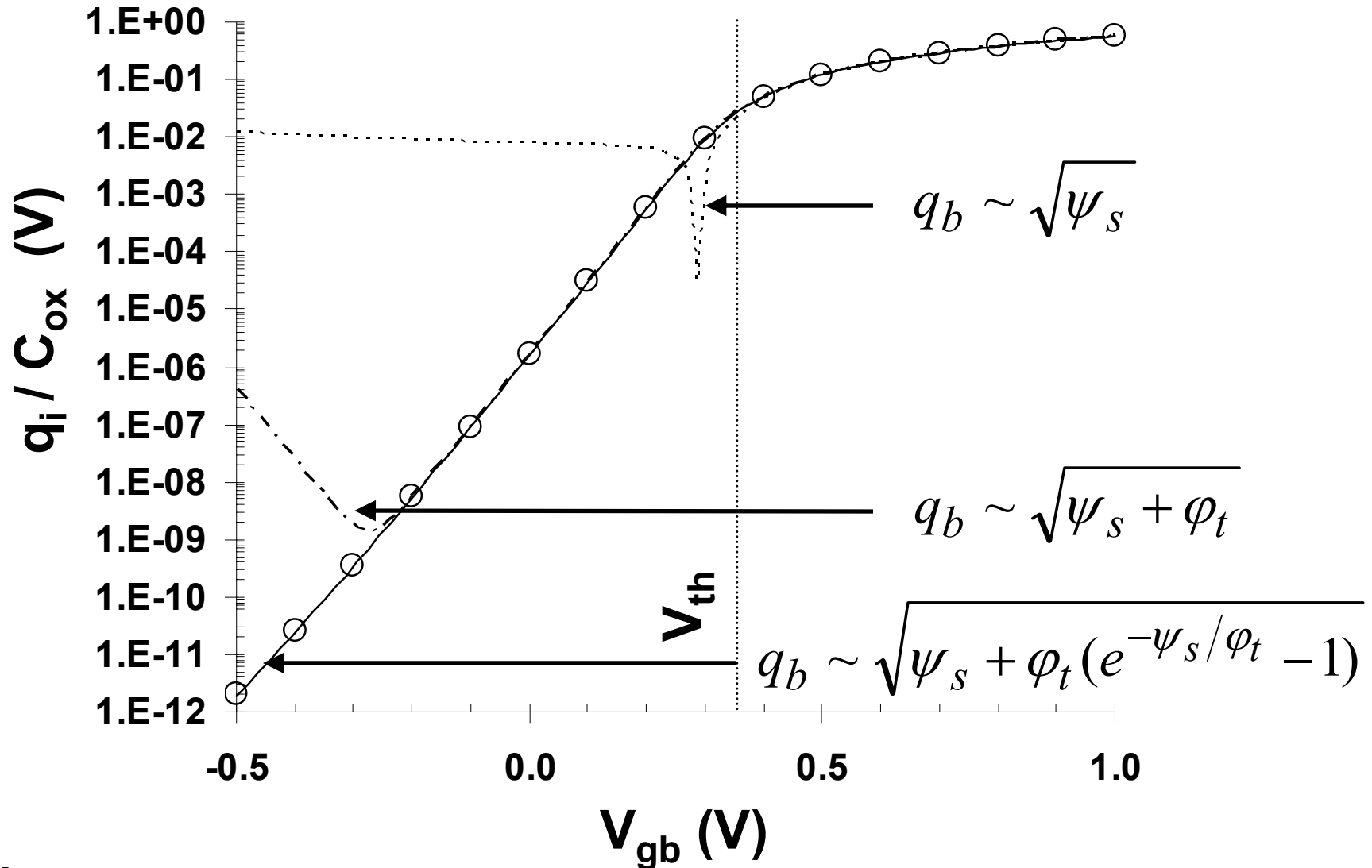
q_b is linearized w.r.t. source and drain end points

- 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 ψ_s

- accurate solution needed for conductance and capacitance

Physical handling of lateral doping profiles (halo)

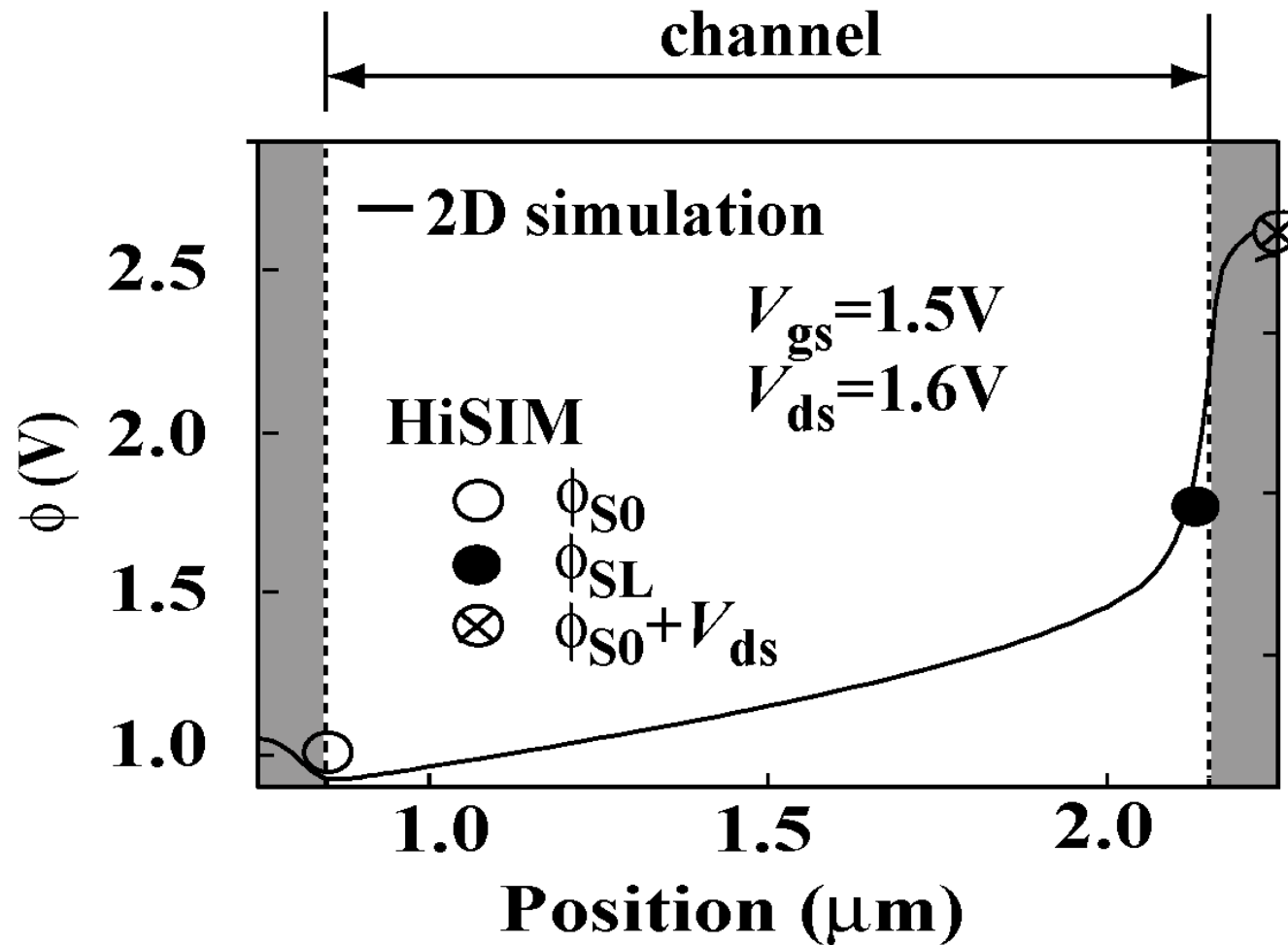
Consistent, simple formulation with a small number of physical parameters

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!

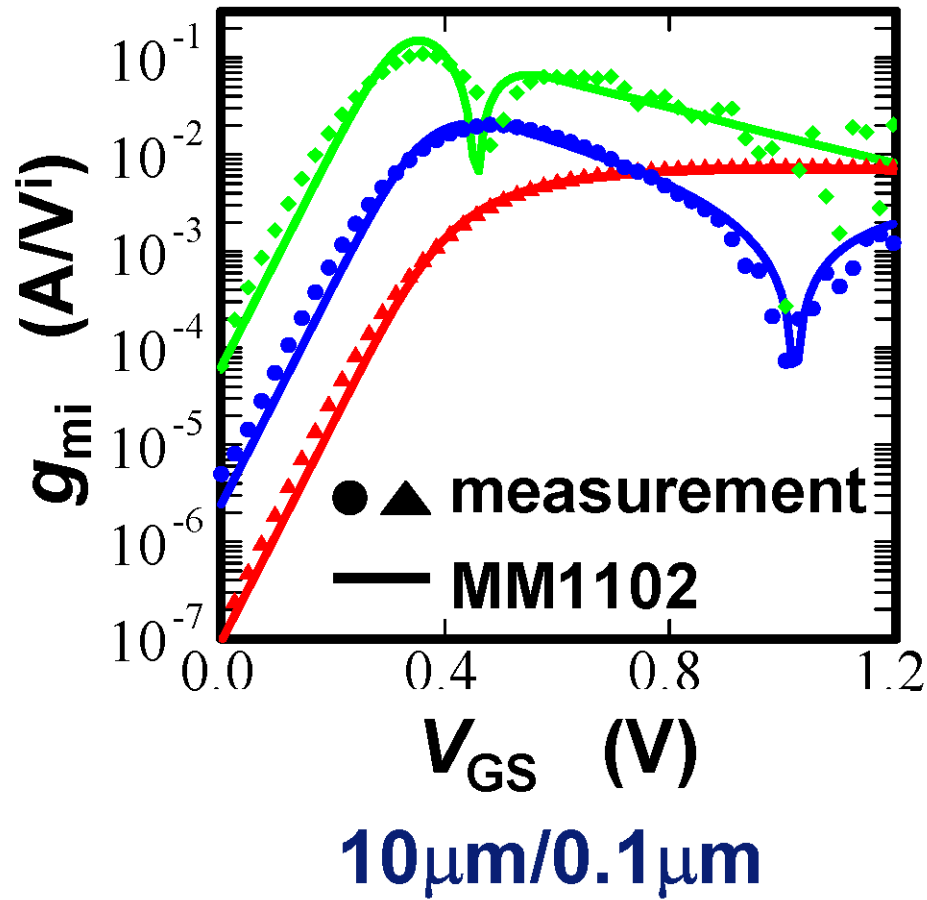
Model structure includes local (miniset, per geometry) and global (maxiset, over geometry) parameters

- 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 ψ_s solution, iterative procedure used since MM1102

MM11



Accurate non-iterative solution for ψ_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

