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# Review of the EKV3.0 MOSFET Model

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# Outline

- Introduction -- Motivation
- Basic EKV Model Formulation
- EKV3.0 Extensions
- Recent Enhancements/Ongoing R&D
- Implementation in circuit simulators
- Conclusions

# Introduction

- MOSFET modeling is increasingly complex
  - Consistent description of DC, AC, NQS, noise, matching behaviour.
- Model should include all pertinent physical aspects, scalability
  - Applicable over a wide range of CMOS technologies.
  - Need high accuracy AND high efficiency.
  - Retain a small number of parameters, simple parameter extraction.
- Physics-based AND design-oriented model needed
  - Design-gap! (particularly for analog).
  - Need design-oriented models and consistent design methods.
- Development of EKV model (and related design methodology) aims at “resolving the puzzle”.

# Ideal MOSFET Model

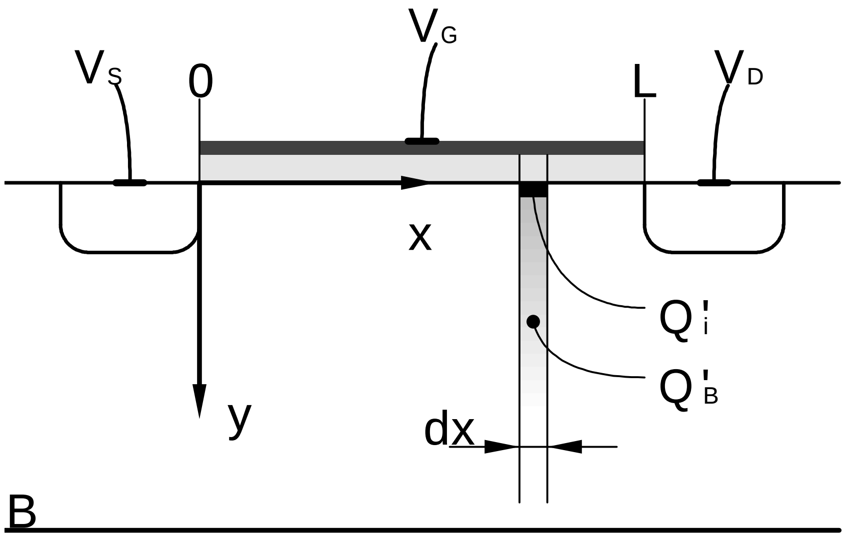
- Basic Model Definitions
- Inversion Charge Modeling
- Charges/Transcapacitances Modeling
- Non-Quasistatic (NQS) Modeling including for noise
- Thermal Noise Modeling

# Analytical Charge Sheet Model

- Physical basis: Surface potential ($\Psi_S$) model as reference
  - Basic problem: solve $Q'_i$ -- V relation (at source/drain) efficiently.
- Inversion charge $Q_i'$ linearization (vs. $\Psi_S$)
  - ... the key technique in the EKV model.
  - Same physics -- increased analytical versatility.
- Ideal framework for analytical compact MOS transistor modeling.
  - Simple ideal model expressions.
  - Charges description is then used throughout the model.

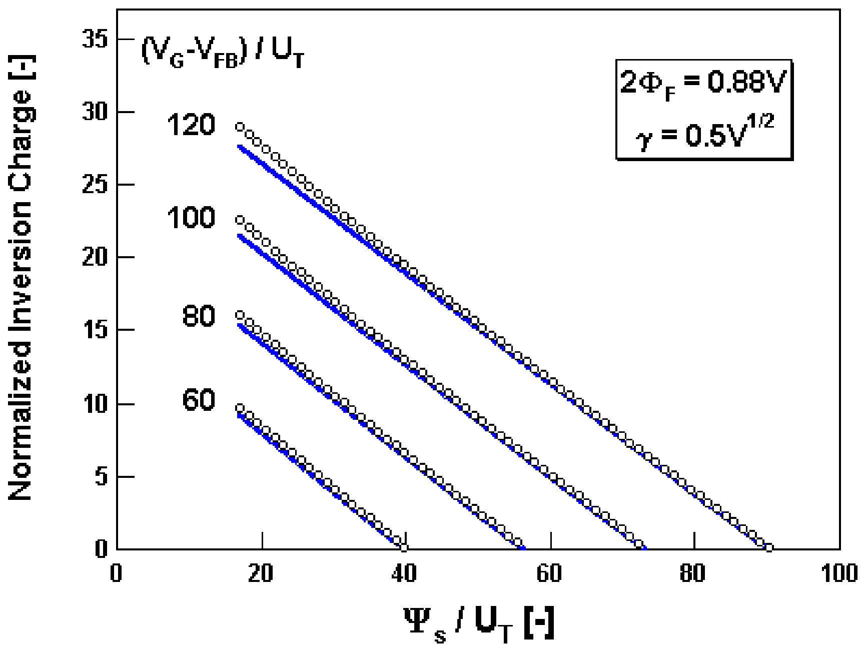
# MOS Transistor Model “Architecture”

- Describe M-O-S structure locally (at any given x)
  - ... substrate reference for voltages is helpful to achieve symmetric modeling
  - .... *analytically* solve local description of MOS...
  - ... requires linearization of inversion charge



- .... integrate along channel (from source to drain)
  - .... obtain integral quantities: drain current, charges, thermal noise
  - .... and derive transconductances, transcapacitances

# Inversion Charge Linearization



**Substrate Effect Factor:** $\gamma = \frac{\sqrt{2q\varepsilon_{si}N_{sub}}}{C'_{ox}}$

**Bulk Fermi Potential (**

$$\Psi_0 \cong 2\phi_F + m \cdot U_T = U_T \cdot \left(2\ln\left(\frac{N_{sub}}{n_i}\right) + m\right)$$

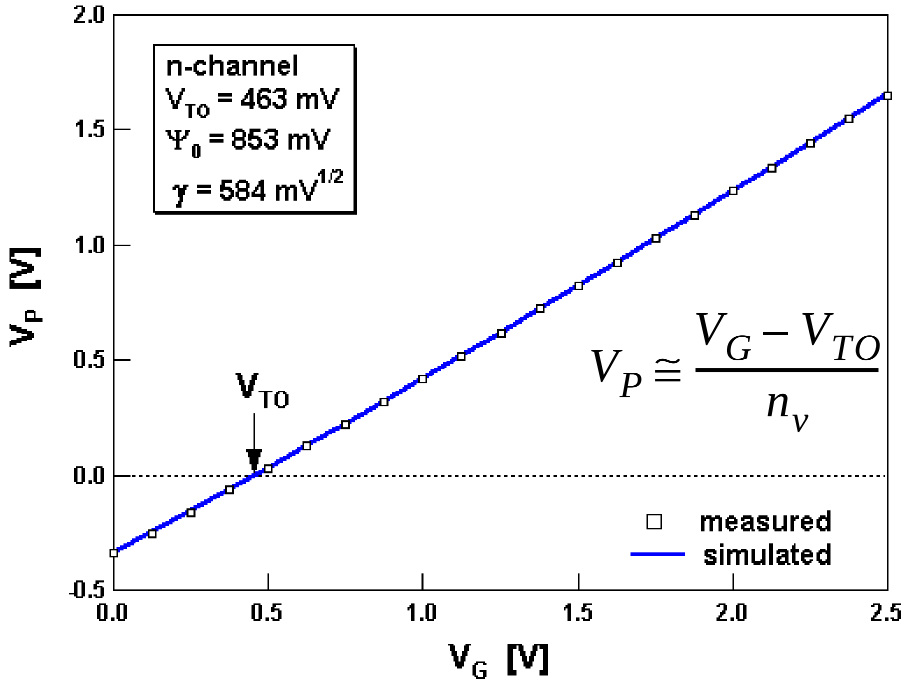
**Pinch-off Surface Potential:** $\Psi_{SP} \equiv \Psi_S\big|_{Q_i = 0}$

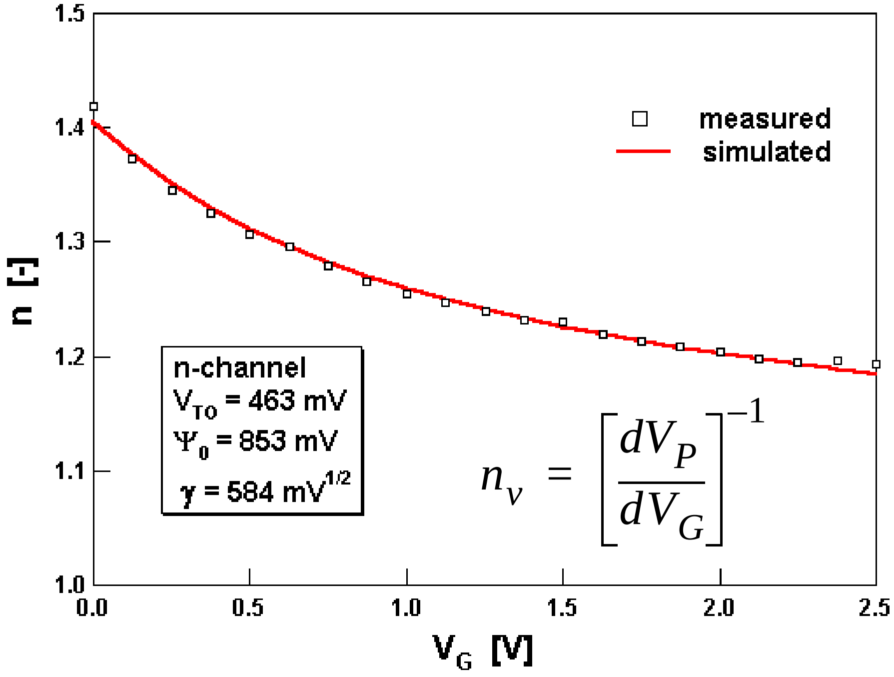
**Pinch-off Voltage:** $V_P \equiv \Psi_{SP} - \Psi_0$

- $Q_i'$ is almost linear w.r.t. surface potential $\Psi_S$ at fixed $V_G$.
- $\Psi_S\big|_{Q_i = 0}$ defines the *pinch-off surface potential* $\Psi_{SP}$
- Inversion charge linearization: $\frac{dQ_i'}{C_{ox}'} = n_q \cdot d\Psi_S$

  ... where $n_q$ is the inversion charge linearization factor

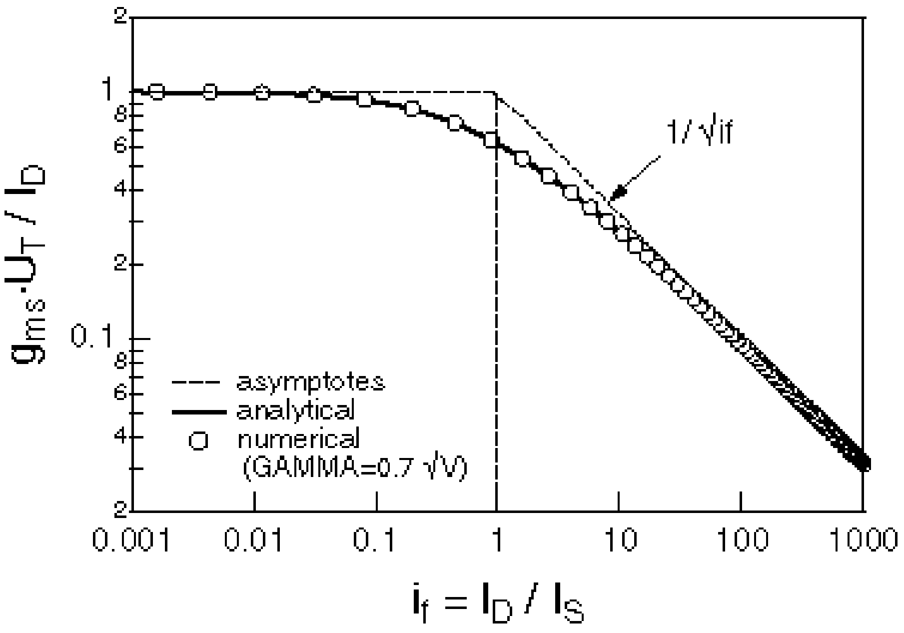
# Pinch-off Voltage $V_P$ and Slope Factor $n_v$

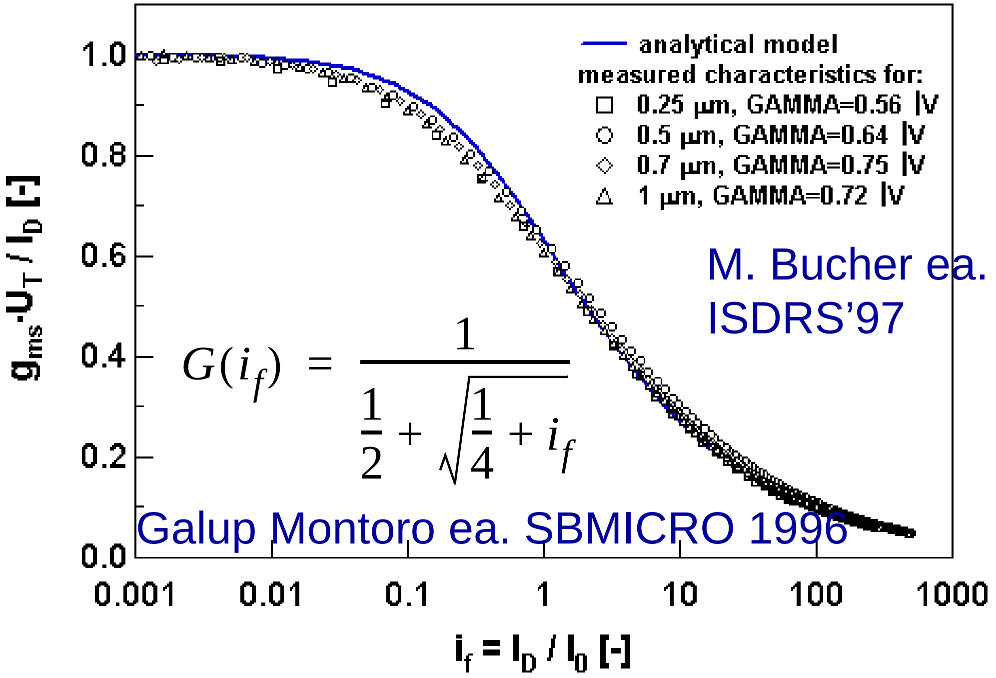




- Pinch-off voltage is a function of gate voltage
- $V_P$ can be measured -- moderate inversion method, M. Bucher ea. ICMTS’96
- Used for parameter extraction ($V_{TO}$, $g$, $Y_0$)
- Slope factor $n_v \equiv dV_G / dV_P$ is related to substrate effect
  & inverse weak inversion slope: $S=2.3*n_v*U_T$

# Transconductance-to-Current Ratio





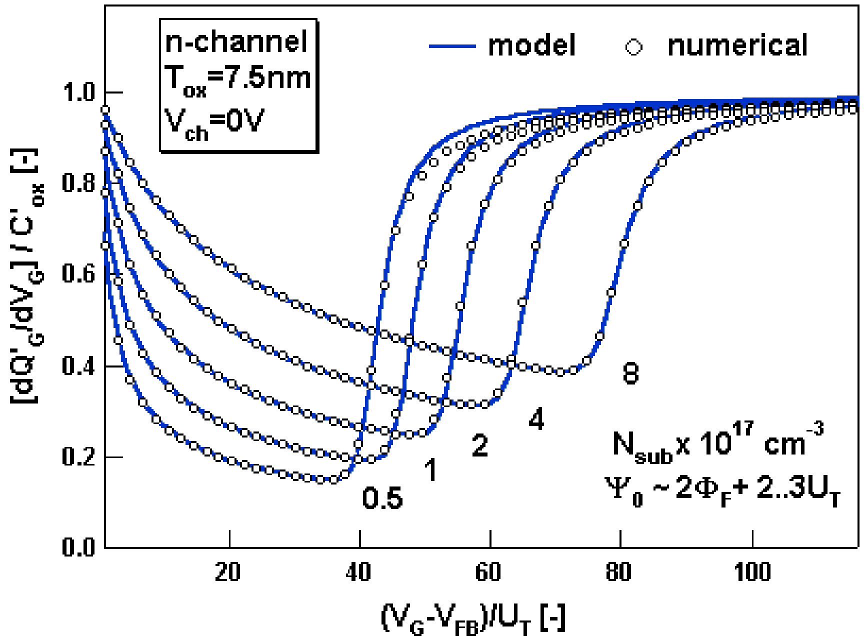
$$G(i_f) = \frac{1}{\frac{1}{2} + \sqrt{\frac{1}{4} + i_f}}$$

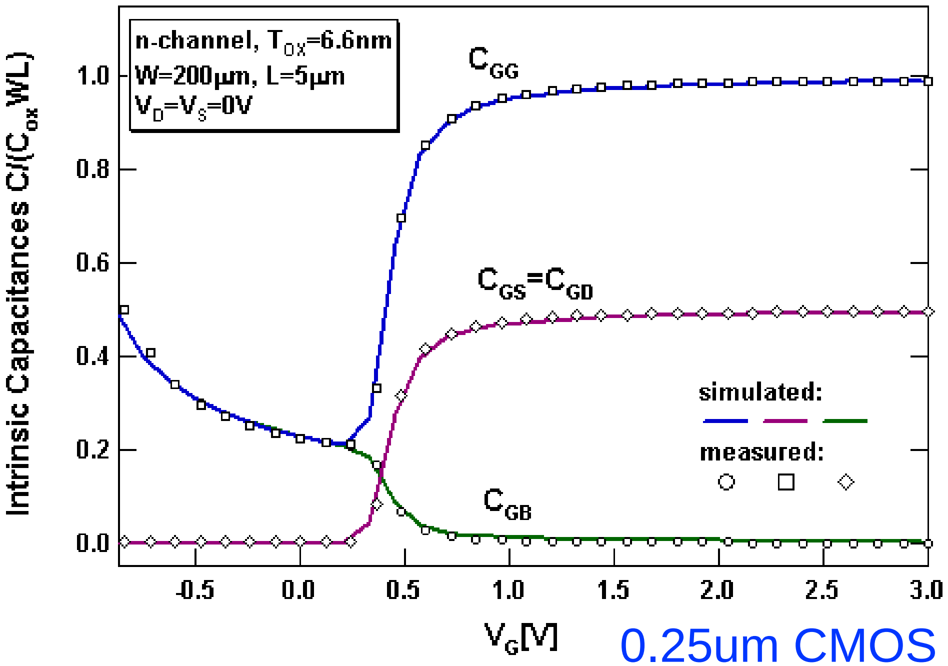
M. Bucher ea. ISDRS'97

Galup Montoro ea. SBMICRO 1996

- Analytical model compared to surface potential model, and compared to measurements (4 different technologies)
- Normalized source transconductance-to-current ratio vs. normalized drain current (in saturation) is *universal*,
  - .... for different *gate voltage*, *temperature*, *technology* (long-channel).

# Transcapacitances





0.25um CMOS

- Analytical model compared to numerical surface potential model
  - Excellent fit, no parameter tuning
- Analytical model compared to measurement

# Ideal Analytical MOSFET Model

Definitons.

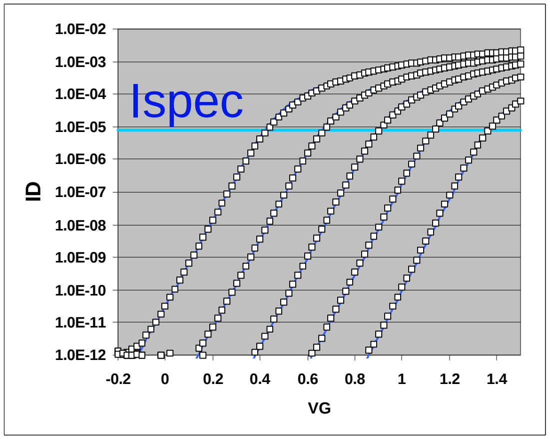
| | |
|---|---|
| $C_{ox}' = \frac{\varepsilon_{ox}}{T_{ox}}$ | $\gamma_s = \frac{\sqrt{2q\varepsilon_{si}N_s}}{C_{ox}'}$<br>$\Psi_0 \cong 2\phi_F = 2U_T\ln\left(\frac{N_S}{n_i}\right)$ |
| $V_{TO} = V_{FB} + \Psi_0 + \gamma_s\sqrt{\Psi_0}$<br>$V_P \cong \frac{V_G - V_{TO}}{n_v}$ | $n_v = 1 + \frac{\gamma_s}{2\sqrt{\Psi_0 + V_P}}$<br>$n_q = 1 + \frac{\gamma_s}{2\sqrt{\Psi_0 + V_P / 2}}$ |

- Definitions of (electrical) parameters, pinch-off voltage, slope factor,and linearization factor

# Ideal Analytical MOSFET Model

Normalizations

| | |
|---|---|
| $I_S = 2n_q U_T^2 \mu C_{ox}' \frac{W}{L}$<br>$Q_0 = 2n_q U_T C_{ox}'$ | $U_T = kT/q$<br>$G_0 = \frac{I_S}{U_T} = 2n_q U_T \mu C_{ox}' \frac{W}{L}$ |
| $I_D = I_F - I_R = I_S \cdot (i_f - i_r)$<br>$Q_{iS(D)}' = \frac{q_{f(r)}}{Q_0}$ | $u_P = \frac{V_P}{U_T}$ $\qquad$ $u_{S(D)} = \frac{V_{S(D)}}{U_T}$ |



- Normalization of: drain current, inversion charge, voltages, transconductances
- Symmetric forward and reverse current and charge components: Inversion charge is evaluated at source and drain

# Ideal Analytical MOSFET Model

Relationships

| | |
|---|---|
| $u_p - u_s = \ln(q_f) + 2q_f$ | $u_p - u_d = \ln(q_r) + 2q_r$ |
| $i_f = q_f^2 + q_f$<br>$q_f = \sqrt{1/4 + i_f} - 1/2$ | $i_r = q_r^2 + q_r$<br>$q_r = \sqrt{1/4 + i_r} - 1/2$ |
| $g_{ms} = G_0 \cdot q_f$<br>$\frac{g_{ms}}{i_f \cdot G_0} = \frac{2}{\sqrt{1 + 4i_f} + 1}$ | $g_{md} = G_0 \cdot q_r$<br>$\frac{g_{md}}{i_r \cdot G_0} = \frac{2}{\sqrt{1 + 4i_r} + 1}$ |

- Analytical relationships among (normalized) voltages, inversion charge, drain current, transconductances.
  - Ideal voltage-charge relationship
  - Symmetry between source/drain sides
  - Analytical asymptotic expressions can be derived

# Compact Expression of Charges, Transcapacitances

Integral charges

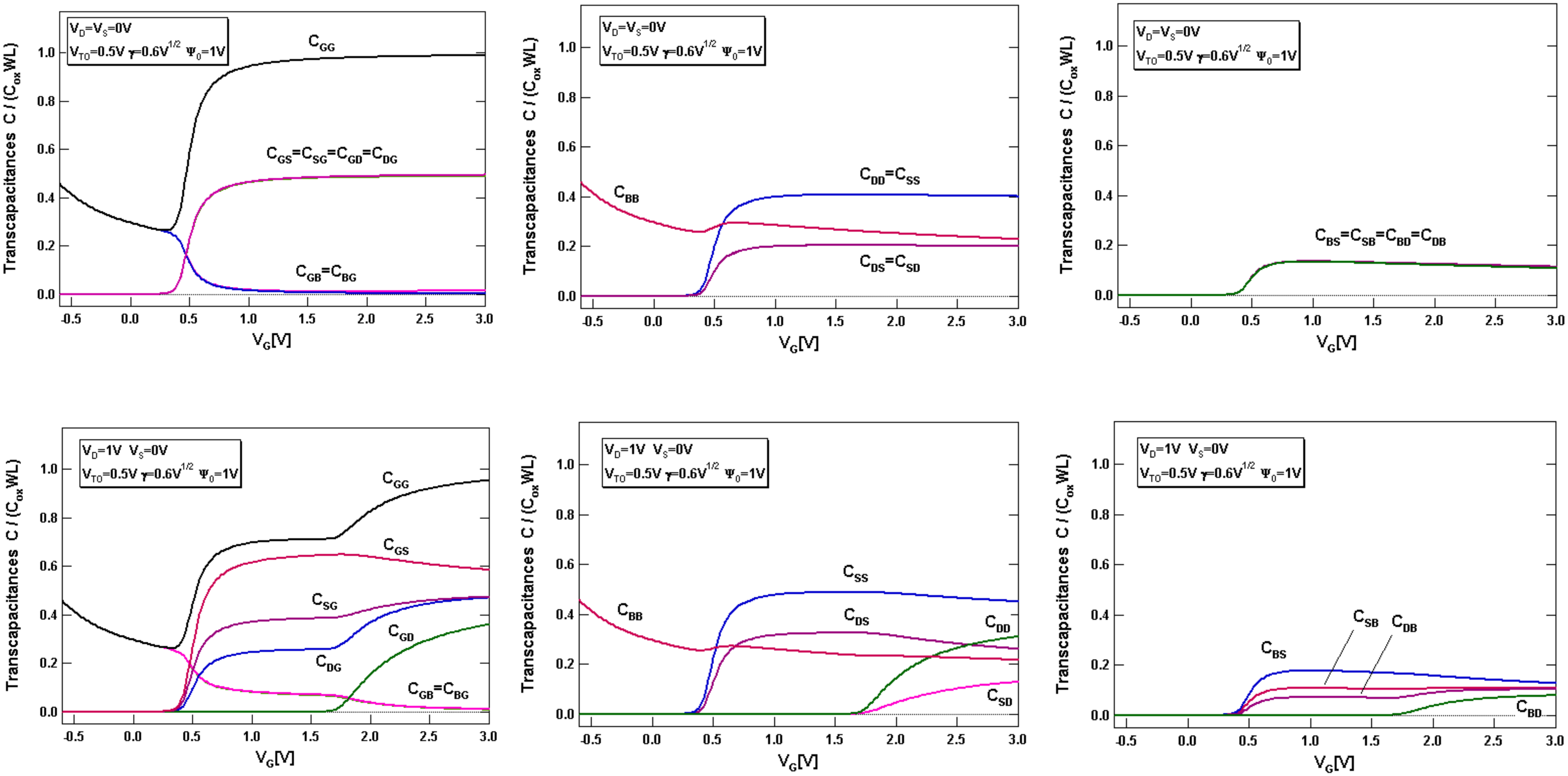
| | |
|---|---|
| $Q_I$ | $-Q_0 \cdot WL \cdot \left[\frac{2}{3}\frac{\chi_f^2+\chi_f\cdot\chi_r+\chi_r^2}{\chi_f+\chi_r}-\frac{1}{2}\right]$ |
| $Q_D$ | $-\frac{Q_0}{2}\cdot WL\cdot\left[\frac{4}{15}\frac{2\chi_f^3+4\chi_f^2\cdot\chi_r+6\chi_f\cdot\chi_r^2+3\chi_r^3}{(\chi_f+\chi_r)^2}-\frac{1}{2}\right]$ |
| $Q_S$ | $-\frac{Q_0}{2}\cdot WL\cdot\left[\frac{4}{15}\frac{3\chi_f^3+6\chi_f^2\cdot\chi_r+4\chi_f\cdot\chi_r^2+2\chi_r^3}{(\chi_f+\chi_r)^2}-\frac{1}{2}\right] = Q_I-Q_D$ |
| $Q_B$ | $-\gamma\cdot C'_{ox}\cdot WL\cdot\sqrt{\Psi_0+V_p}-\frac{n-1}{n}\cdot Q_I$ |
| $Q_G$ | $-(Q_I+Q_B)$ |
| where: $\chi_{f(r)} = \sqrt{\frac{1}{4}+i_{f(r)}}$ | |

Transcapacitances (excerpt)

| | |
|---|---|
| $C_{GS}$ | $-\frac{2}{3}\left[1-\frac{\frac{1}{2}\chi_f+\chi_r+\chi_r^2}{(\chi_f+\chi_r)^2}\right]$ |
| $C_{GD}$ | $-\frac{2}{3}\left[1-\frac{\chi_f^2+\chi_f+\frac{1}{2}\chi_r}{(\chi_f+\chi_r)^2}\right]$ |
| $C_{GG}$ | $\frac{n_v-1}{n_v}-\frac{C_{GS}+C_{GD}}{n_v}$ |
| $C_{GB}$, $C_{BG}$ | $-\frac{n_v-1}{n_v}\cdot[1+C_{GS}+C_{GD}]$ |
| $C_{BS}$ | $(n_v-1)\cdot C_{GS}$ |
| $C_{BD}$ | $(n_v-1)\cdot C_{GD}$ |

- Compact expressions for charge, transcap., etc. are obtained.

# Transcapacitances

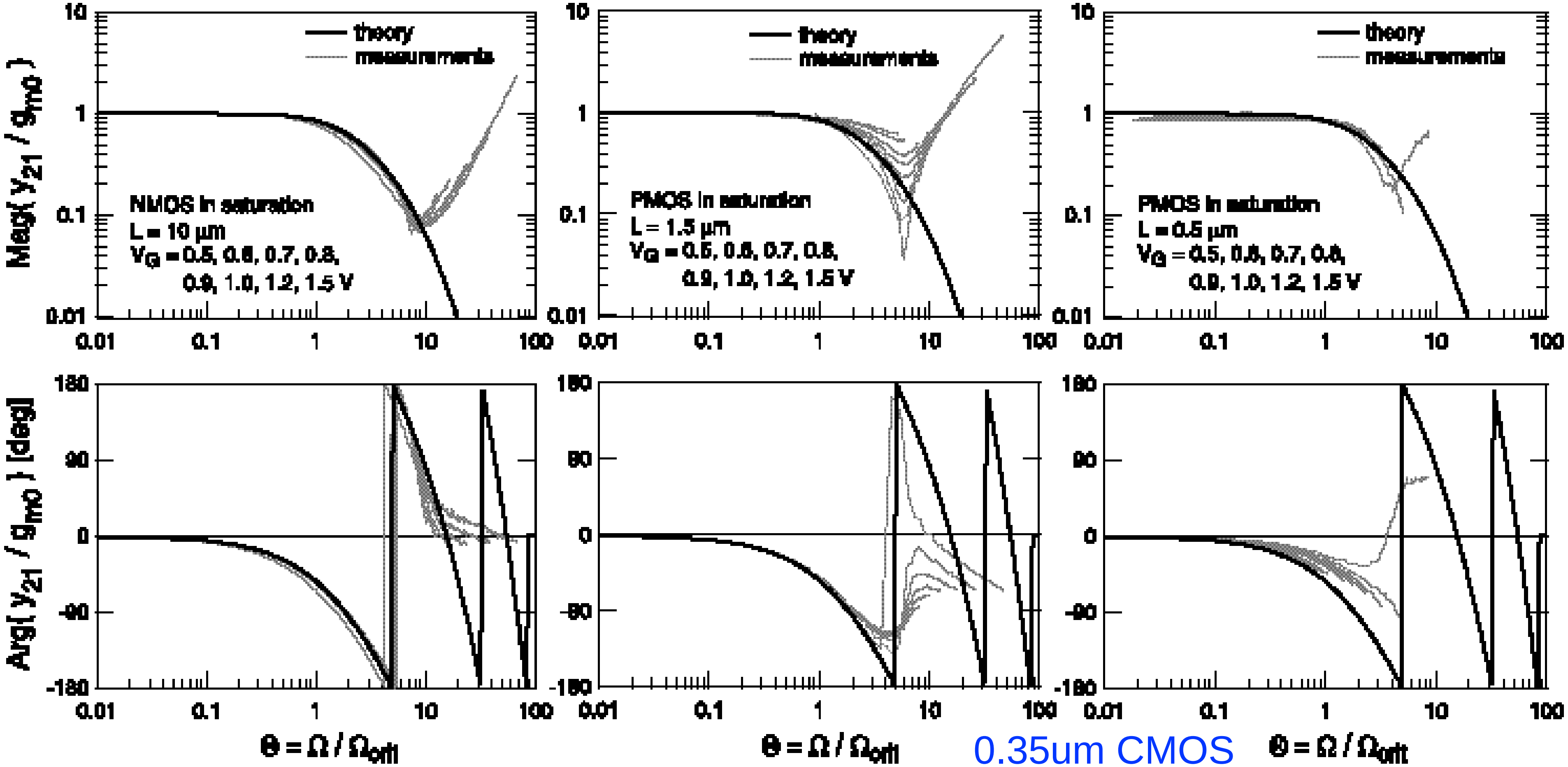


- Correct asymptotic behavior, linear/saturation, weak/strong inversion

# Non-Quasi-Static (NQS) Model

- NQS effects are more severe in...
  - longer-channel,
  - moderate/weak inversion,
  - PMOS (lower mobility) vs. NMOS
- NQS modeling approach based on small-signal (AC) analysis
- Small-signal NQS behavior can be accurately modeled:
  - requires no additional parameters
  - valid in all operating regions
    -- particularly also in moderate & weak inversion
  - makes wide use of normalization including for frequency

# Non-Quasi-Static Model



0.35um CMOS

- Normalized NQS AC model (black), measurements (grey)
- Frequency is also normalized (in two steps) A.-S. Porret ea. TED 8/2001

# NQS Noise -- Induced Gate & Substrate Noise

- Channel thermal noise is the predominant noise source at high frequencies.
- Channel thermal noise is coupled to the gate *and to the substrate* at high frequencies.
  - Previous modeling approaches usually do not cover moderate & weak inversion
  - Previous modeling approaches ignore coupling to the substrate
- The NQS modeling approach is consistently extended to model induced gate/substrate noise in all operating regions.

# Summary of Ideal Analytical MOSFET Model

- The EKV MOSFET model approach is based on surface potential, combined with inversion charge linearization technique.
  - ❒ Provides framework to ideal analytical MOSFET model.
  - ❒ Symmetric forward/reverse operation,
    valid & continuous in all operating regions.
  - ❒ Uses the same physical parameters as the surface-potential model.
- Coherent charge-based framework for static/dynamic aspects:
  - ❒ Current, transconductances, charges, transcap., NQS model, noise.
  - ❒ Same Basis for EKV 2.6, EKV3.0.
- The EKV MOSFET model approach is analog-design-oriented.
  - ❒ Uses consistent normalization of: voltage, drain current, charges,
    transconductance, frequency.
  - ❒ Supports advanced analog IC design practice.

# EKV3.0 -- Motivations

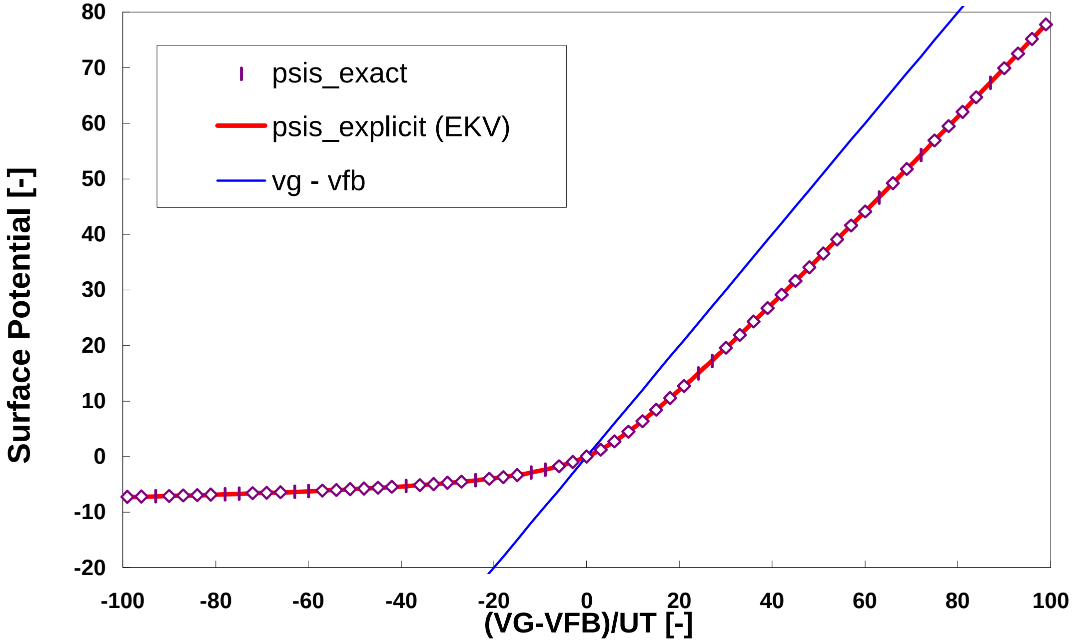
- Includes all pertinent physical aspects, scalability in deep submicron CMOS.
- Applicable over a wide range of CMOS technologies.
- Symmetrical forward/reverse operation, continuous derivatives at forward/reverse boundary ($V_D=V_S$).
- Accuracy-complexity trade-off, reasonable number of parameters, computational efficiency is important.
- Hierarchical structure, eases parameter extraction, hand calc. &c.
- Includes device matching.
- Predictiveness.
- Design methodologies related to model.

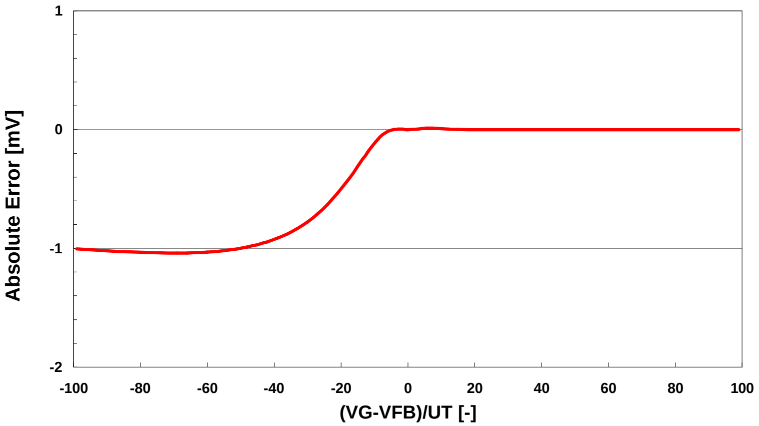
# EKV3.0 -- Extensions of Ideal Charges Model

- Effects that affect the pinch-off voltage - gate voltage relationship
  - Non-uniform Doping Effects
  - Polydepletion, Quantum Effects
  - Source-Drain Charge Sharing
  - Drain Induced Barrier Lowering

- Effects that affect the mobility - charge relationship
  - Effective field-dependent mobility
  - Velocity Saturation
  - Channel Length Modulation, etc.
  - Series resistance.

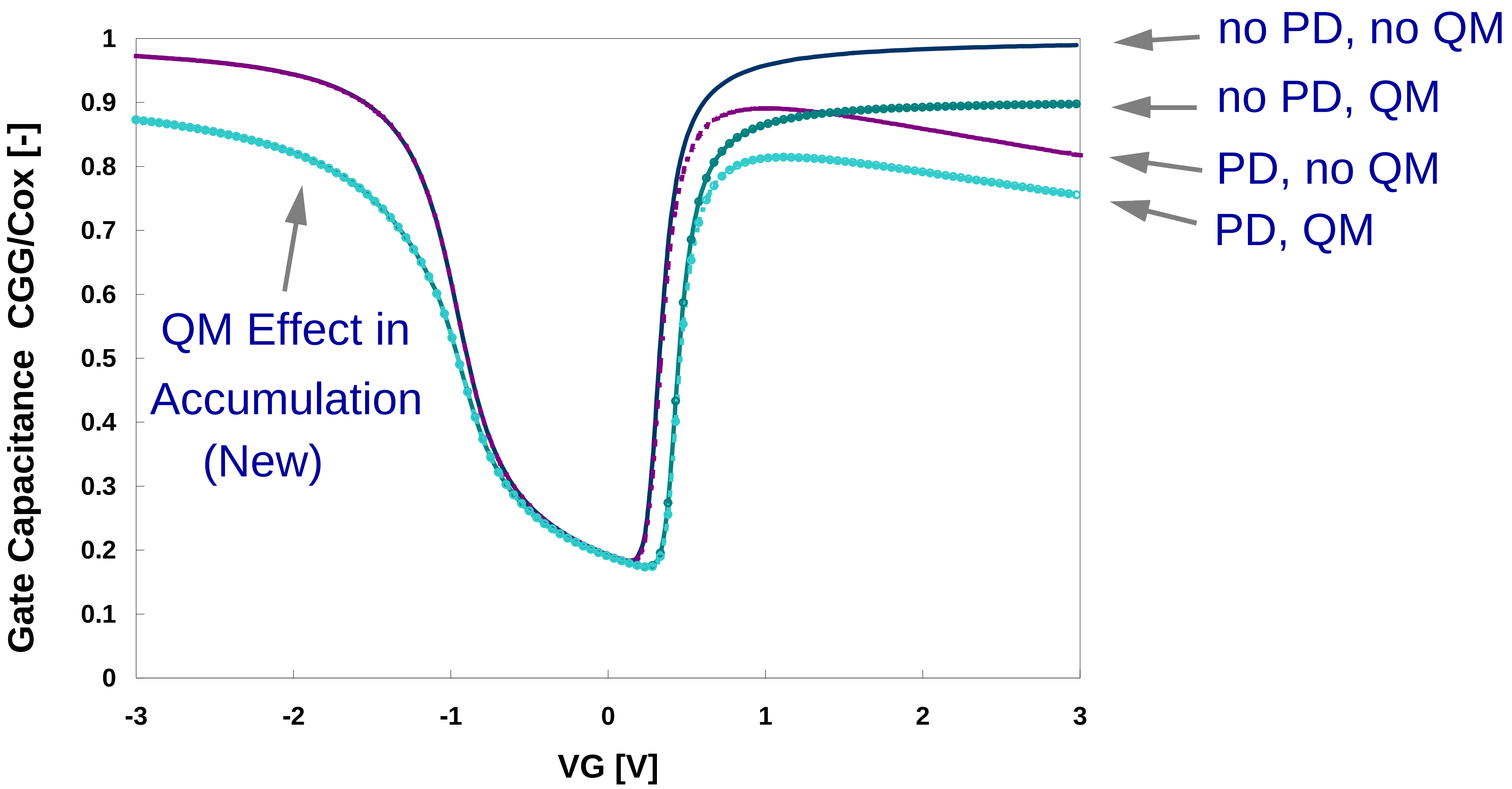
# EKV3.0 -- Explicit Evaluation of Surface Potential





- ❒ Example shows accumulation-depletion surface potential approximation used in EKV3.0 for accumulation charge modeling
- ❒ Provides physical, continuous depletion-accumulation charge model
- ❒ Continuous, maximum error 1mV w.r.t surface potential -- not critical!
- ❒ Similar technique used for accumulation-depletion-inversion

# EKV3.0 -- Polydepletion and Quantum Effects



no PD, no QM

no PD, QM

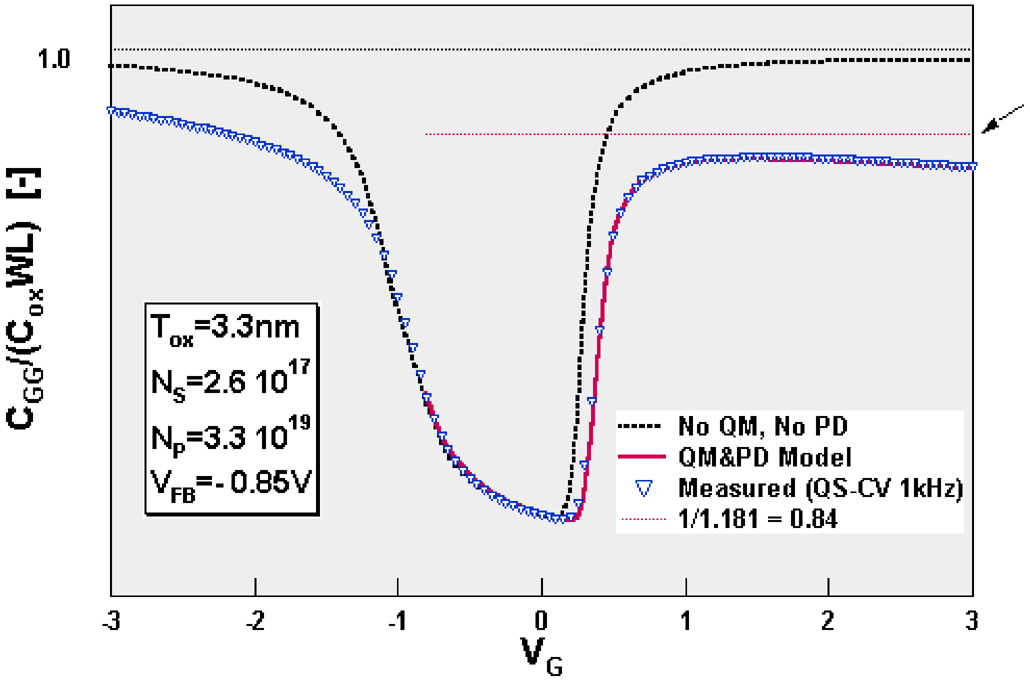
PD, no QM

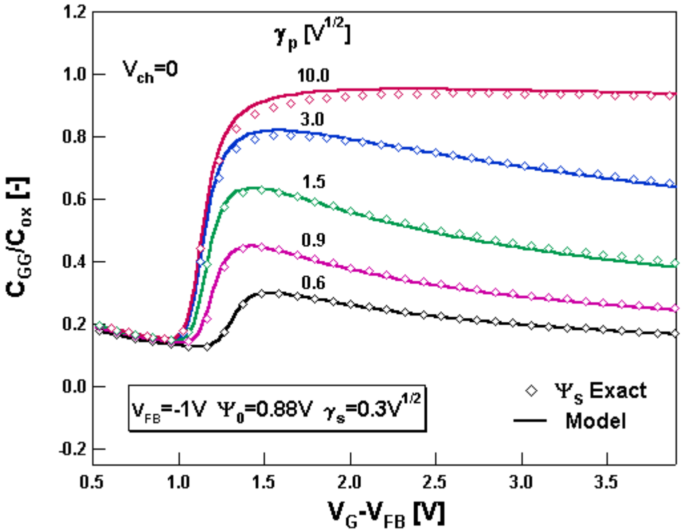
PD, QM

QM Effect in Accumulation (New)

- EKV3.0 model without & with PD, QM effects
  - ❐ Physical, continuous, no glitches at accumulation/depletion boundary

# EKV3.0 -- Polydepletion & Quantum Effects

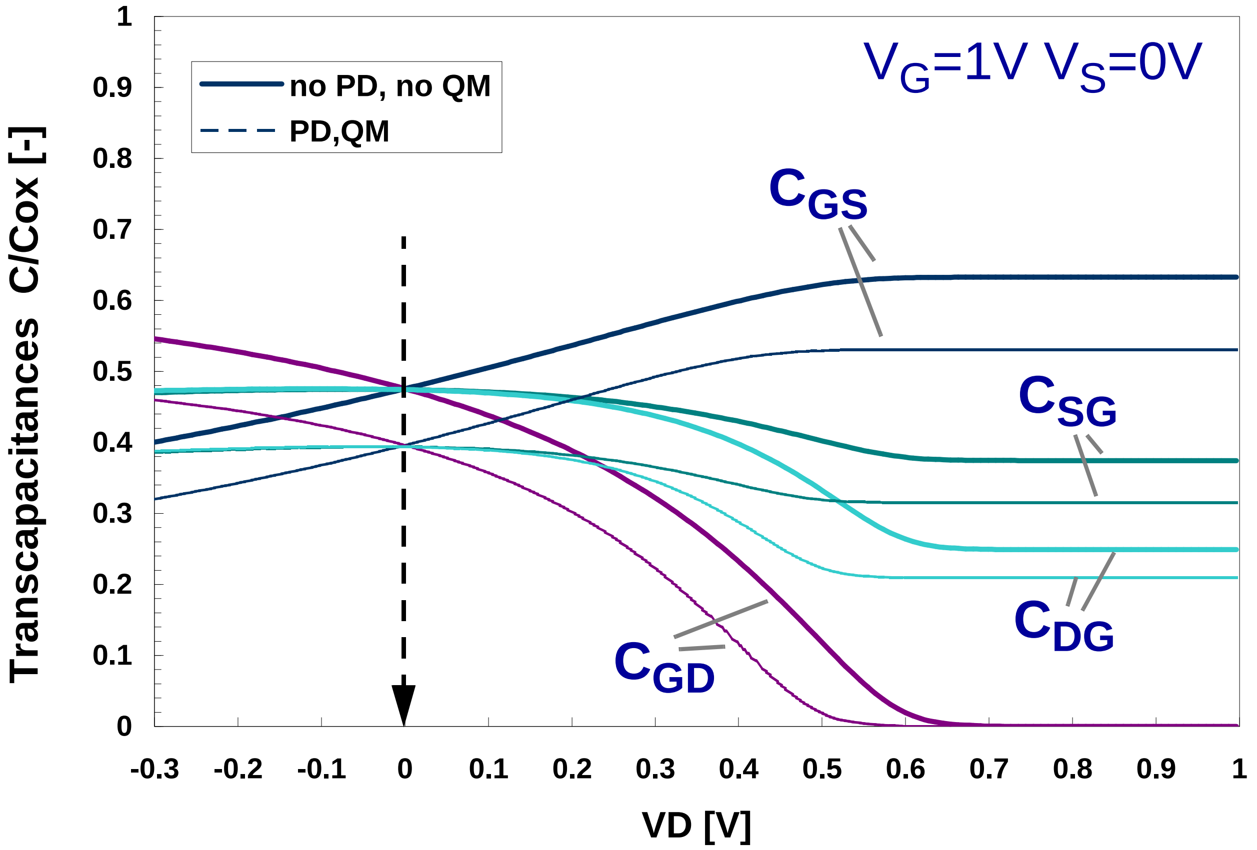




J.-M. Sallese ea. SSE 8/2000
M. Bucher e.a. SISPAD 2000
C. Lallement e.a. TED 2/2003

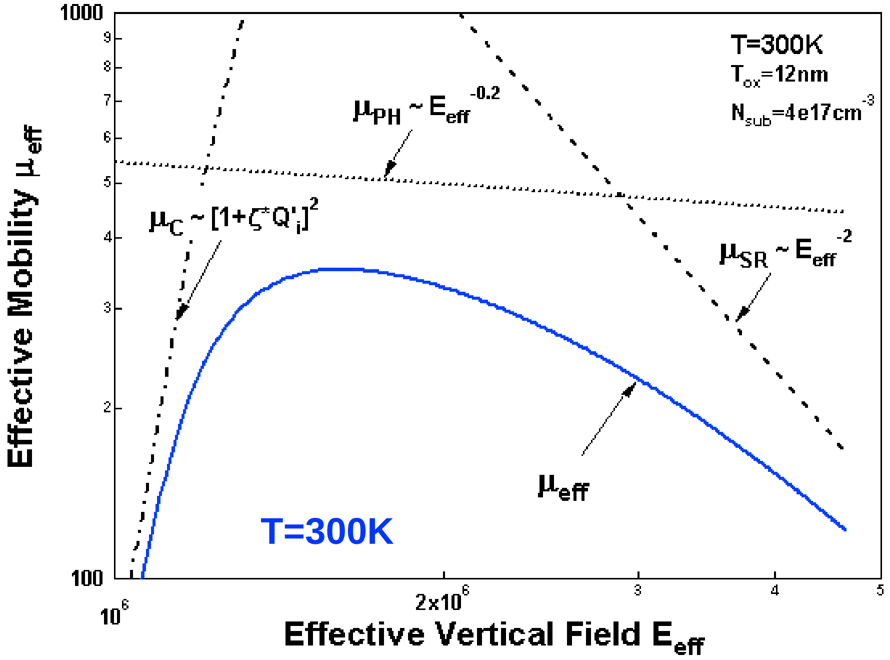
- Model fit to CV measurement, surface potential model.
  - One new parameter, $N_{poly}$ (or $g_{poly}$) for PD
  - One additional parameter for QM effects

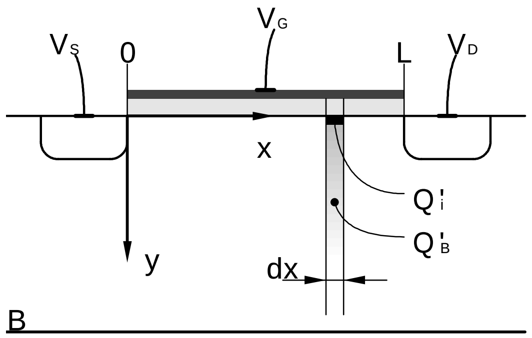
# EKV3.0 -- S-D Symmetry of Transcapacitances



- $C_{GS}$, $C_{GD}$, $C_{SG}$, $C_{DG}$ without & with PD, QM effects
  - ❒ Symmetry at VD=VS

# EKV3.0 -- Charge-based Mobility Model



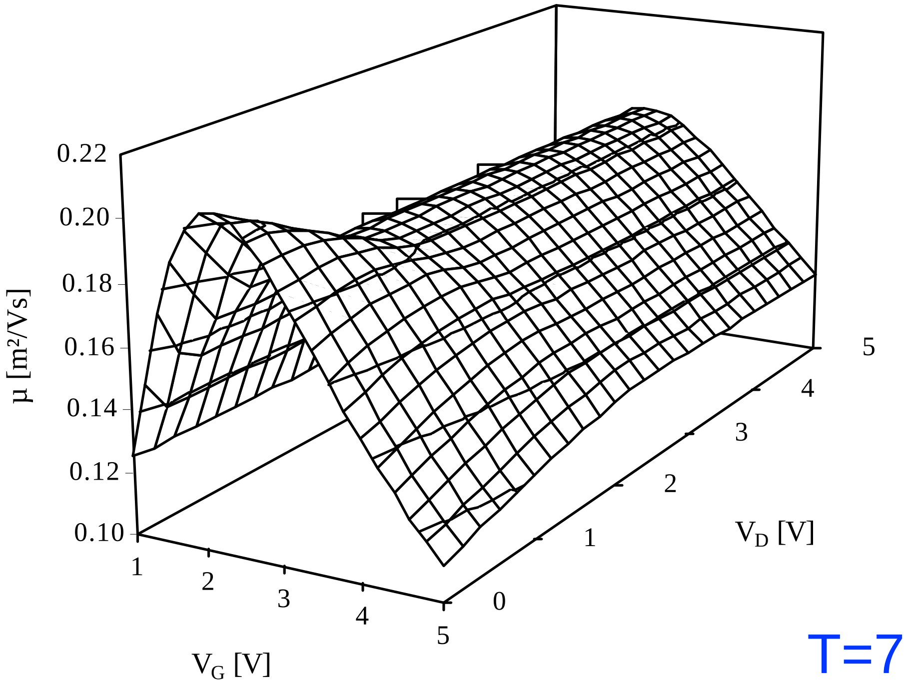


$$E_{eff}(x)=Q_B'(x)+\eta Q_i'(x)$$

$\eta$=1/2 (NMOS), $\eta$=1/3 (PMOS)

- Effective-field based mobility modeling
  - Surface-roughness scattering (high vertical field)
  - Phonon-scattering intermediate field strengths
  - Coulomb scattering effects
    (low vertical field; particularly at very high Nsub, low T)

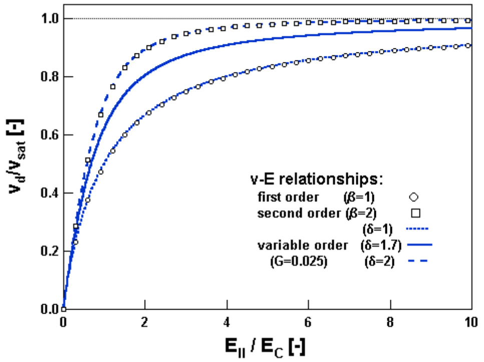
# EKV3.0 -- Charge-based Mobility Model

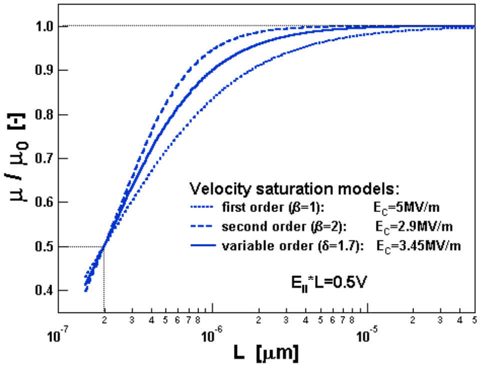


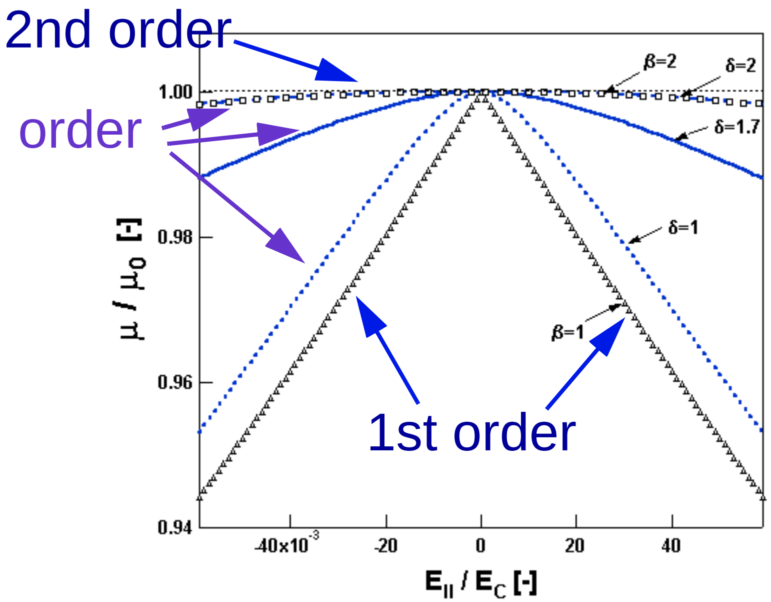
T=77K

- Mobility is field-dependent, field is charge-dependent, charge is position-dependent: integrate mobility along the channel
  - ❒ Therefore, mobility depends *both* on gate *and* drain voltage
  - ❒ Long-channel; for short-channel, there is also Vel. Sat., CLM.

# EKV3.0 -- Velocity Saturation Modeling





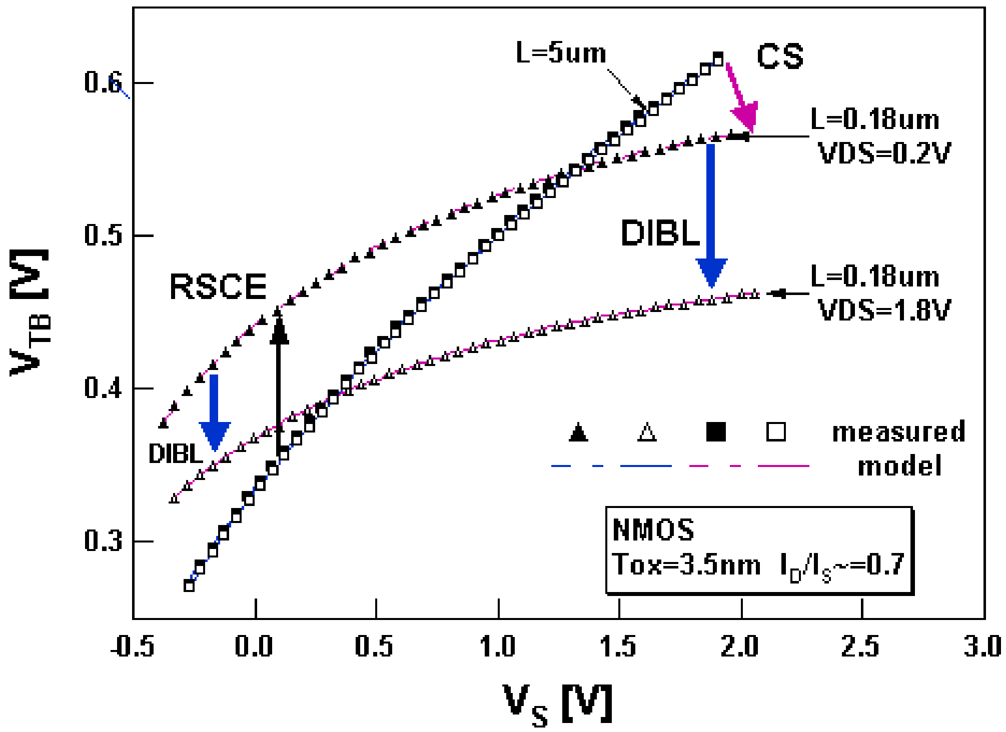


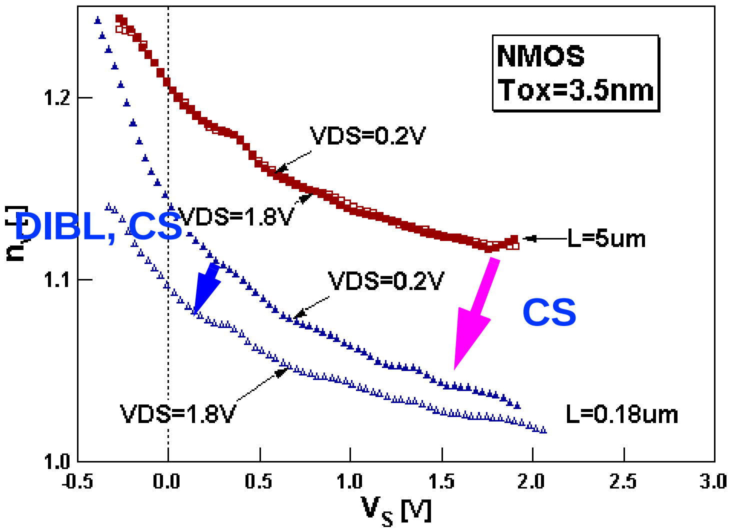
- Consider a *variable-order* (1st-2nd) velocity-field relationship
    - Parameters: Ec, DELTA.
    - *Continuous* at VD=VS!
- New charge-based channel length modulation (CLM) model.

# EKV3.0 -- Effects Dominating Weak/Moderate Inversion

- Vertical Non-Uniform Doping
  - Considers step/retrograde doping profiles, pocket implants
- Longitudinal Non-Uniform Doping/Oxide Charge
  - Reverse Short Channel Effect (RSCE)
- 2D Charge-Sharing
- Drain Induced Barrier Lowering (DIBL)
- Considers also *inter-relation* of:
  - non-uniform doping, charge-sharing, polydepletion/quantum effects.

# EKV3.0 -- Threshold Voltage Modeling

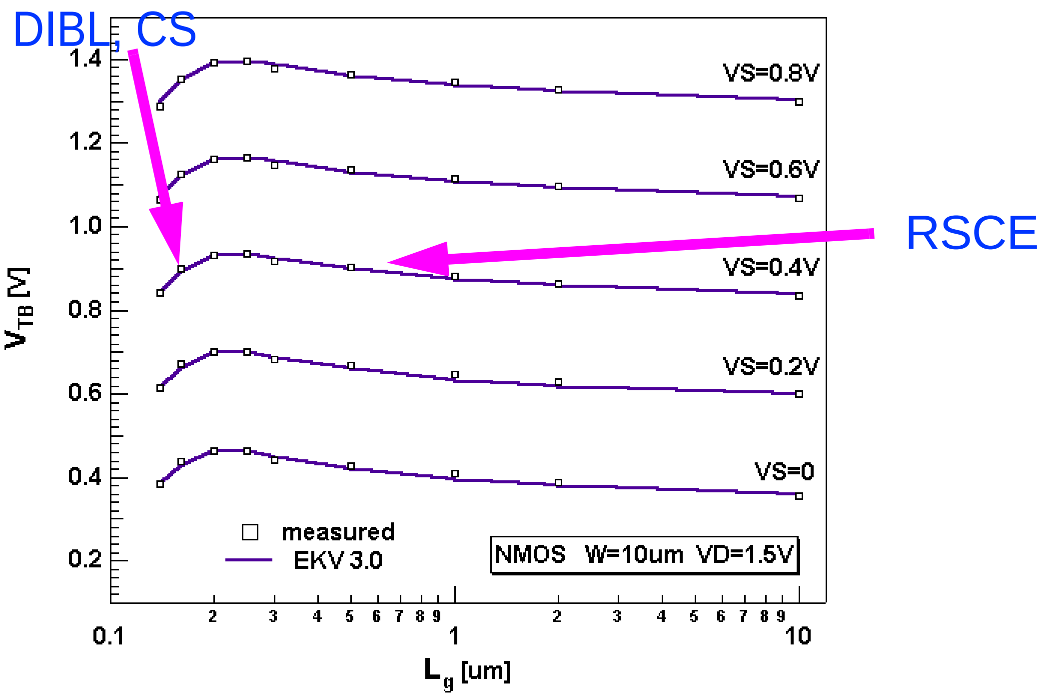




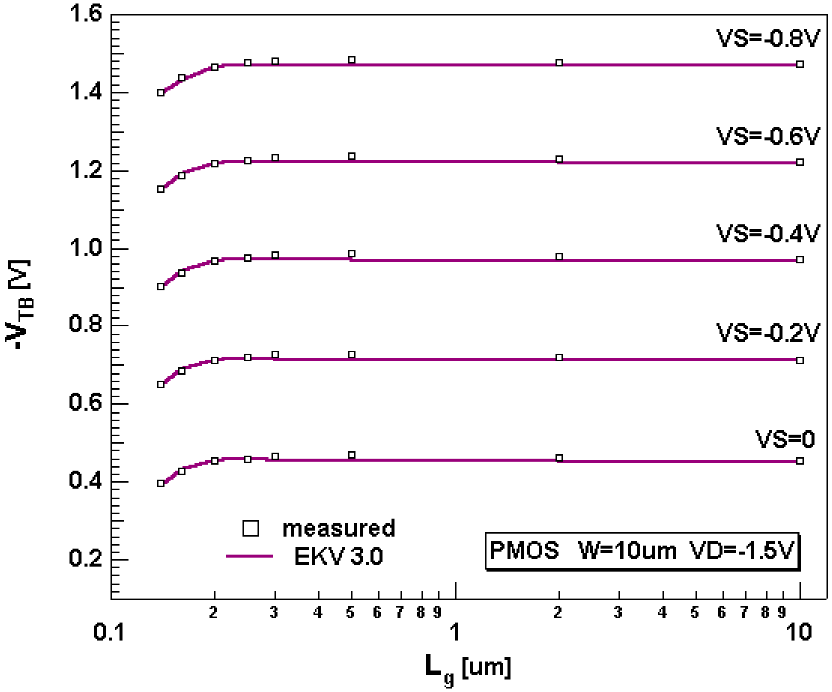
0.18um CMOS

- Combination of all effects:
  - Charge Sharing (CS) reduces substrate effect
  - DIBL reduces threshold voltage @ short L, high $V_D$ (*but not only*)

# EKV3.0 -- Threshold Voltage/RSCE Modeling


DIBL, CS

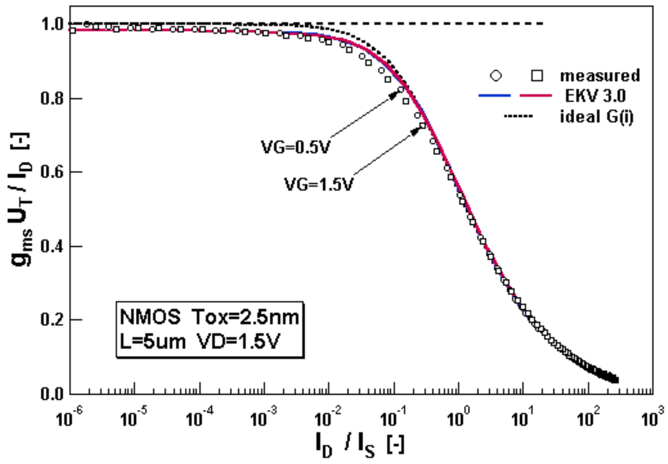
RSCE



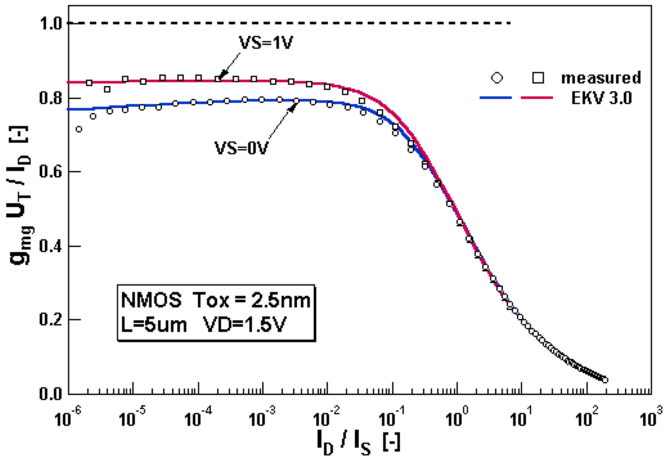
NMOS 0.13um CMOS PMOS

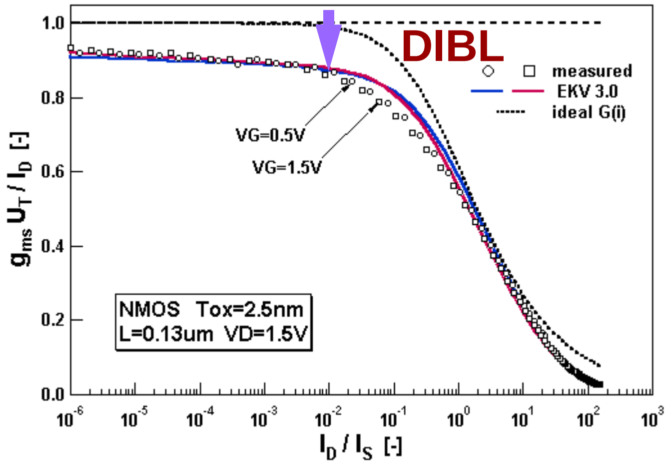
- Reverse Short-Channel Effect
  - $V_T$ roll-up: Non-uniform doping/oxide charge
  - $V_T$ roll-off: due to both charge-sharing and DIBL

# EKV3.0 -- Normalized Transconductances vs. ID

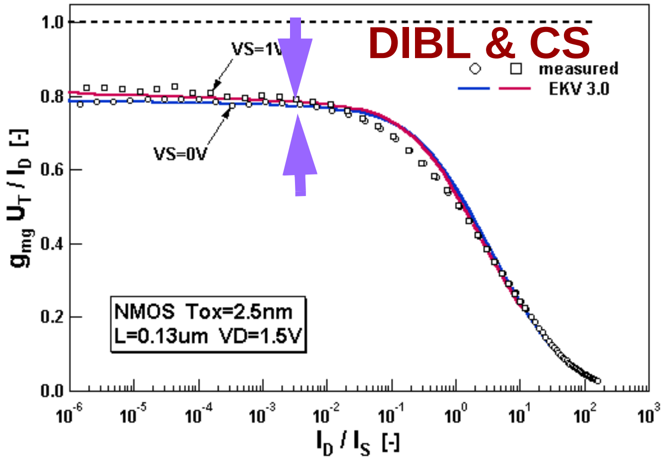


L=10um





L=0.13um



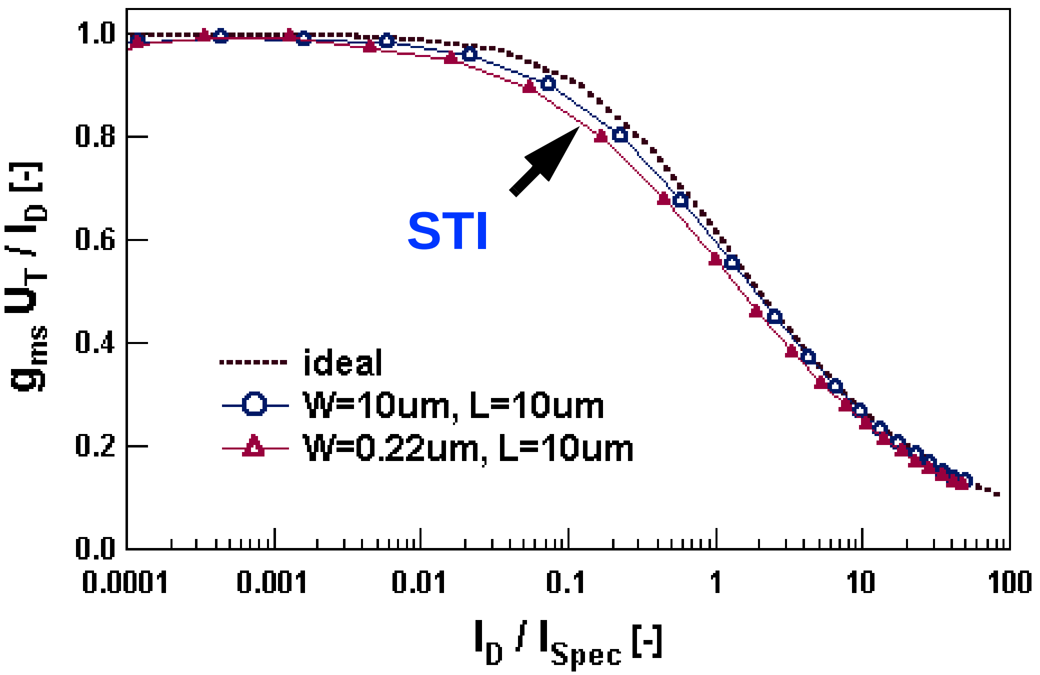
$g_{ms}{*}U_T/I_D$

0.13um CMOS

$g_{mg}{*}U_T/I_D$

❒ Source- &gate transconductance-to-current ratio vs. norm. $I_D$.

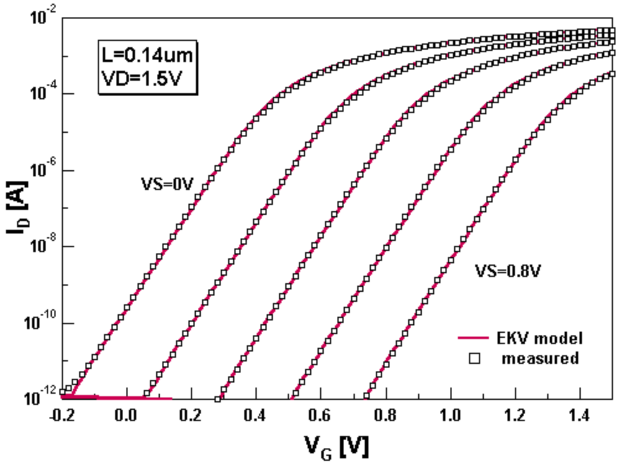
# Narrow-channel Effects

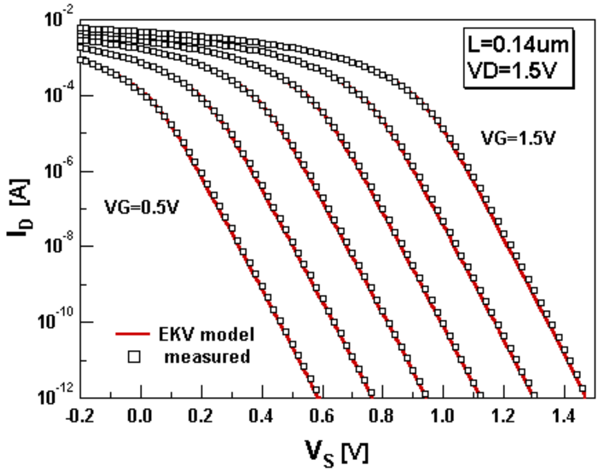


0.13um CMOS

- Shallow Trench Isolation (STI) effects may degrade normalized gm/ID, particularly in moderate inversion.
- EKV3.0 includes STI-Edge-device modeling.

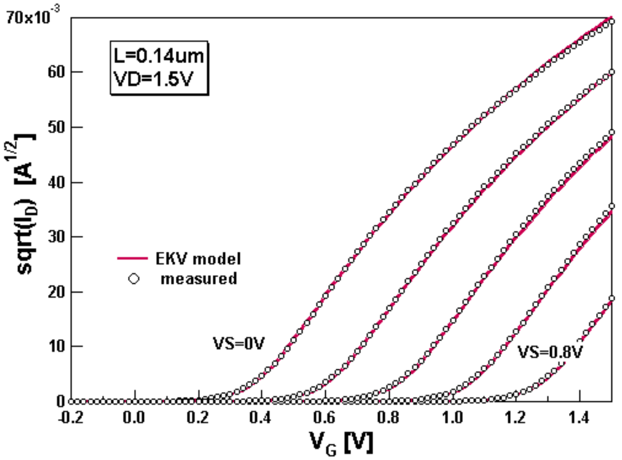
# EKV3.0 -- Drain Current vs. VG, VS, VD

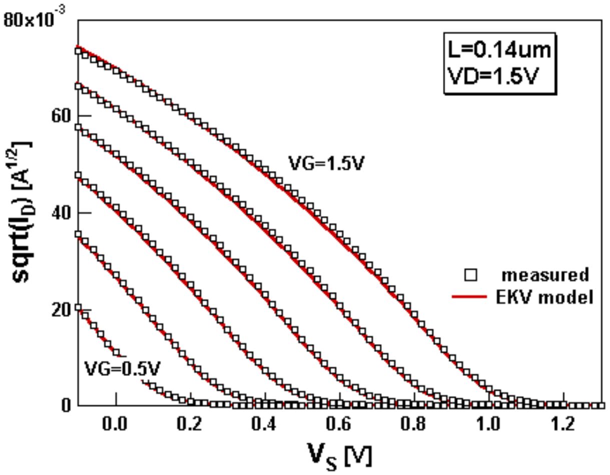


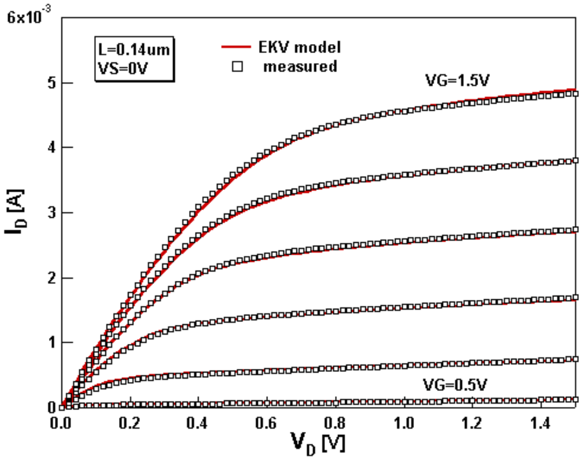


L=0.13um

NMOS







$I_D$ vs. $V_G$

$I_D$ vs. $V_S$

$I_D$ vs. $V_D$

- Consistent short-channel effect modeling vs. VG, VS, VD.

# Additional Features of EKV3.0

- Optional internal, bias-dependent, charge-based Rseries model.
  - Avoids internal nodes -- increases efficiency.
- Bias-dependent Leff model.
  - Important for weak/moderate inversion
- Modeling of short-channel charge/capacitances
  - Account for CLM & VSAT in transcapacitances
  - Bias-dependent overlap capacitances
- 2nd-order scaling of parameters.
  - Includes length-dependence of mobility.
- More analog-design oriented features:
  - Local mismatch models built-in.

# Recent Enhancements/Ongoing R&D

- Continuous, physical accumulation charge model
  - including QM effects in accumulation
  - including PD effects in accumulation for MOS Varactor modeling
- Gate current
- Induced gate & substrate noise
- Short-channel effects on thermal noise.
  - Upcoming paper: C. Enz, A. S. Roy, Symp. on Fluctuation & Noise, Maspalomas, Spain, May 25-28, 2004.
- Outlook: ongoing R&D
  - 1/f noise modeling.
  - Pocket implant effects on long-channel devices.
  - Large-signal NQS modeling.

# Model Implementation

- Verilog-A used as basic model development platform
  - ❐ Permits model implementation of standard IV, QV, noise.
  - ❐ Transportability among simulators
  - ❐ Updated Verilog-A versions should enhance usability for CM
- Verilog-A based model synthesizers
  - ❐ ADMS (Motorola) -- ongoing; Tiburon's -- tbd.
  - ❐ Essential benefit is ensuring compatibility among circuit simulators -- one code update for all simulators.
  - ❐ May at present yet have restrictions (noise, matching,...) related to Verilog-A and/or model interfaces to circuit simulators.
- C-code where Verilog-A synthesizers are restrictive.
  - ❐ Ongoing implementation in ELDO for comparisons w.r.t synthesized code.

# Summary EKV3.0

- EKV3.0 is a physics-based, analytical compact model.
  - Includes all major physical effects for present CMOS technologies.
  - Continuous, analytical model, symmetric forward-reverse operation.
  - Validated for 0.13um CMOS -- 90nm CMOS underway.
- Coherent charge-based framework for static and dynamic model.
  - Addresses static to NQS effects, noise, matching in a consistent way.
  - Favorable efficiency/complexity trade-off.
  - Number of parameters: 45 (basic intrinsic) + 20 (2nd order scaling).
  - Supports advanced analog IC design practice.
- Model is intended to be made public-domain.
  - Privileged access in R&D phase to industry when support is available.

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EKV 2.6 website: http://legwww.epfl.ch/ekv

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