

Benchmark Tests on SP Models And PUNSIM Development

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Outline

- **Philosophy of MOSFET Modeling**
- **Approaches of Compact Modeling**
- **Benchmark test on SP models**
- **PUNISM development**
- **Conclusions**

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Philosophy of MOSFET Modeling

- Challenges of Modeling
- Device Physics Strategy
- Physics and Fitting

Philosophy of MOSFET Modeling

Challenges of modeling

Aggressive Device Technologies

- New physics effects
 - QME, GDE, 2-D and 3-D effects, overshoot, ballistic transport, Coloumb scattering, energy engineering
- New process technologies
 - Halo, retrograde, high k, SiGe(C) channel
- Non-classical structures
 - DG, SG, MG, FinFET, UTB (**charge-sheet, size**)
- RF/analog performance
 - Gm/I, Noise, NQS, leakage prediction

All these need the unified, flexible, and physics-based model

Philosophy of MOSFET Modeling

Challenges of modeling

Circuit Simulation and Design

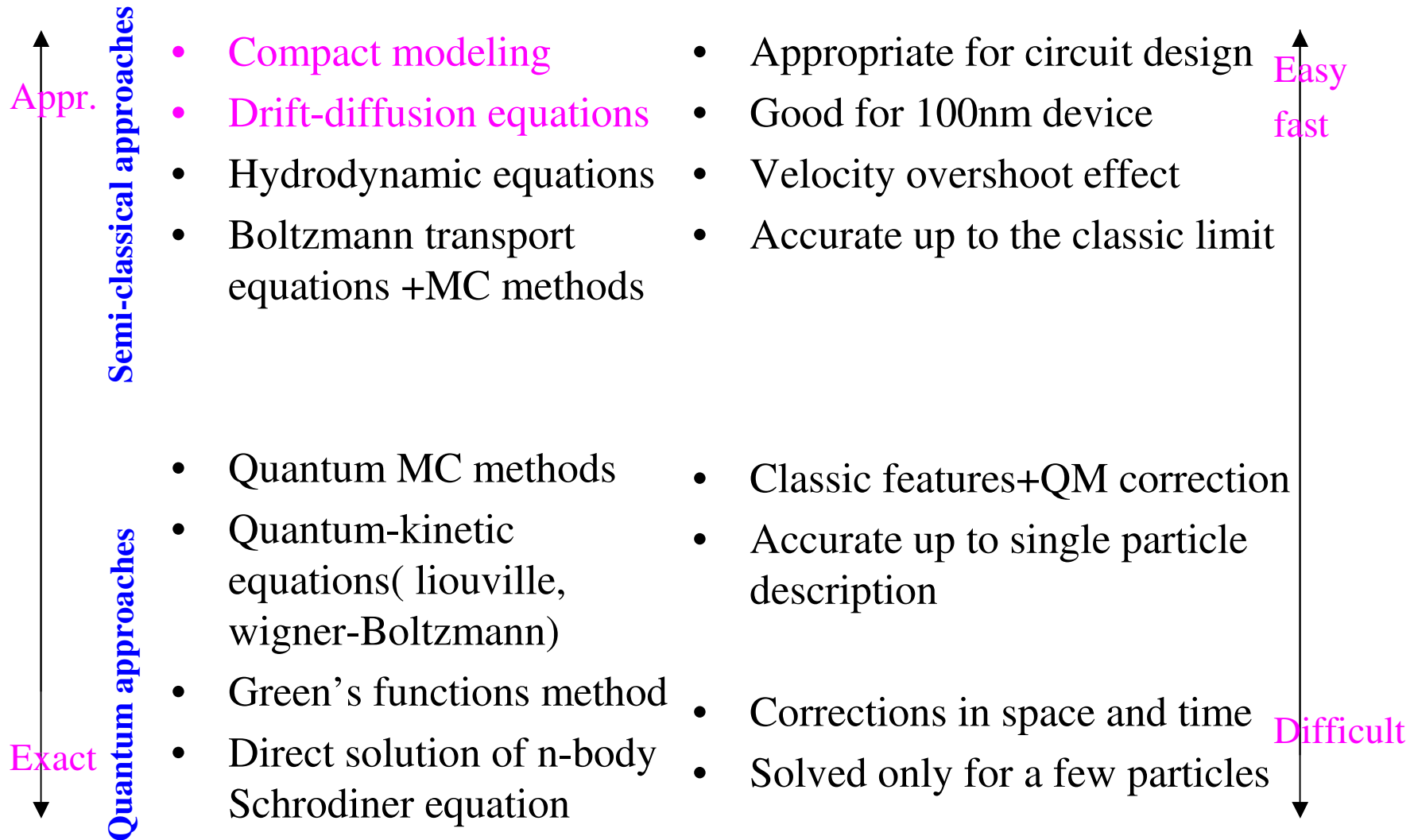
- Basic requirements
 - Continuity for all operations
 - Infinite differentiation
 - High accuracy
 - symmetry for benchmark tests
- Enhancement requirements
 - Concise model structures for simulation speed
 - Analytical expressions for RF/analog design

All these need the analytical, concise and simple compact modeling

Philosophy of MOSFET Modeling

Device Physics: From complexity to simplicity

Hierarchy of Transport Model



Philosophy of MOSFET Modeling

Device Physics: From complexity to simplicity

Present bases of compact modeling

- + Vigorous Poisson equation solution
- + Vigorous current density equation
- Physics based surface potential and charge equation
- Physics based surface potential solution, channel current solution

Different Model Approaches used the different approximations for all above mentioned

Philosophy of MOSFET Modeling

Physics and fitting

Why Fitting is important

- Physical picture is beautiful; Device data is ugly and complex, e.g., leakage of device.
- Physics approximation provides a basic device trend; fitting compensates the simplicity of the physics approximation.
- Pure mathematic fitting is possible for high accuracy yet computation burden; Physics approx+fitting provides a good tradeoff between computation efficiency and accuracy.
- Fitting loses the prediction characteristic of the model while provides accurate circuit simulation.
- Compact model must introduce fitting parameters so to become a useful model for device and circuit simulations

BSIM success depends on the de-coupling fitting to some extent

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Approaches of Compact Modeling

- Region-based approach
- Charge-based approach
- Surface-based approach

Approaches of Compact Modeling

Region-based approach

Representative of BSIM

- Surface potential pinched on 2-fold Fermi-potential.
- Different charge expression derived from charge-sheet model.
- Smooth function used to link the different regions.
- More semi-empirical parameters used.

$$q_{in} = \frac{\frac{2nkT}{q} \ln \left[1 + \exp \left(\frac{q(V_{gs} - V_{th})}{2nkT} \right) \right]}{1 + \frac{2nC_{ox}}{C_{dep}} \exp \left(- \frac{q(V_{gs} - V_{th} - V_{off})}{nkT} \right)}$$

$$I_{ds} = \frac{\mu C_{ox} W}{L} \left[q_{in} - \frac{A_{bulk}}{2} V_{ds} \right] V_{ds}$$

Approaches of Compact Modeling

Region-based approach

Present BSIM3/4

- Advantages
 - Sufficient for IV and CV high accuracy fitting
 - Open platform for process and physics advancements
 - Successfully extended to SOI
 - Enhancement RF/Analog simulation
- Disadvantages
 - Insufficient physics basement: non-pin-off
 - Symmetry and negative capacitance
 - Too much parameters ?

Approaches of Compact Modeling

charge-based approach

EKV, ACM, USIM, BSIM5

- Unified charge equation derived from charge-sheet model.
- Current equation derived consistently from charge equation.
- Included Vth Concept.

$$\frac{q_{in}}{n} + \ln \left[\frac{q_{in}}{n} \right] = v_p - v_{ch} + k$$

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

Approaches of Compact Modeling

Region-based approach

EKV, ACM, USIM, BSIM5

- Advantages

- Physics based model derivation
- Continuous and symmetric
- Successfully extended to Non-classical CMOS
- Simple and concise model architecture

- Disadvantages

- A little physics rather than the surface potential based model ?
- Extended to accumulation region ?
- Extended to overlap region?

Approaches of Compact Modeling

SP-based approach

SP, MOS-11, PSP, HISIM, PUNSIM

- Surface potential obtained with different methods from different equations.
- Current equations have different formulations.
- As much as possible device physics. Story ?
- Only for uniform doped.

$$U_{GB} - U_{FB} - \phi_s = \pm \left(\frac{2\epsilon_s q^2 N_A}{C_{ox}^2 kT} \right)^{1/2} \left\{ [\exp(-\phi_s) + \phi_s - 1] + \exp(-2U_F - U_{ch}) [\exp(\phi_s) - \phi_s - 1] \right\}^{1/2}$$

$$I_{ds} = \frac{\mu_{eff} W}{L_{eff}} \int_{V_s}^{V_d} Q_I dV_{ch}$$

Approaches of Compact Modeling

SP-based approach

SP, MOS-11, PSP, HISIM, PUNSIM

- Advantages
 - Physics based model derivation.
 - Continuous and symmetric .
 - Reduced parameters. ??????
- Disadvantages
 - Requirement for high precise surface potential calculation.
 - Only for uniform doping formulation.
 - Difficult to handle second-order effects.

Seemly very fashion SP model from Device physics review

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Benchmark Test on SP Models

- Surface potential equation
- Surface potential calculation
- Inversion charge calculation
- Channel current calculation
- Short-channel effects

Benchmark Test on SP Model

Surface potential equation

Which is physics based

- Complete SP equation

$$V_{GB} - V_{FB} - \phi_s = \gamma \sqrt{\phi_s + \phi_t e^{-\phi_s / \phi_t} - \phi_t + \exp^{-(2\phi_f + \phi_n) / \phi_t} [\phi_t e^{\phi_s / \phi_t} - K \phi_s - \phi_t]}$$

- Original Pao-Sah SP equation issues

$$V_{GB} - V_{FB} - \phi_s = \gamma \sqrt{\phi_s + \phi_t e^{-\phi_s / \phi_t} - \phi_t + \exp^{-(2\phi_f + \phi_n) / \phi_t} [\phi_t e^{\phi_s / \phi_t} - \phi_s \exp^{\phi_n / \phi_t} - \phi_t]}$$

C.C. Andrew modification

$$V_{GB} - V_{FB} - \phi_s = \gamma \sqrt{\phi_s + \phi_t e^{-\phi_s / \phi_t} - \phi_t + \exp^{-(2\phi_f + \phi_n) / \phi_t} [\phi_t e^{\phi_s / \phi_t} - \phi_s - \phi_t]}$$

SP or PSP modification

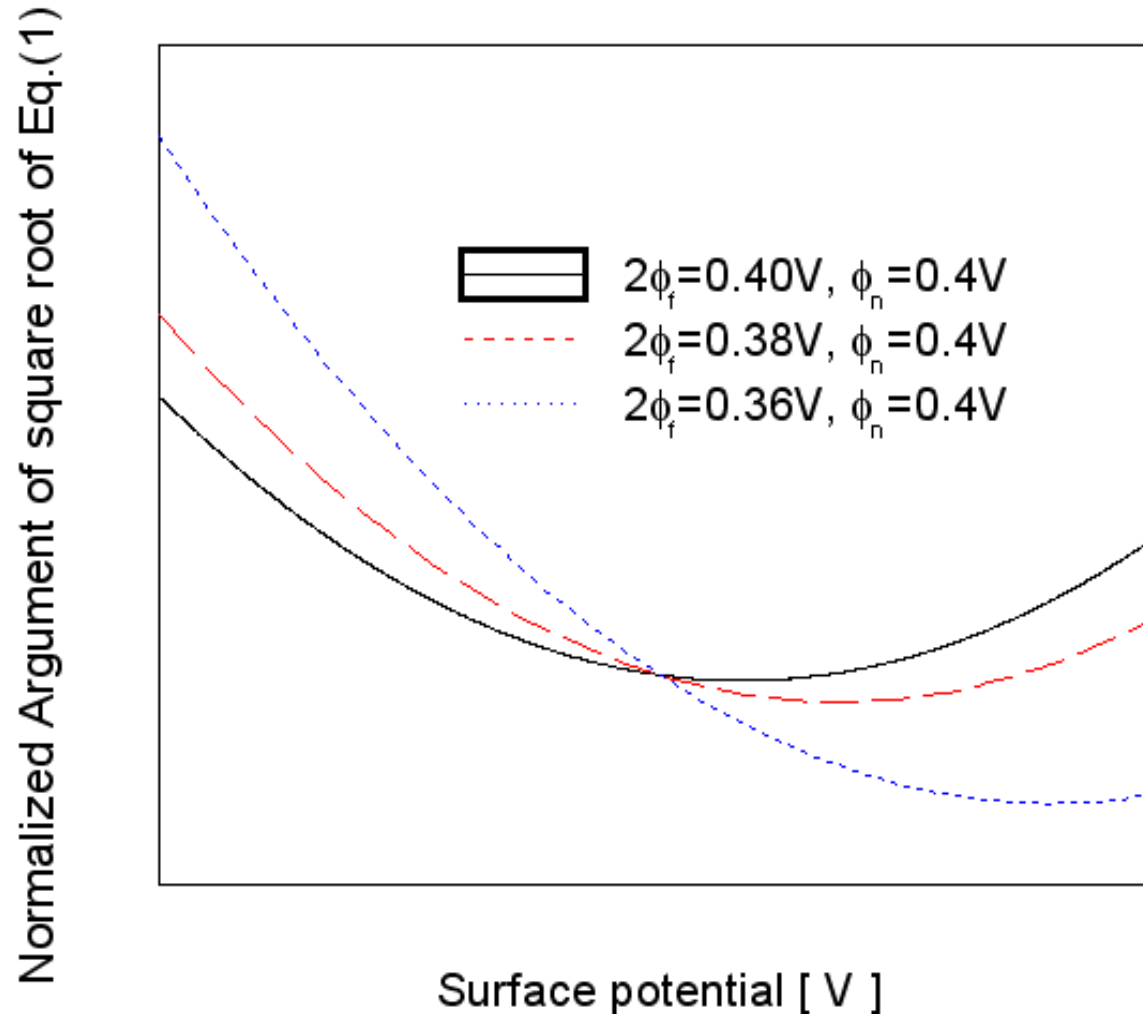
$$V_{GB} - V_{FB} - \phi_s = \gamma \sqrt{\phi_s + \phi_t e^{-\phi_s / \phi_t} - \phi_t + 2 \exp^{-(2\phi_f + \phi_n) / \phi_t} [\sinh(\phi_s / \phi_t) - \phi_t]}$$

Benchmark Test on SP Model

Surface potential equation

Which is physics based

- Original Pao-Sah SP equation issues

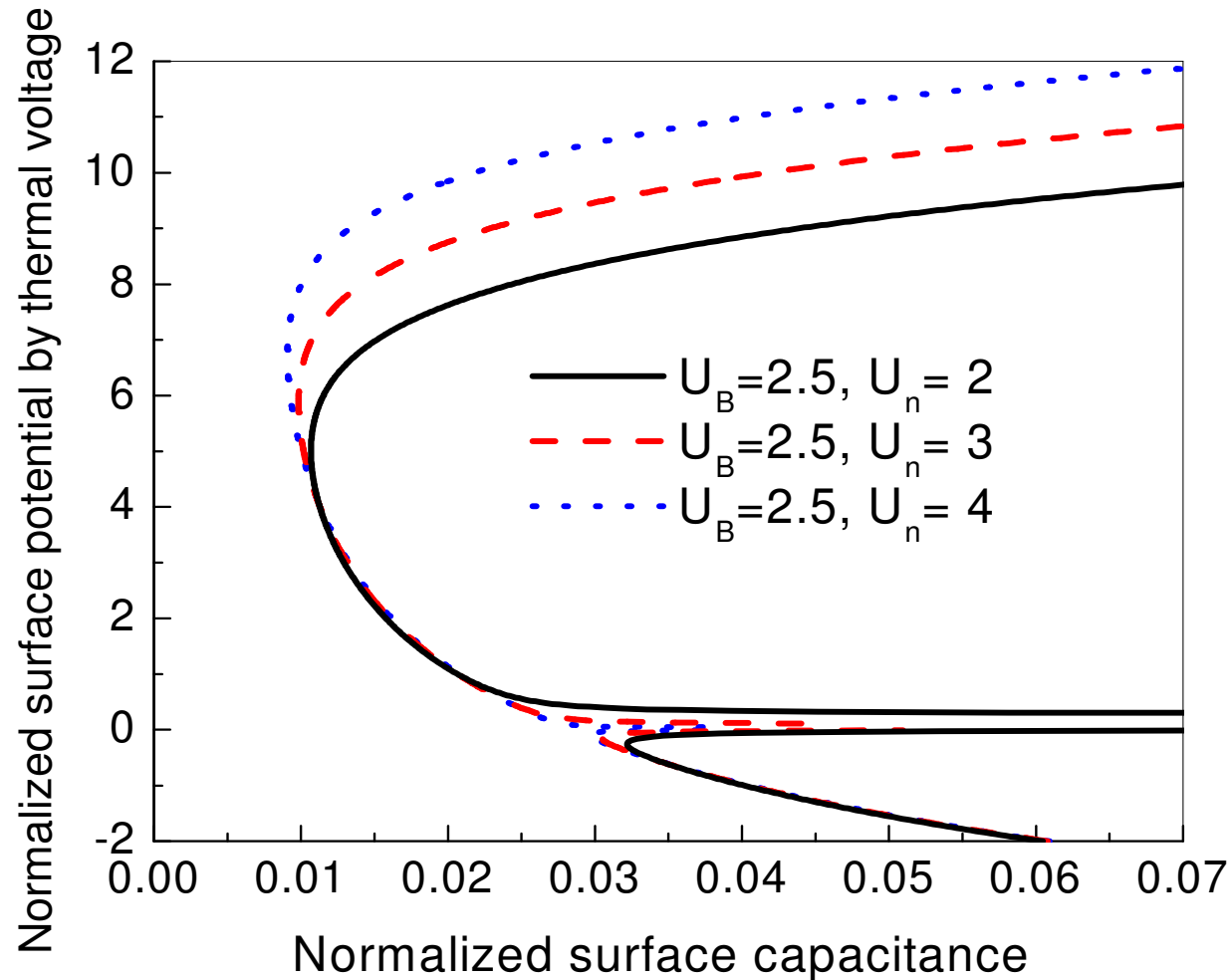


Benchmark Test on SP Model

Surface potential equation

Which is physics based

- Original Pao-Sah SP equation issues



Benchmark Test on SP Model

Surface potential equation

Which is physics based

**Can we find a complete SP equation from
device physics review ??**

- Original Pao-Sah equation always has continuity issues
- C.C.Andrew modification is based mathematic correct
- SP or PSP correction is based equivalent mathematic analysis
- PUNSIM derived the physics based SP equation

Benchmark Test on SP Model

Surface potential calculation

Which SP equation is used

- Complete SP equation

$$V_{GB} - V_{FB} - \phi_s = \gamma \sqrt{\phi_s + \phi_t e^{-\phi_s / \phi_t} - \phi_t + \exp^{-(2\phi_f + \phi_n) / \phi_t} [\phi_t e^{\phi_s / \phi_t} - \phi_s - \phi_t]}$$

- Normalized SP equation

$$v_G - x = G \sqrt{x + e^{-x} - 1 + e^{-x_n} [e^x - x - 1]}$$

Original MOS-11 (From depletion approximation)

$$v_G - x = G \sqrt{x + e^{x-x_n}}$$

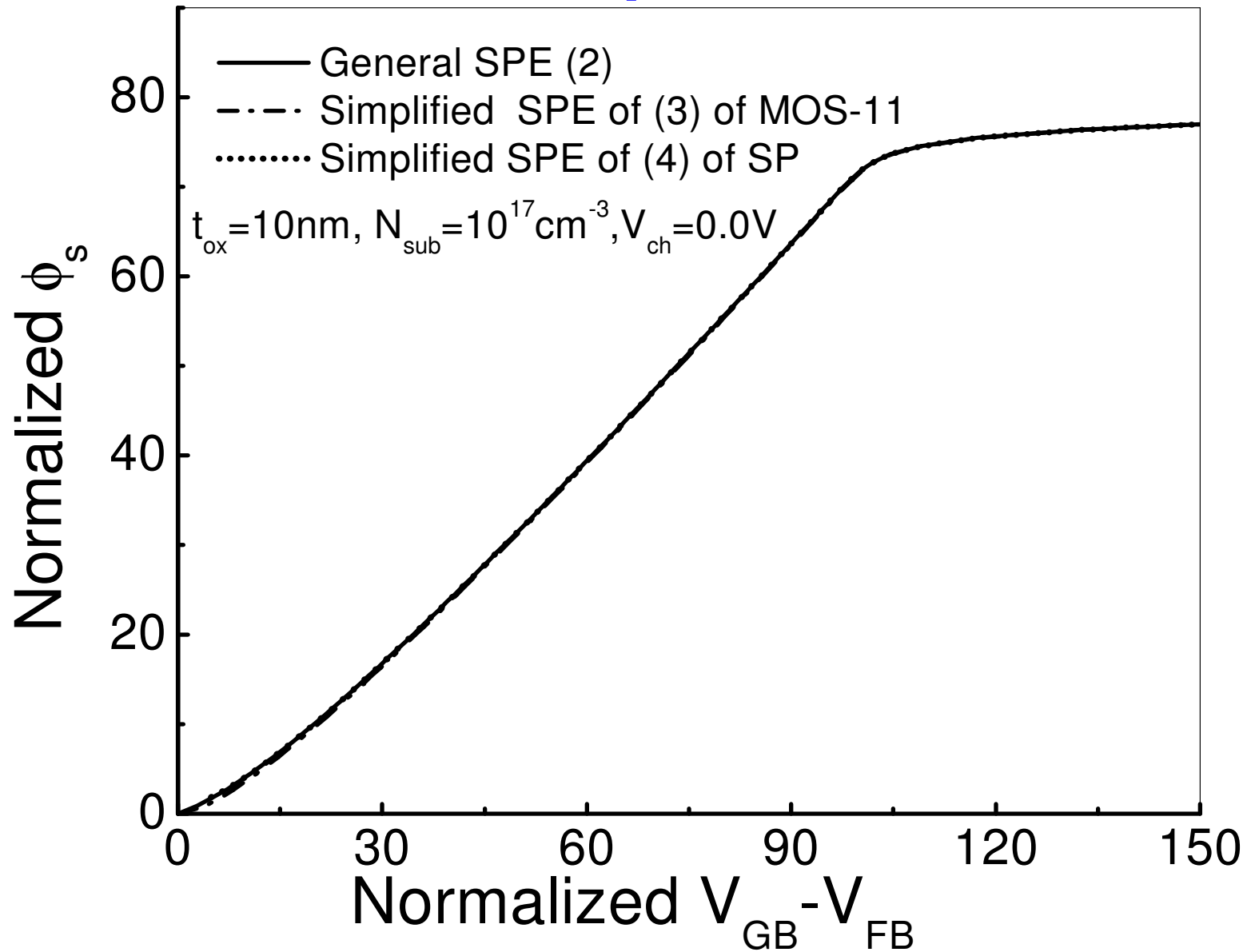
Original SP (From charge-sheet approximation)

$$v_G - x = G \sqrt{x - 1 + e^{x-x_n}}$$

Benchmark Test on SP Model

Surface potential calculation

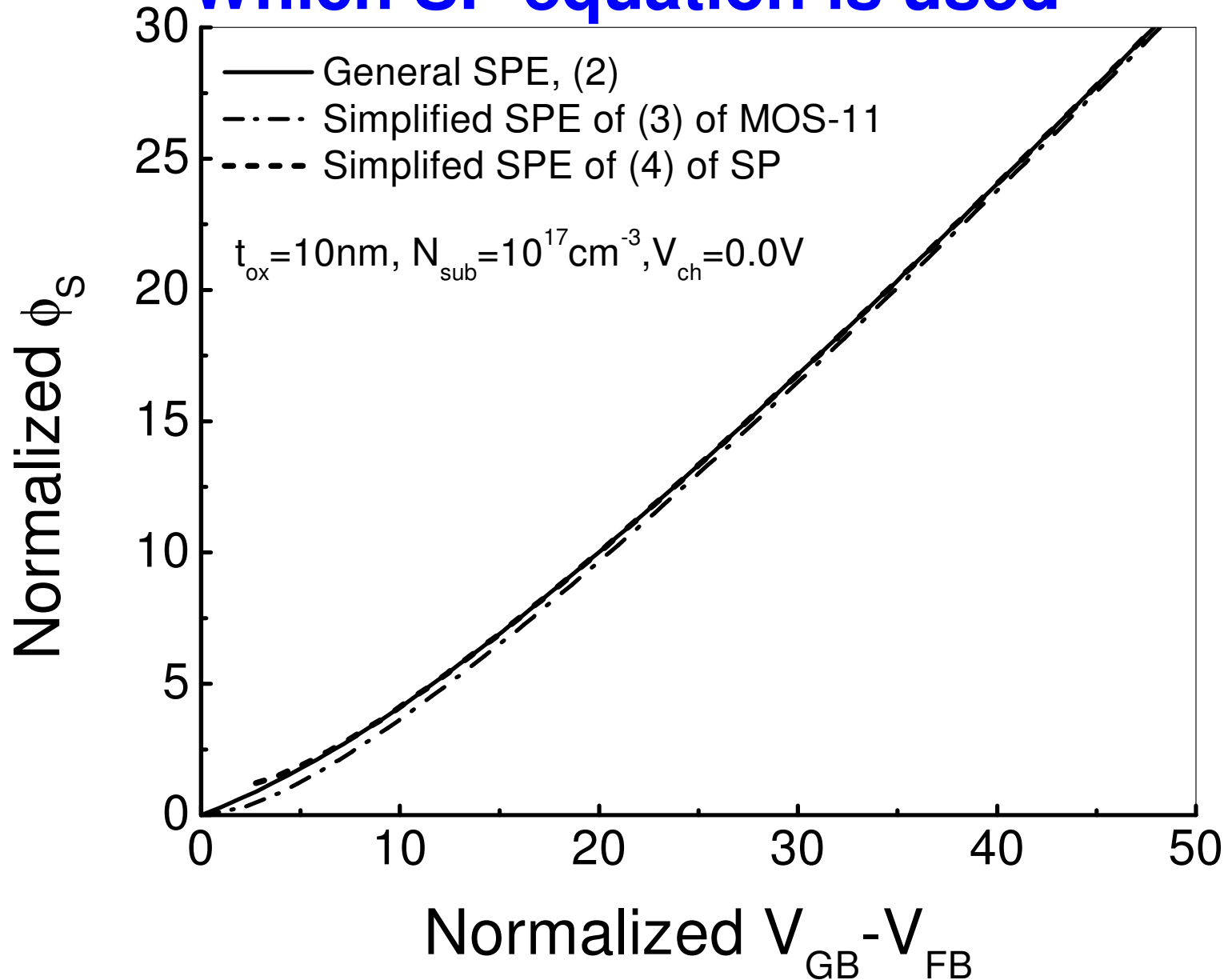
Which SP equation is used



Benchmark Test on SP Model

Surface potential calculation

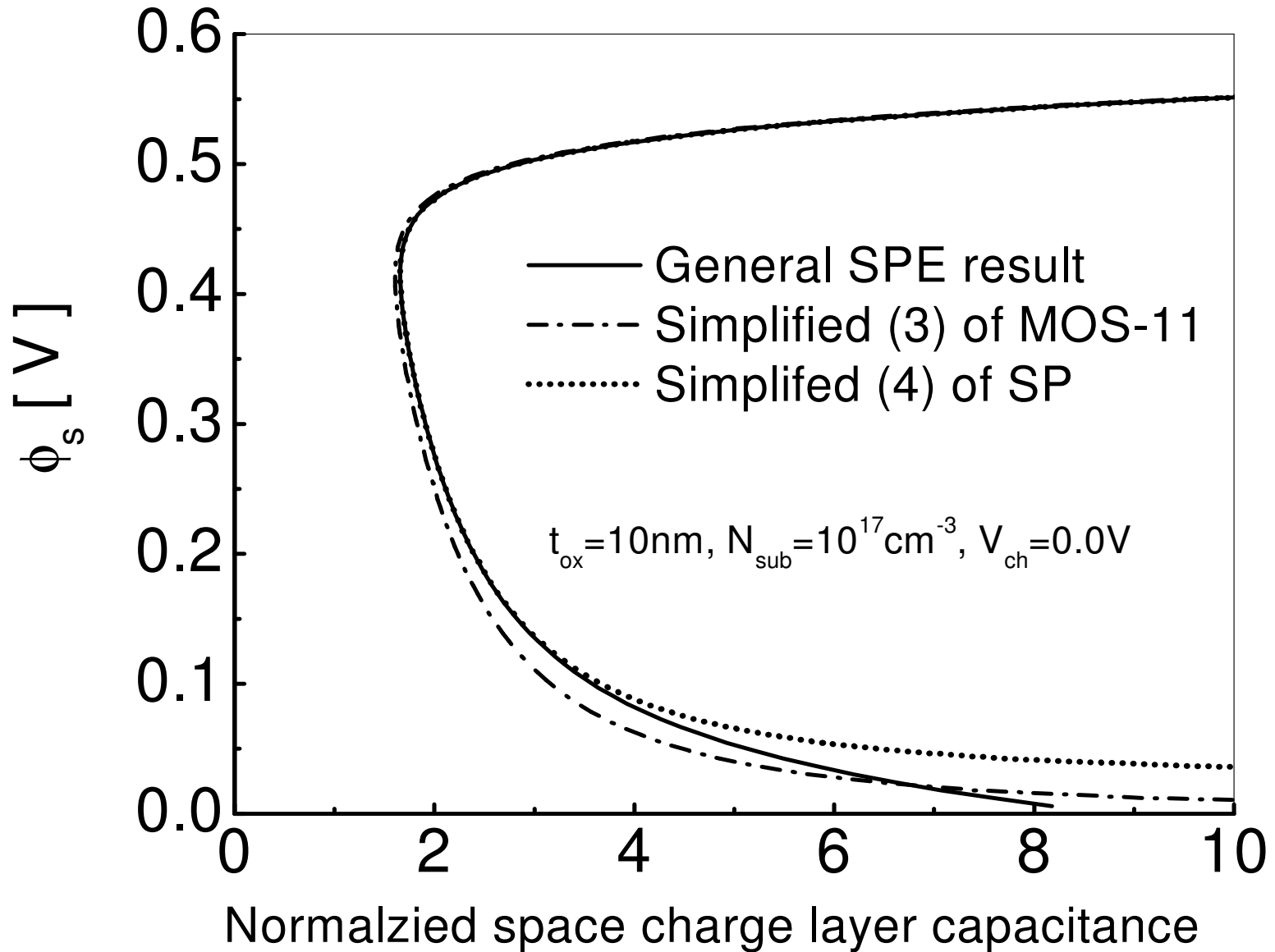
Which SP equation is used



Benchmark Test on SP Model

Surface potential calculation

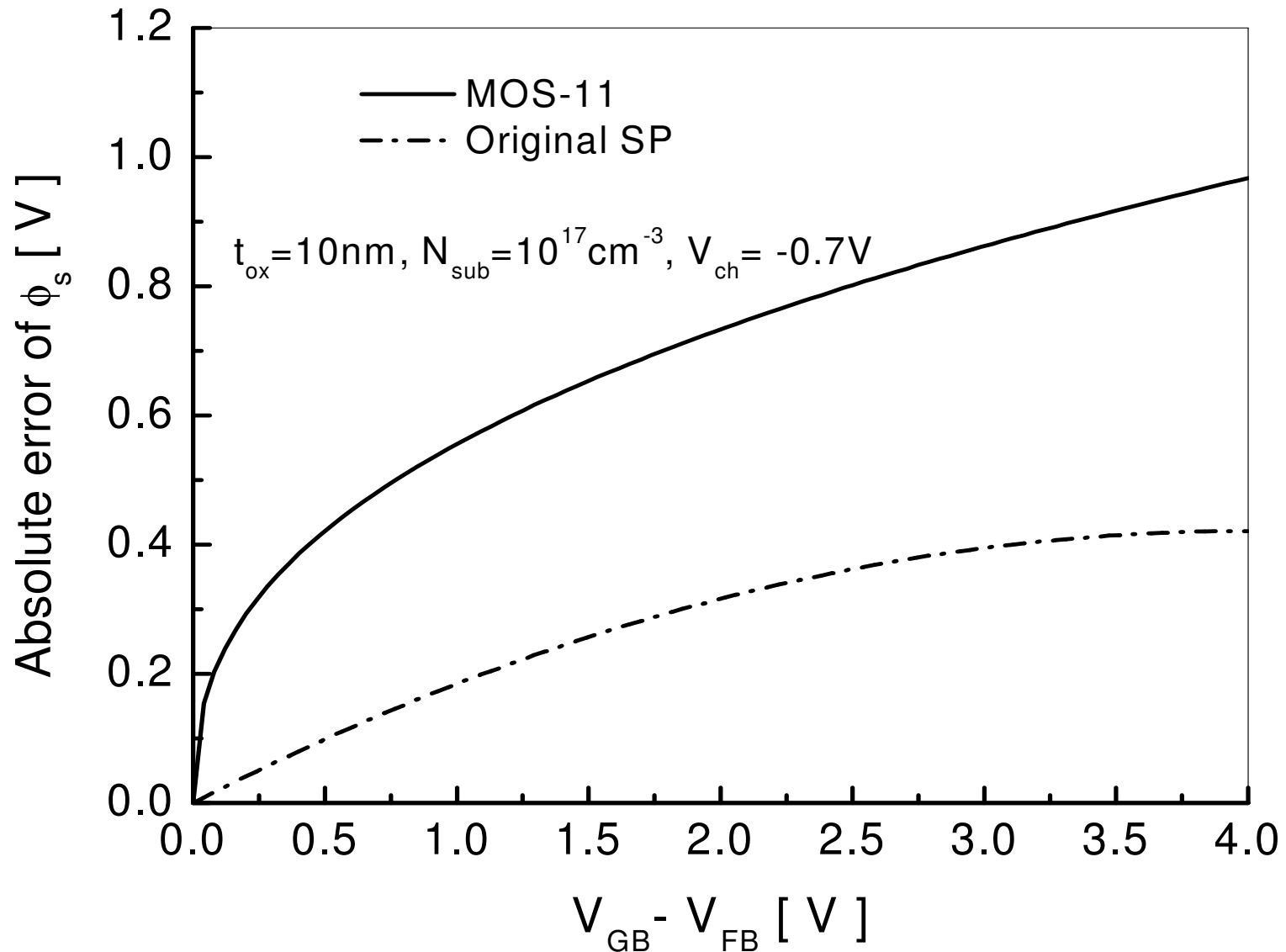
Which SP equation is used



Benchmark Test on SP Model

Surface potential calculation

Which SP equation is used



Benchmark Test on SP Model

Inversion charge calculation

Which Qb equation is used

- Complete SP equation

$$v_G - x = G \sqrt{x + e^{-x} - 1 + e^{-x_n} [e^x - x - 1]}$$

- Pao-Sah inversion charge equation

$$q_m = \int_0^{\phi_s} \frac{\sqrt{2qN_a \epsilon_{si}} \exp\left(\frac{\phi - 2\phi_F - V_{ch}}{\phi_t}\right) d\phi}{\left[\phi_t \exp\left(-\frac{\phi}{\phi_t}\right) + \phi - \phi_t + \exp\left(-\frac{2\phi_F + V_{ch}}{\phi_t}\right) \left(\phi_t \exp\left(\frac{\phi}{\phi_t}\right) - \phi - \phi_t \right) \right]^{1/2}}$$

Depletion approximation

$$q_m = C_{ox}(V_{GB} - V_{FB} - \phi_s) - \gamma C_{ox} \sqrt{\phi_s}$$

Charge-sheet approximation

$$q_m = C_{ox}(V_{GB} - V_{FB} - \phi_s) - \gamma C_{ox} \sqrt{\phi_s - \phi_t}$$

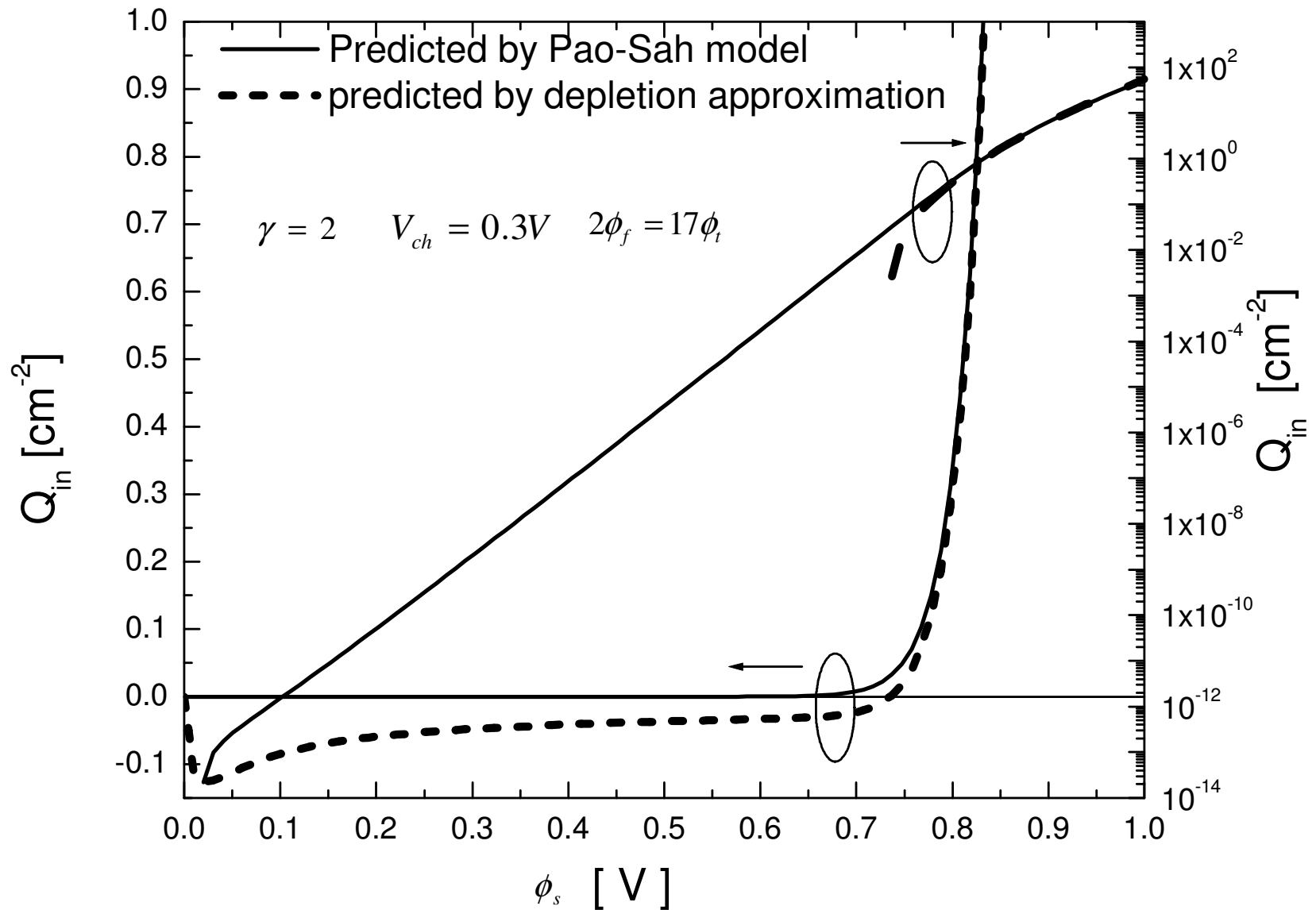
Improved charge-sheet approximation

$$q_m = C_{ox}(V_{GB} - V_{FB} - \phi_s) - \gamma C_{ox} \sqrt{\phi_s - \phi_t [1 - \exp(-\phi_s / \phi_t)]}$$

Benchmark Test on SP Model

Inversion charge calculation

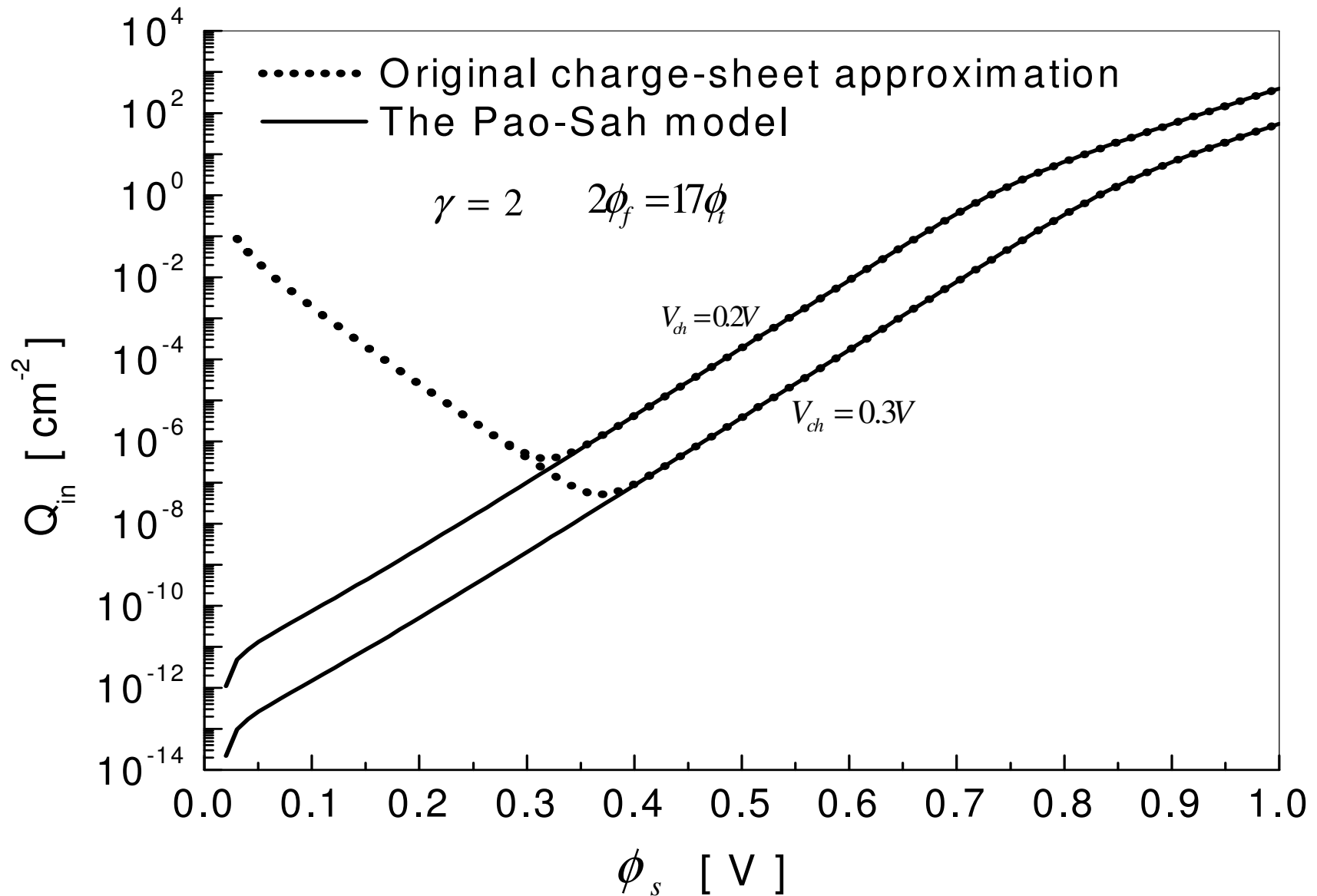
Which Qb equation is used



Benchmark Test on SP Model

Inversion charge calculation

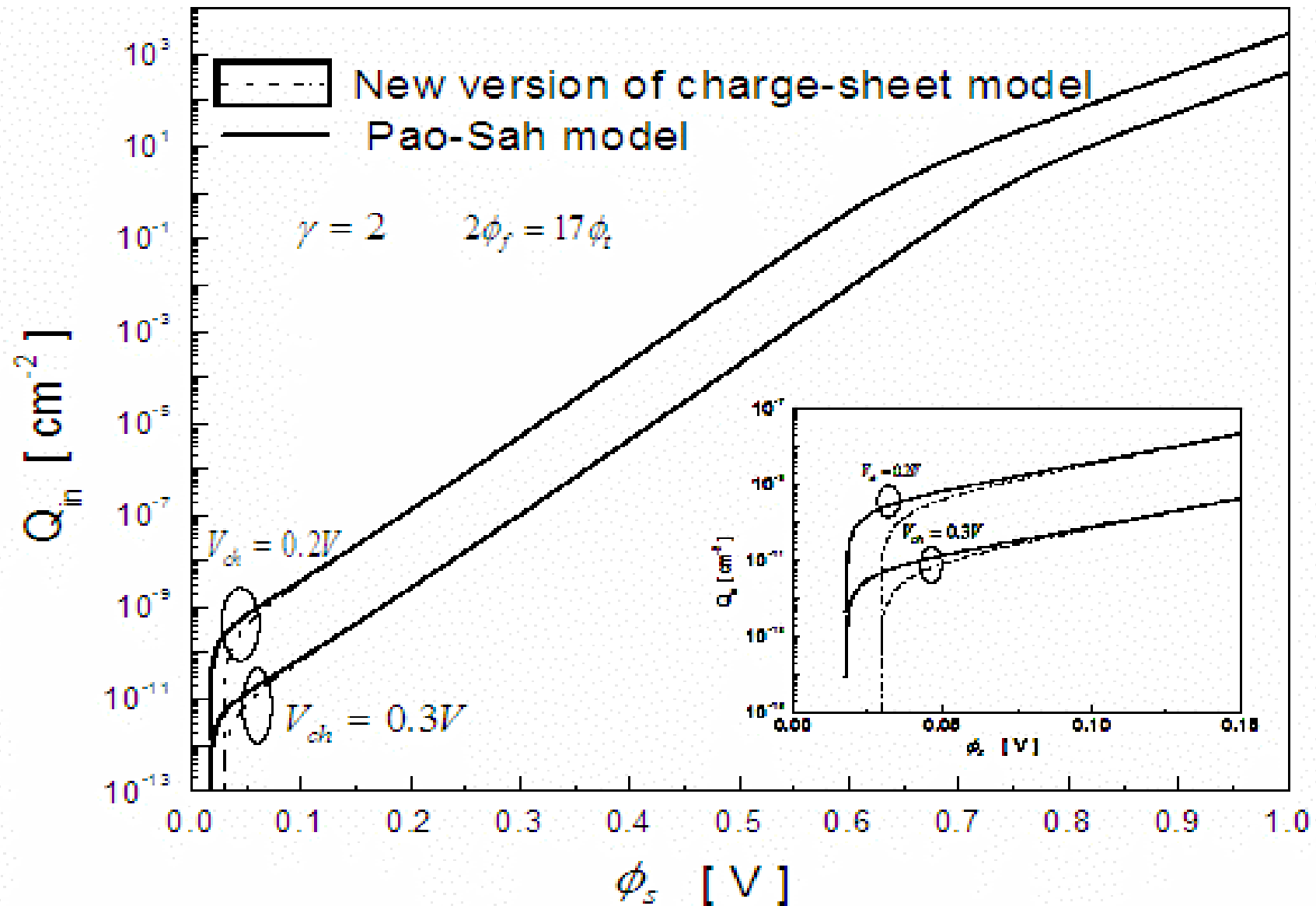
Which Qb equation is used



Benchmark Test on SP Model

Inversion charge calculation

Which Qb equation is used



Benchmark Test on SP Model

Channel current calculation

Which equation is used

- Pao-Sah's current equation

$$I_{ds} = \frac{\mu_{eff} W}{L_{eff}} \int_{V_s}^{V_d} Q_I dV_{ch}$$

- J.R.Brews's current equation

$$I_{drift} = \frac{W \mu_{eff} C_{ox}}{L_{eff}} \left[(V_{GB} - V_{FB})(\phi_d - \phi_s) - \frac{1}{2}(\phi_d^2 - \phi_s^2) - \frac{2}{3} \gamma (\phi_d^{3/2} - \phi_s^{3/2}) \right]$$

$$I_{diffusion} = \frac{W \mu_{eff} C_{ox}}{L_{eff}} \left[V_t (\phi_d - \phi_s) + V_t \gamma (\phi_d^{1/2} - \phi_s^{1/2}) \right]$$

SP or PSP current equation

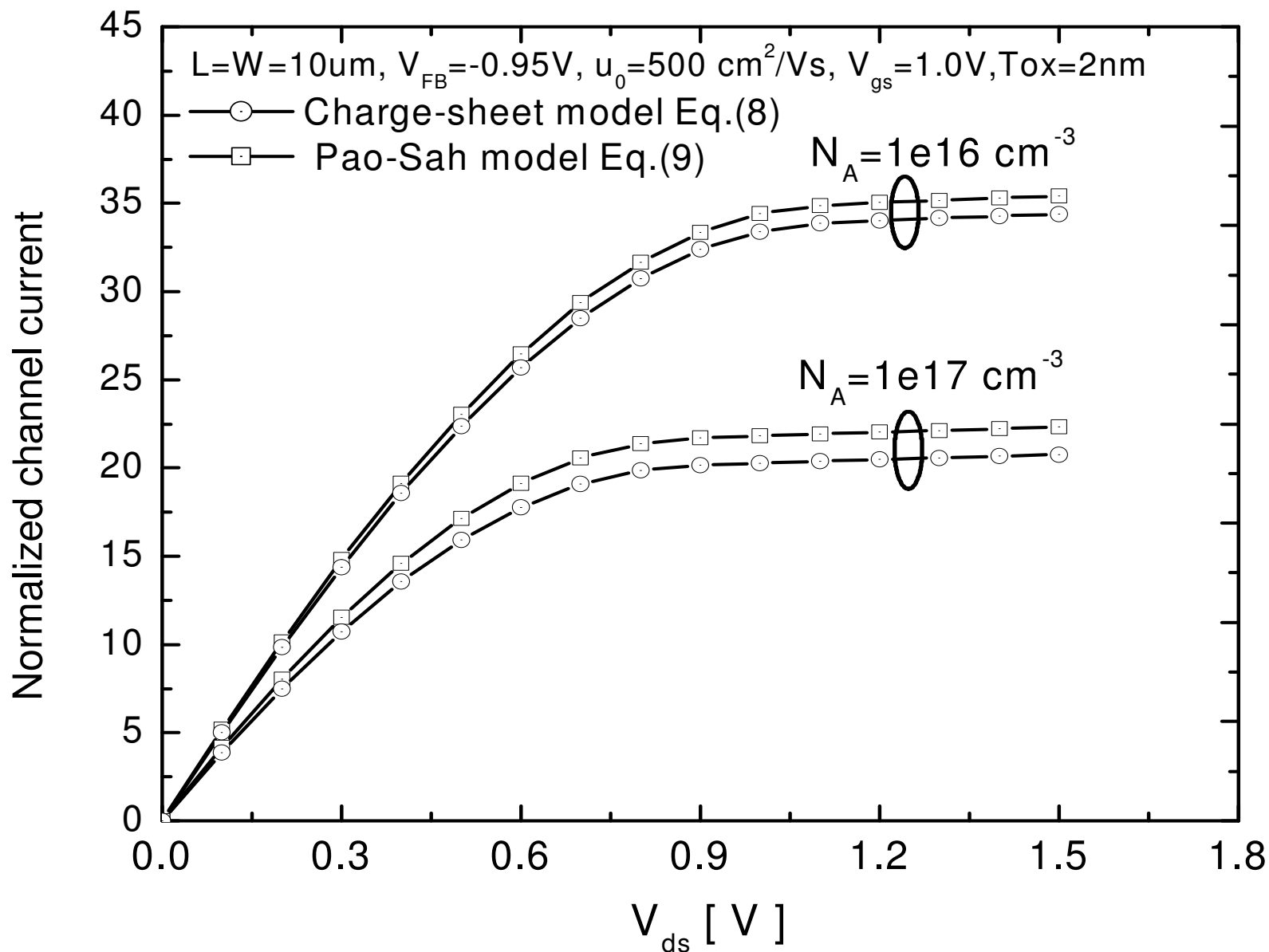
BSIM5 current equation

$$I_{ds0} = \frac{W \mu_{eff}}{L_{eff}} \left[\frac{Q_s^2 - Q_d^2}{2nC_{ox}} + V_t (Q_s - Q_d) \right]$$

Benchmark Test on SP Model

Channel current calculation

Which equation is used



Benchmark Test on SP Model

Channel current calculation

Which equation is used

- Charge-sheet model current equation

$$q_m \frac{d\phi_s}{dx} - \phi_t \frac{dq_m}{dx} = q_m \frac{dV_{ch}}{dx} \quad \Leftrightarrow \quad q_m = q_0 \exp \left[\frac{\phi_s - V_{ch}}{\phi_t} \right]$$

- Pao-Sah's model current equation

$$q_m = \frac{\gamma \exp \left(-\frac{2\phi_F + V_{ch}}{\phi_t} \right) \left[\exp \left(\frac{\phi_s}{\phi_t} \right) - \phi_s - \phi_t \right]}{q_m + q_b}$$

$$T = q_m + q_b \quad \eta_{\phi_s} = \frac{1}{T} \frac{\partial T}{\partial \phi_s} \quad \eta_{V_{ch}} = \frac{1}{T} \frac{\partial T}{\partial V_{ch}}$$

$$q_m \frac{dV_{ch}}{dx} = q_m \frac{d\phi_s}{dx} - \phi_t \frac{dq_m}{dx} - q_m \left[\eta_{\phi_s} \frac{d\phi_s}{dx} + \eta_{V_{ch}} \frac{dV_{ch}}{dx} \right]$$

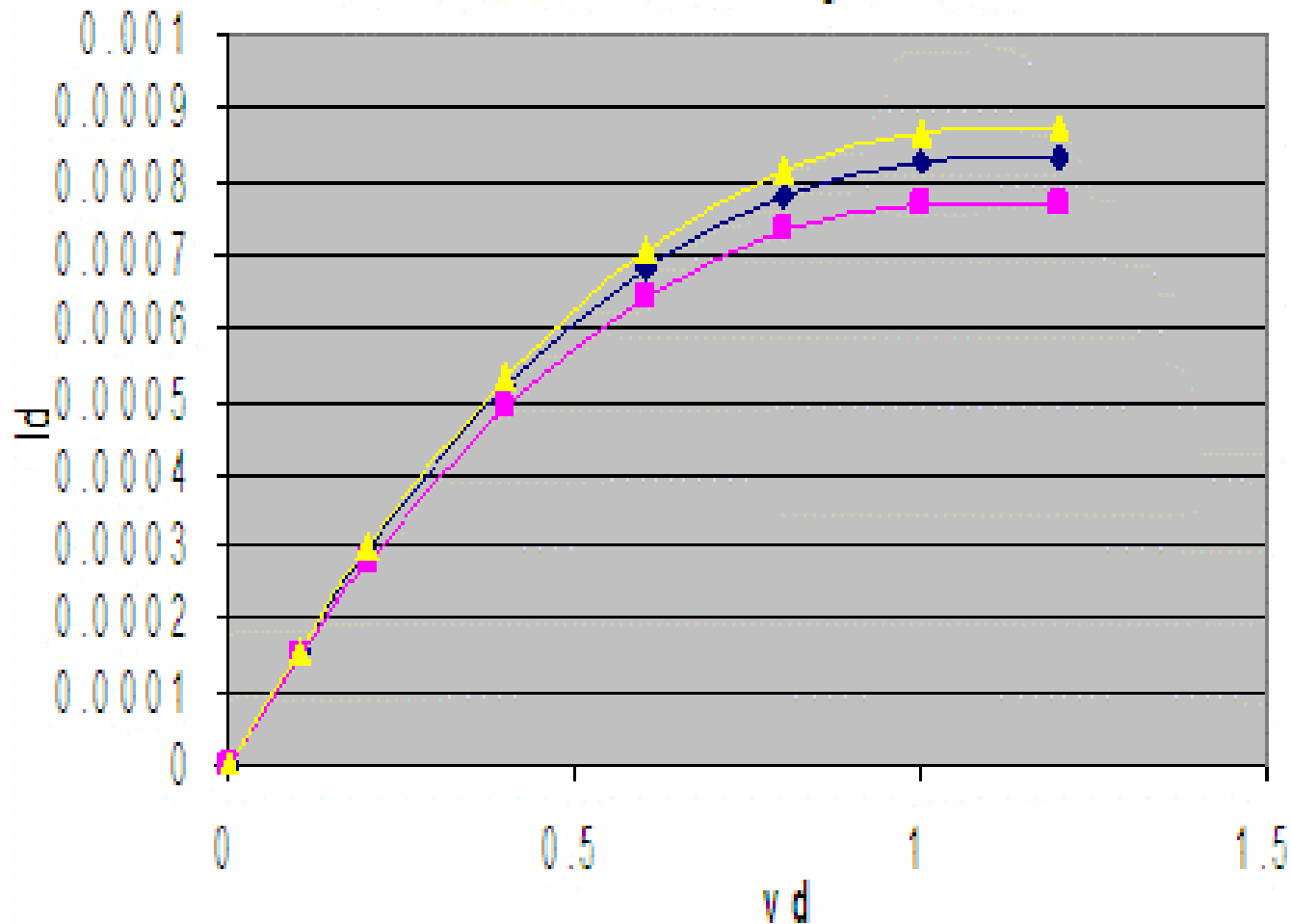
Benchmark Test on SP Model

Channel current calculation

Which equation is used

◆ Pao-Sah ■ PSP ▲ BSIM5

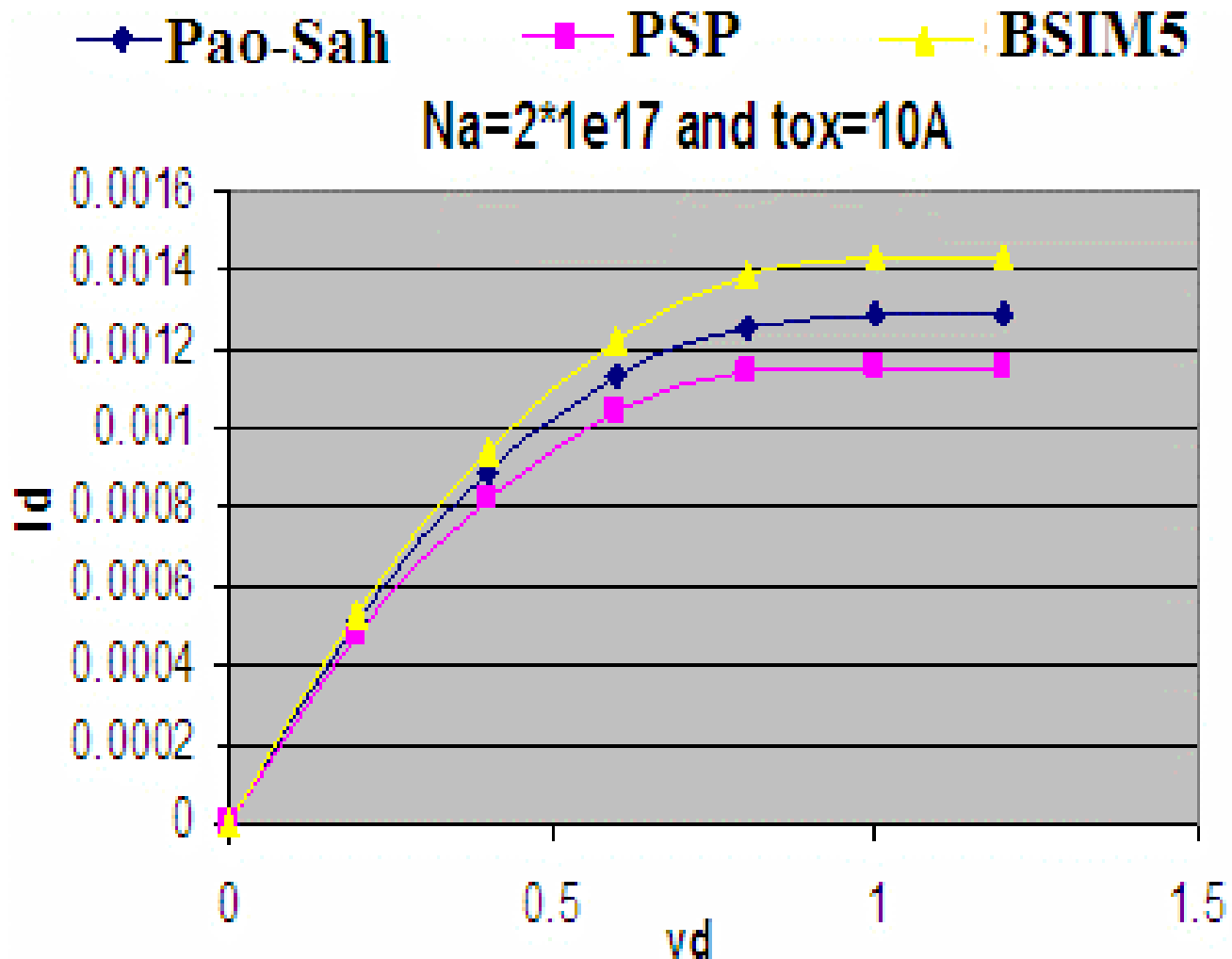
$N_a = 2 \times 10^{16}$, $t_{ox} = 20 \text{ \AA}$, $v_{gs} = 1.5$, $W = L$



Benchmark Test on SP Model

Channel current calculation

Which equation is used



Benchmark Test on SP Model

Short-channel effect modeling

Lateral field gradient concept

- Lateral field gradient used to analyze V_{th} (IEDM, 1984)
- HISIM used it to model short-channel effect (TCAD, 1994)
- SP and PSP used it via bias dependence
- It can model V_{th} versus L , but slope versus L non-physical

$$V_G - x = G \sqrt{f(x-1) + e^{x-x_n}}$$

$$f = 1 - F(V_{ds}, L, N_a, V_{bi}) \approx 1 - \frac{\alpha V_{ds}}{L^2}$$

To prevent f from negative, SP or PSP used $F_0/(1+aV_{ds}/L)$

Benchmark Test on SP Model

Short-channel effect modeling

Lateral field gradient concept

- Correct V_{th} versus L : L decreases, f decreases, V_{th} decreases

$$v_T = v_{fb} + x + G\sqrt{f(x-1)} \approx v_{fb} + 2x_f + G\sqrt{f(2x_f - 1)}$$

- Non-physical slope V_{th} versus L : L decreases, f decreases, slope decreases, improve the sub-threshold performance

$$n = \frac{\partial v_G}{\partial \phi_s} = 1 + \frac{G\sqrt{f}}{2\sqrt{x-1}} \approx 1 + \frac{G\sqrt{f}}{2\sqrt{2x_f-1}}$$

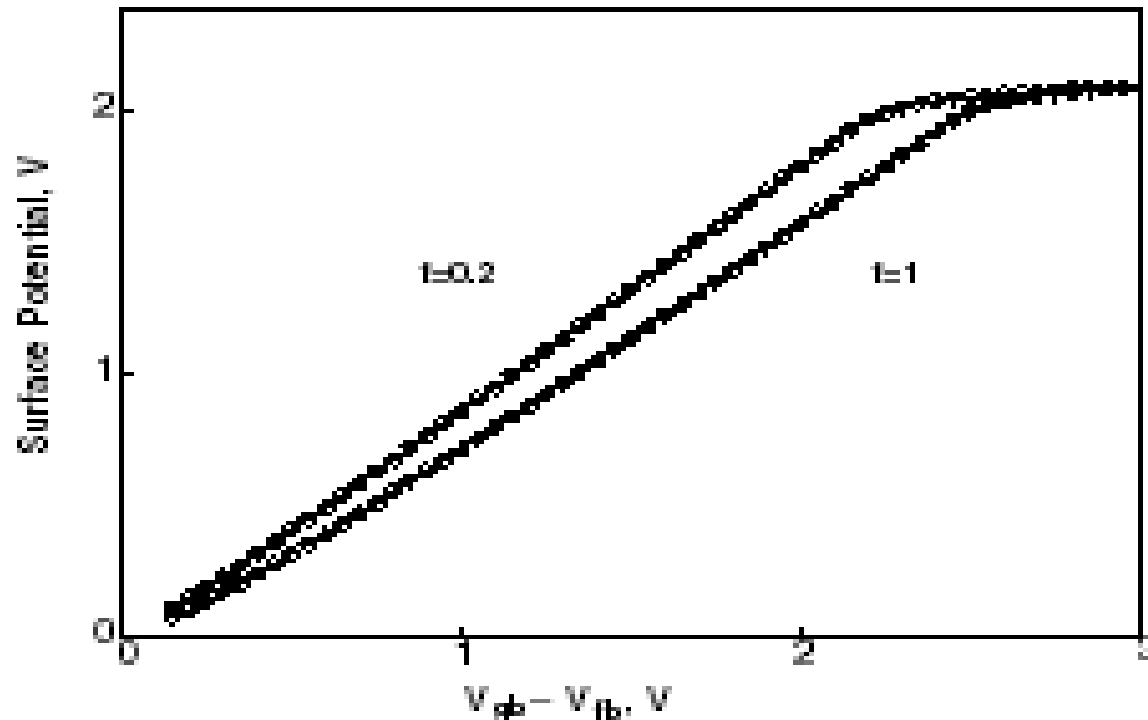
- Ideal case, L approaches 0, $f=0$, $n=1$??????????
can you believe ?????? It is just PSP

Benchmark Test on SP Model

Short-channel effect modeling

Lateral field gradient concept

- SP or PSP example



- Surprise news from recent PSP: giving up lateral field gradient
- How SP or PSP beyond GCA without lateral field gradient

Benchmark Test on SP Model

Summary SP models

- Complete surface potential equation derivation needed
- Physics-based SP solution needed
- Physics-based channel current needed
- Correct inversion charge calculation needed
- Physics-based short-channel effect modeling needed

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- **Conclusions**

PUNSIM Development

(Peking University Nano Scale Insulator gate MOSFET Model)

- Derivation of SP equation
- Physics-based SP solution
- Physics-based current equation
- Physics-based SCE modeling

Derivation of complete SP equation

Quasi-equilibrium concept

- Poisson's equation

$$\frac{dE}{dx} = -\frac{\rho}{\epsilon_s} = -\frac{q}{\epsilon_s} [p - n + (p_0 - n_0)]$$

- Quasi-equilibrium concept

$$\Delta n = n - n_0 = n_i e^{-U_F - U_n} [e^{\phi(x)} - 1]$$

$$\Delta p = p_0 - p = n_i e^{U_F} [1 - e^{-\phi(x)}]$$

- Poisson's equation formulation

$$\frac{d^2 \phi}{dx^2} = -\left[\frac{q^2 n_i}{\epsilon_s kT} \right] [e^{\phi(x) - U_B - U_n} - e^{U_B - \phi(x)} + e^{U_B} - e^{-U_B - U_n}]$$

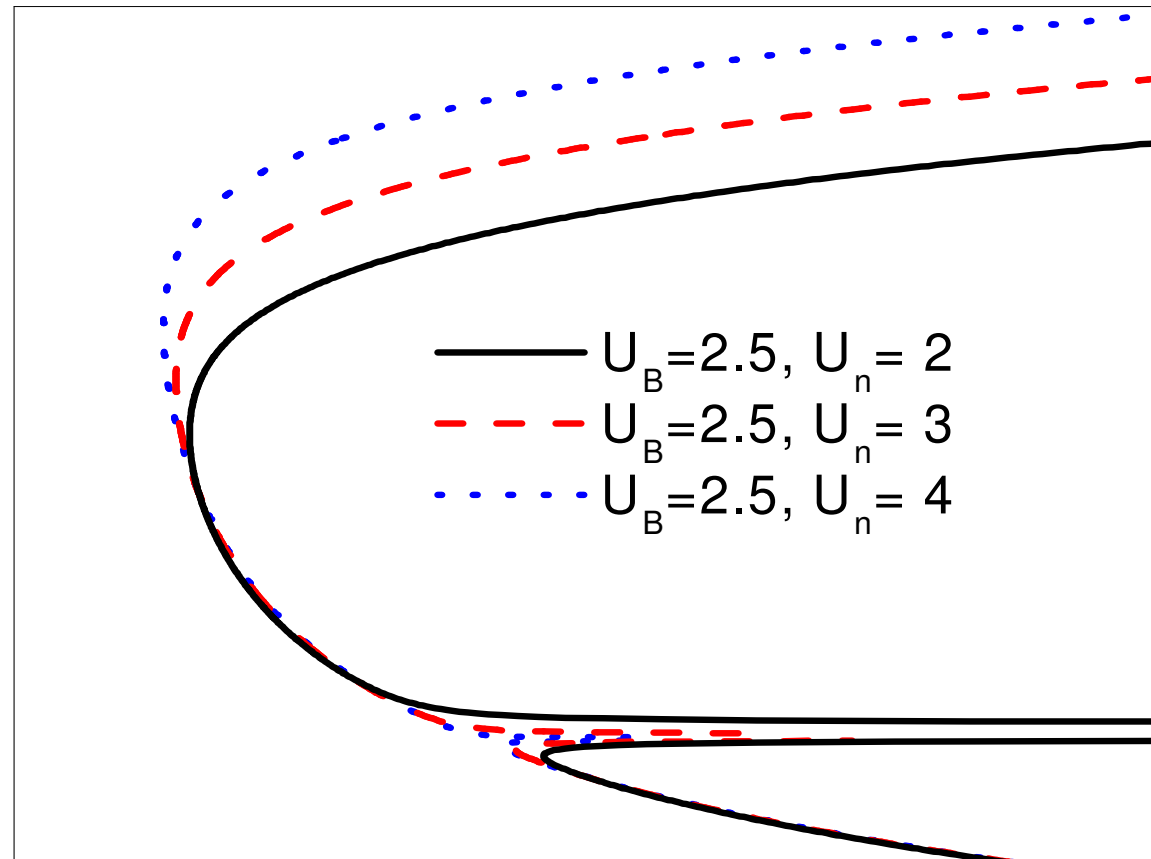
Integration results

$$U_{GB} - U_{FB} - \phi_s = \pm \left(\frac{2\epsilon_s q^2 N_A}{C_{ox}^2 kT} \right)^{1/2} \{ [\exp(-\phi_s) + \phi_s - 1] + \exp(-2U_F - U_{ch}) [\exp(\phi_s) - \phi_s - 1] \}^{1/2}$$

PUNSIM development
Derivation of complete SP equation
Quasi-equilibrium concept

Original equation result

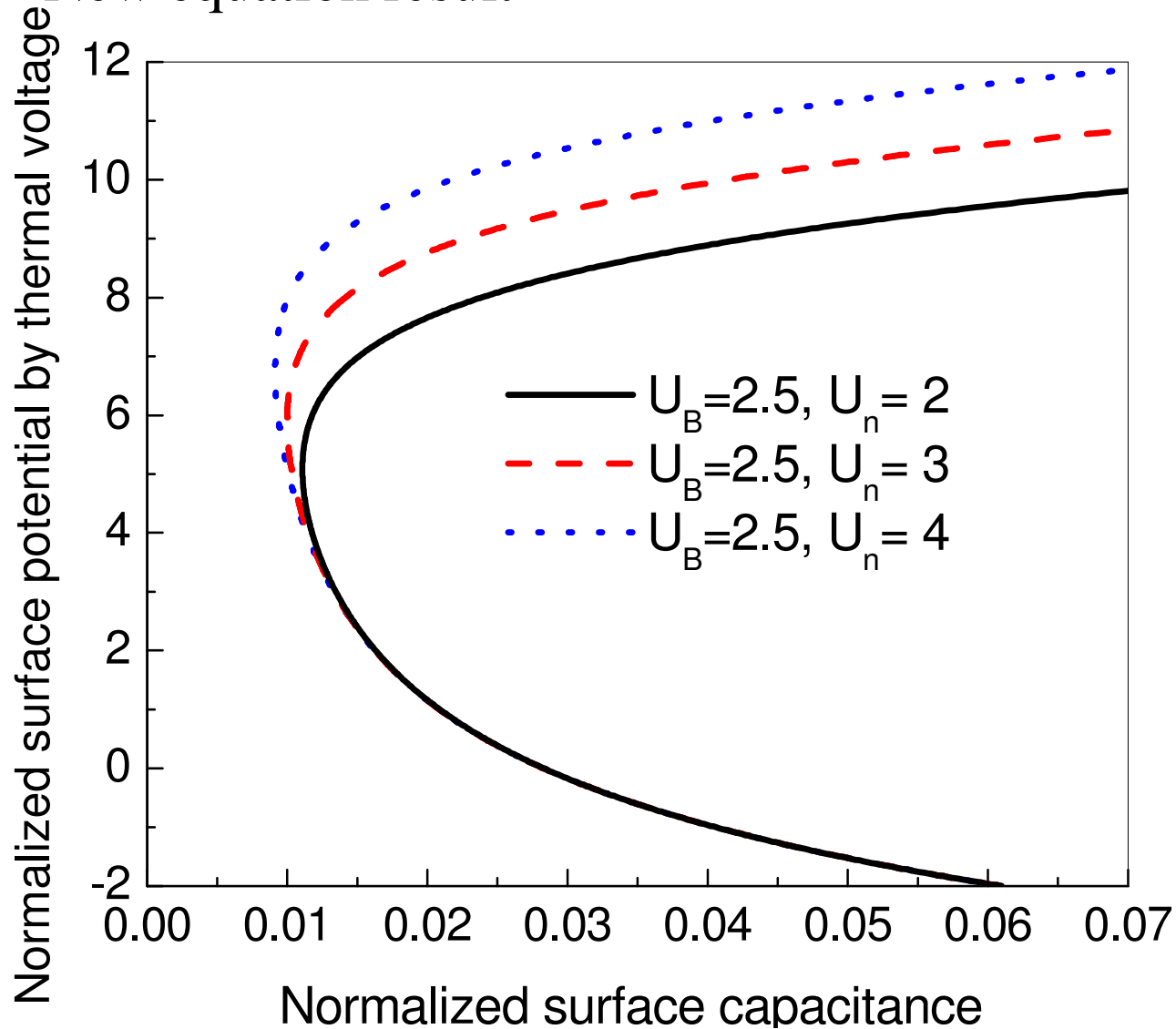
Normalized surface potential by thermal voltage



Normalized surface capacitance

PUNSIM development
Derivation of complete SP equation
Quasi-equilibrium concept

- New equation result



PUNSIM development
Physics based SP solution
New analytic solution

- Poisson's equation solution

$$U_{GB} - U_{FB} - \phi_s = \pm \left(\frac{2\epsilon_s q^2 N_A}{C_{ox}^2 kT} \right)^{1/2} \{ [\exp(-\phi_s) + \phi_s - 1] + \exp(-2U_F - U_{ch}) [\exp(\phi_s) - \phi_s - 1] \}^{1/2}$$

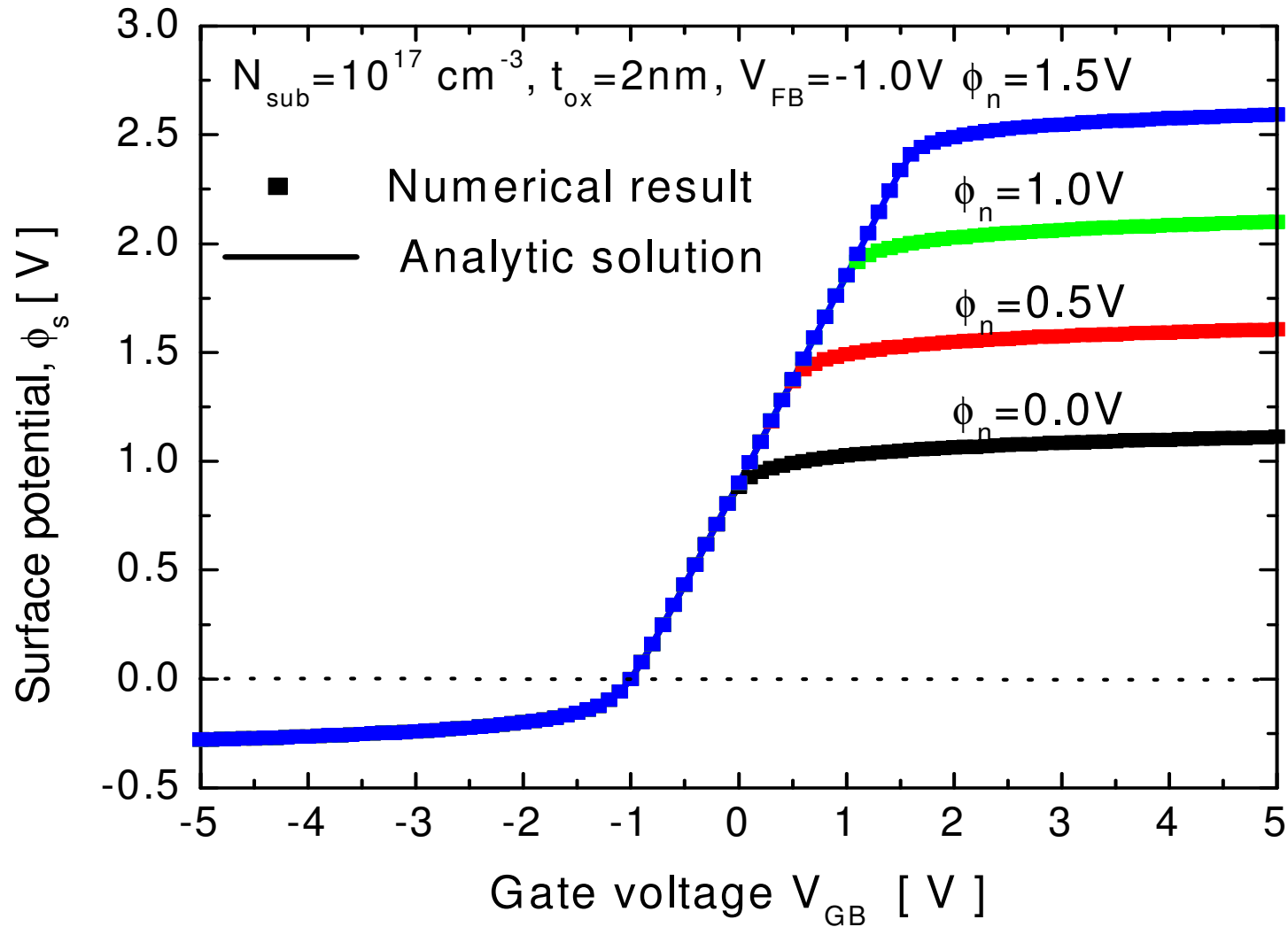
- Physics-based SP solution

$$\phi_s = \begin{cases} \phi_I = \text{sgn}(\phi) \left(\frac{x_D + f_I + f_I(1 - e^{-x_D})}{1 - f_I} - W_0 \left[\frac{f_I}{1 - f_I} e^{\frac{x_D + f_I x_D + f_I + f_I(1 - e^{-x_D})}{1 - f_I}} \right] \right) & \text{for } V_{GB} - V_{FB} \geq 0 \\ \phi_A = \text{sgn}(\phi) \left(\frac{x_D + f_A + f_I(1 - e^{-x_D})}{1 - f_I} - W_0 \left[\frac{f_A}{1 - f_I} e^{\frac{x_D + f_A + f_I(1 - e^{-x_D})}{1 - f_I}} \right] \right) & \text{for } V_{GB} - V_{FB} \leq 0 \end{cases}$$

- Both correction functions to be used for enhance analytical solution accuracy

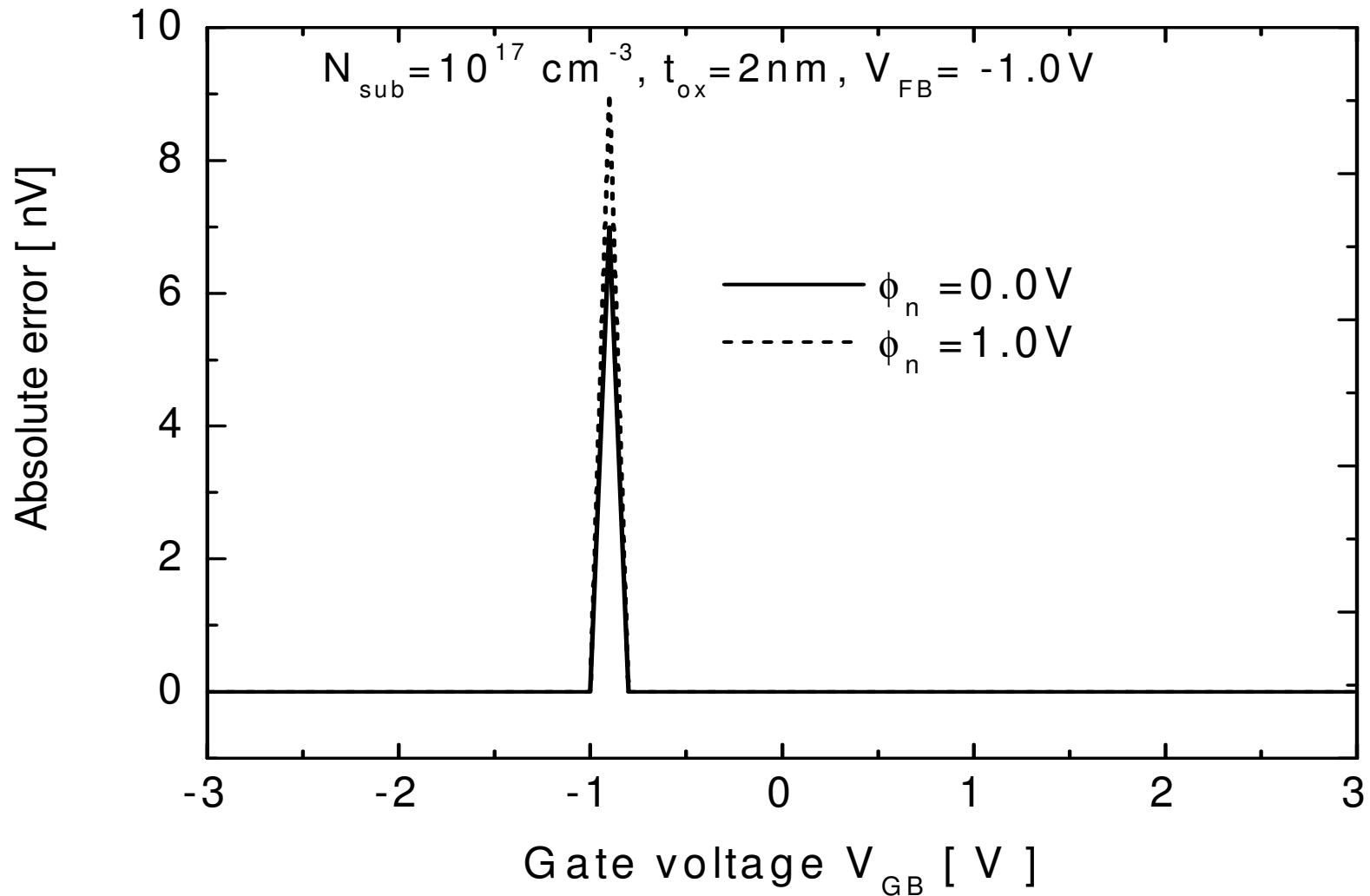
PUNSIM development
Physics based SP solution
New analytic solution

- Analytic solution result



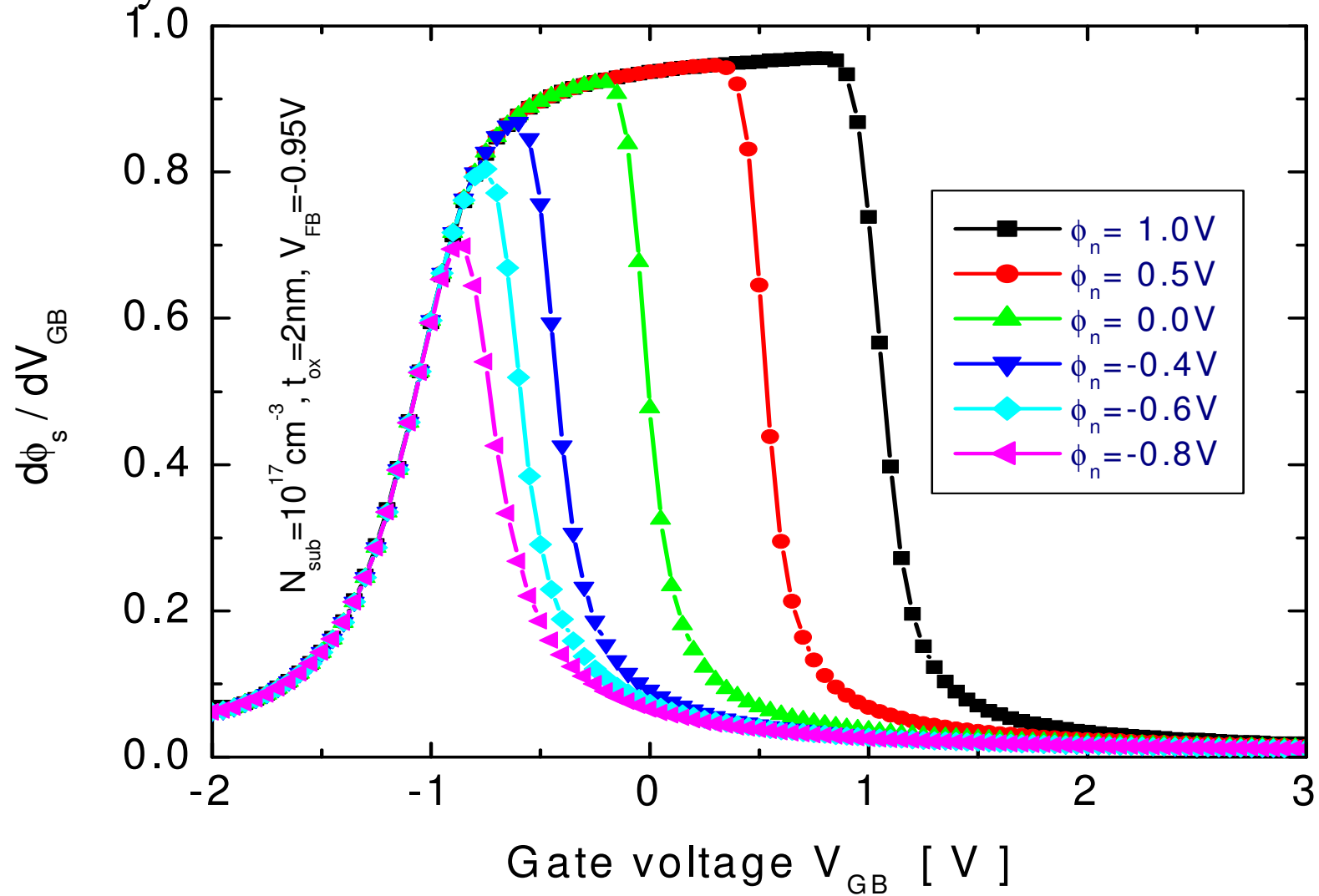
PUNSIM development
Physics based SP solution
New analytic solution

- Analytic solution result



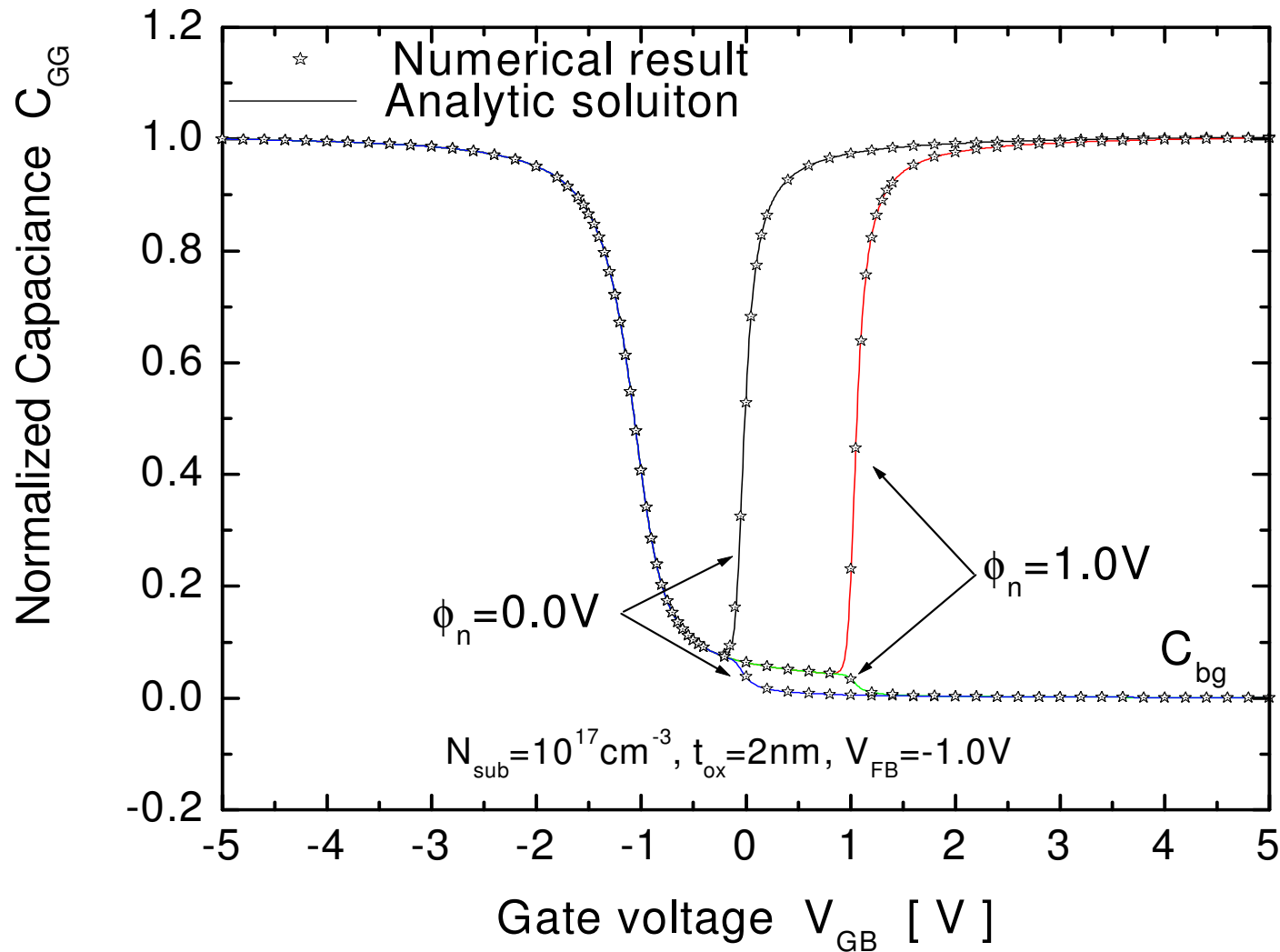
PUNSIM development
Physics based SP solution
New analytic solution

- Analytic solution result



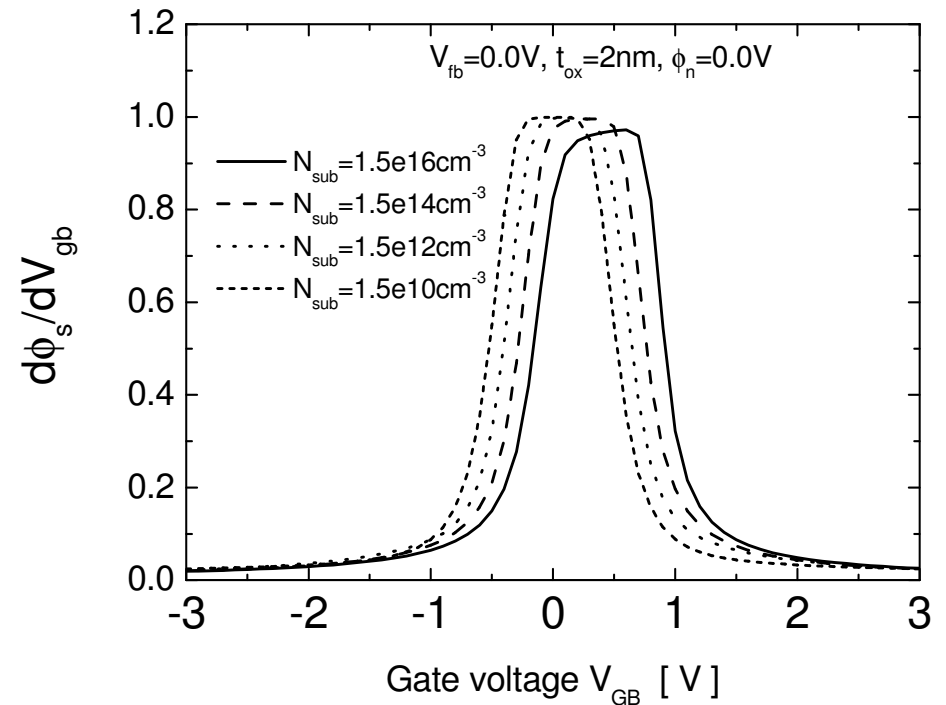
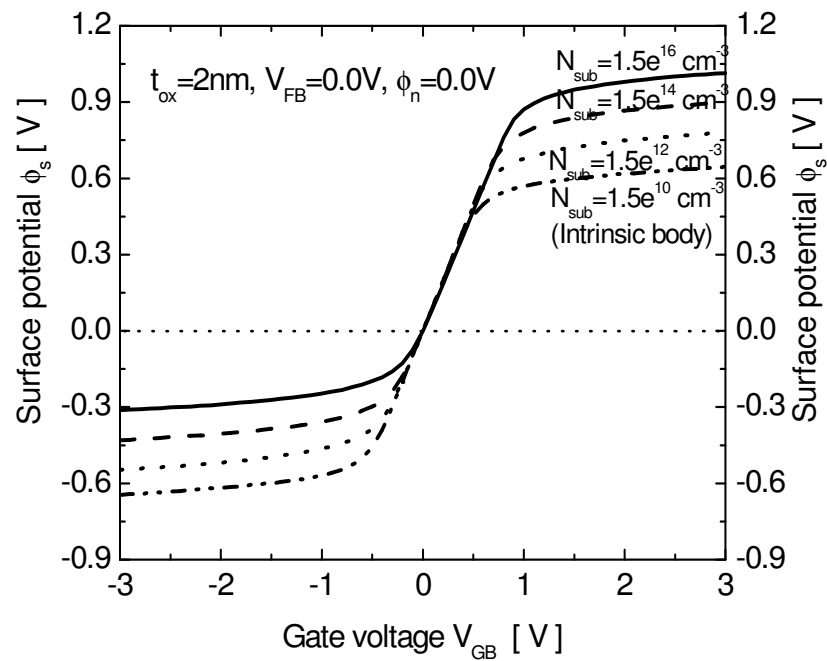
PUNSIM development
Physics based SP solution
New analytic solution

- Analytic solution result



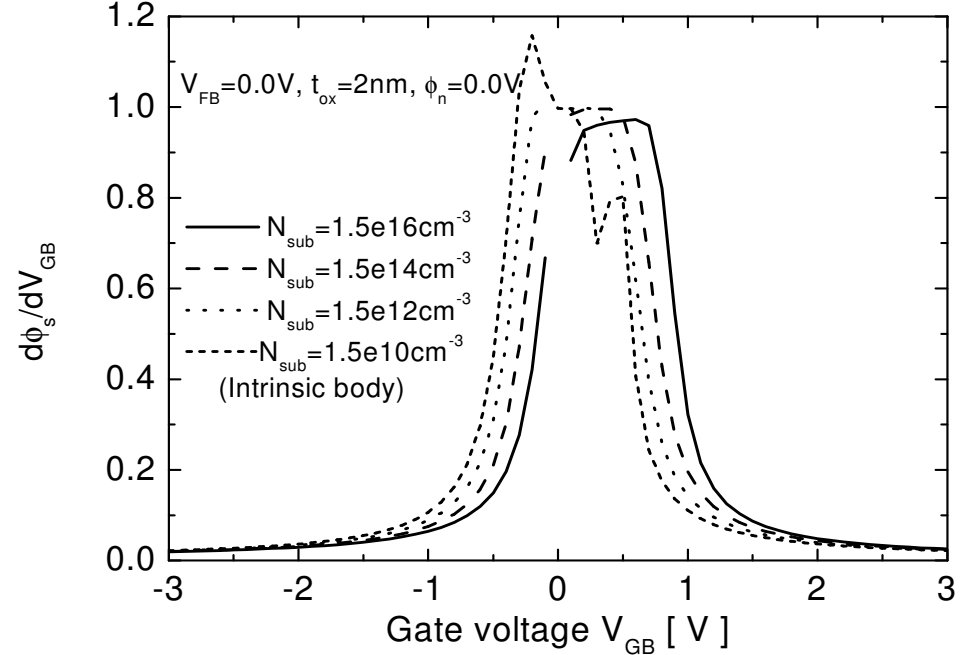
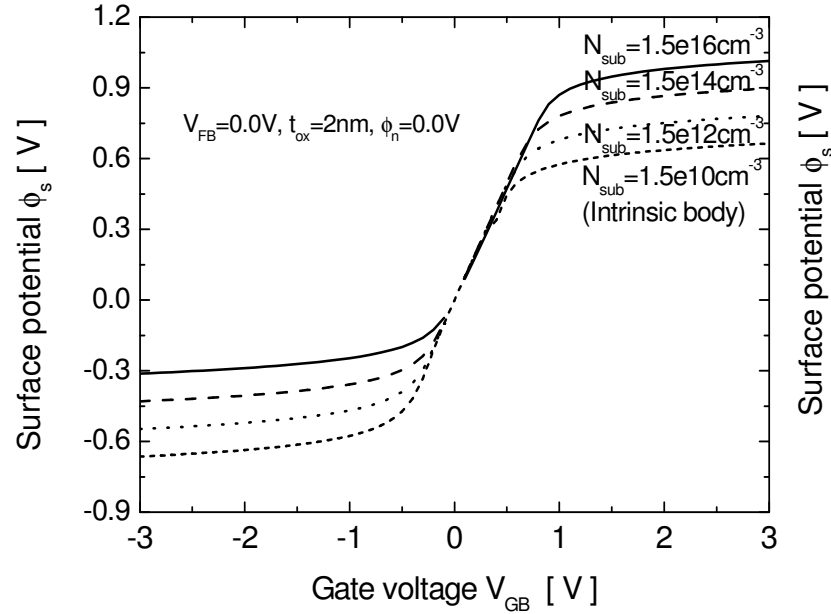
PUNSIM development
Physics based SP solution
New analytic solution

- PUNSIM scaling for doping concentration



PUNSIM development
Physics based SP solution
New analytic solution

- PSP scaling for doping concentration



Physics based Current equation

Consistent with SP solution

- Poisson's equation solution

$$U_{GB} - U_{FB} - \phi_s = \pm \left(\frac{2\epsilon_s q^2 N_A}{C_{ox}^2 kT} \right)^{1/2} \left\{ [\exp(-\phi_s) + \phi_s - 1] + \exp(-2U_F - U_{ch}) [\exp(\phi_s) - \phi_s - 1] \right\}^{1/2}$$

- Physics-based quasi-Fermi-potential expression

$$V = \phi_s - 2\phi_F - \phi_t \ln(q_{in} / \phi_t) - \phi_t \ln \left[\frac{q_{in} + 2q_b}{\gamma^2} \right]$$

- Physics-based derivation of quasi-Fermi-potential

$$dV = d\phi_s - \frac{1 + 2q_{in} / 2q_b}{1 + q_{in} / 2q_b} \frac{dq_{in}}{q_{in}}$$

- Physics-based current equation in PUNSIM

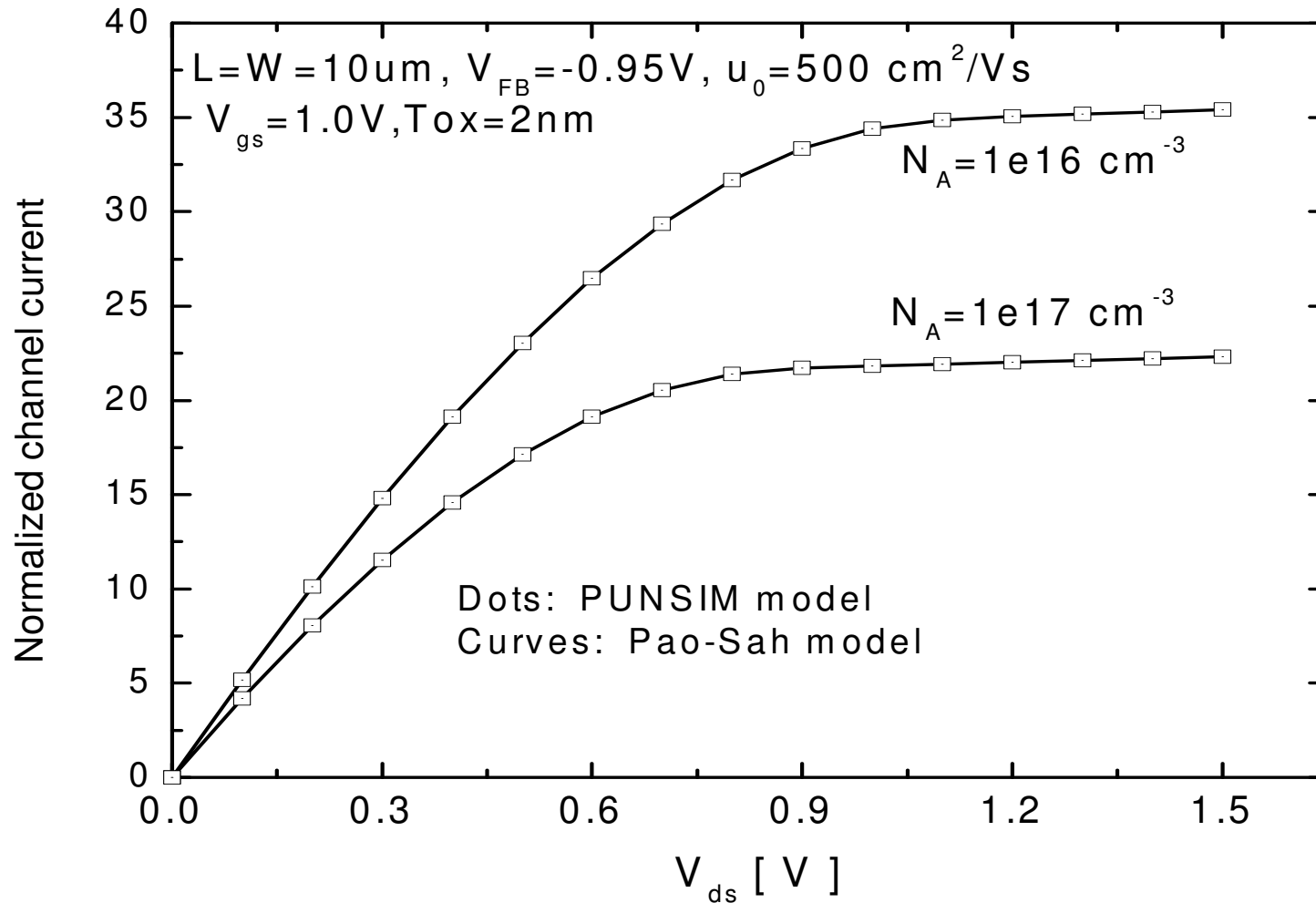
$$I_{ds} dx = W \mu q_{in} \left[d\phi_s - \frac{1 + 2q_{in} / 2q_b}{1 + q_{in} / 2q_b} \frac{dq_{in}}{q_{in}} \right]$$

- Final formulation in PUNSIM

$$I_{ds} = \frac{\mu C_{ox} W}{L} \left[\frac{q_s^2 - q_d^2}{2a_m} + \frac{1 + 2(a_m - 1)q_{im} / \gamma^2}{1 + (a_m - 1)q_{im} / \gamma^2} (q_s - q_d) \right]$$

PUNSIM development
Physics based Current equation
Consistent with SP solution

- PUNSIM current equation result



PUNSIM development
Physics based SCE modeling
Quasi 2-D method

- 2-D Poisson's equation

$$\frac{\partial^2 \phi_s}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = N_A + N_A \exp\left[\frac{q(\phi - V_{ch} - \phi_B)}{kT}\right]$$

- Quasi-2D equation solution

$$\phi_S(y) = \phi_{SL} + (V_{DB} + V_{bi} - \phi_{SL}) \exp\left[-\frac{y}{l}\right] + (V_{SB} + V_{bi} - \phi_{SL}) \exp\left[-\frac{L-y}{l}\right]$$

- Lateral field average value represents SCE

$$\frac{\partial^2 \phi_s}{\partial y^2} \approx \frac{V_{DS} + 2V_{bi} - 2\phi_{SL}}{l^2} \exp\left(-\frac{L}{l}\right)$$

- Gauss law including Short-channel effects

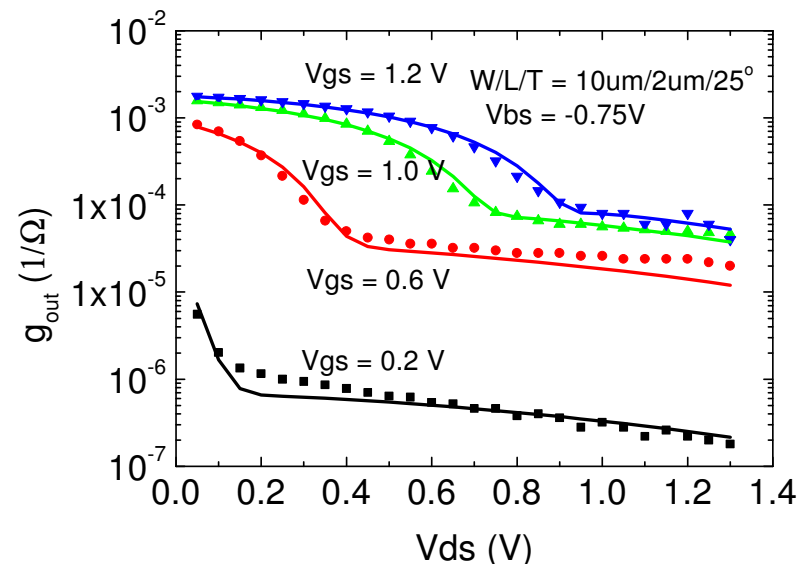
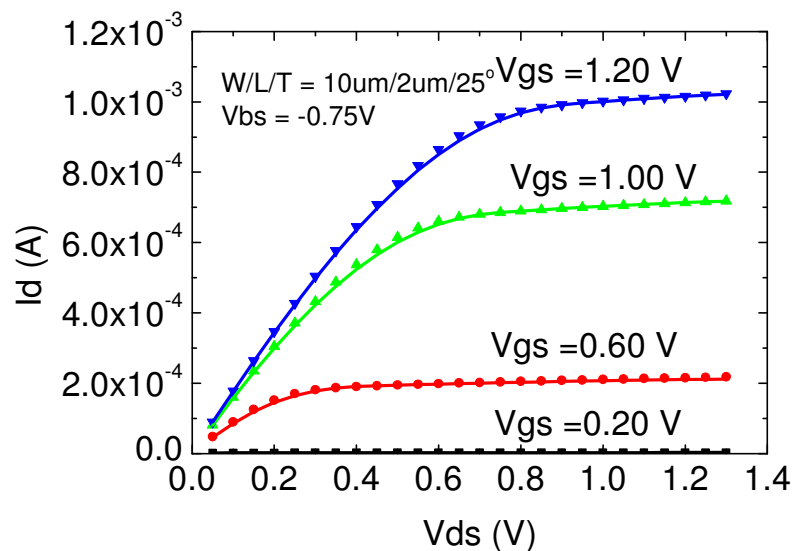
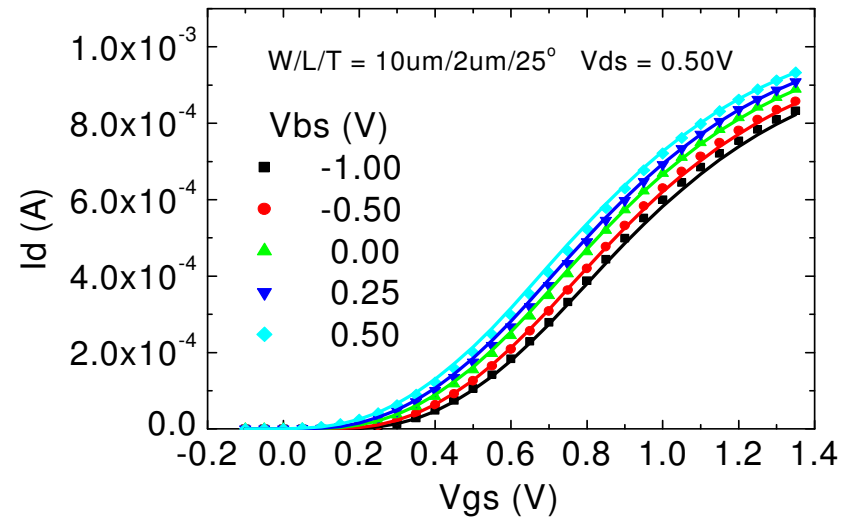
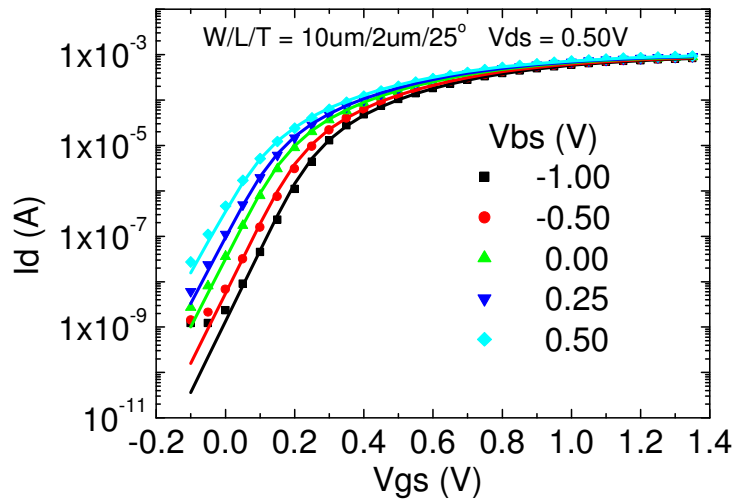
$$q_B + q_I = (V_{GB} - V_{FB}) - (1 + 2f)\phi_s + f(V_{DB} + V_{SB} + 2V_{bi})$$

- Final formulation in PUNSIM

$$\gamma \sqrt{\phi_s - \phi_t + e^{-\phi_s} + e^{-V_{ch} - 2\phi_f} [e^{\phi_s} - \phi_s - \phi_t]} = (V_{GB} - V_{FB}) - (1 + 2f)\phi_s + f(V_{DSx} + 2V_{bi})$$

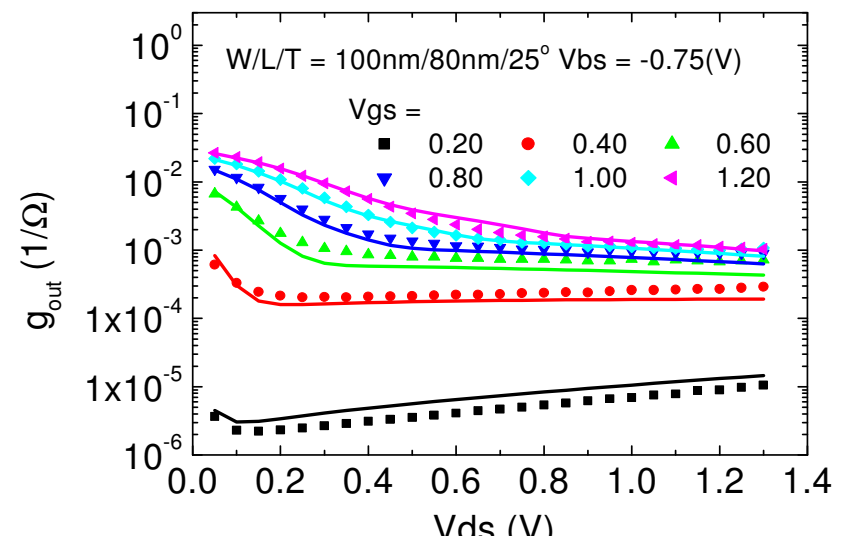
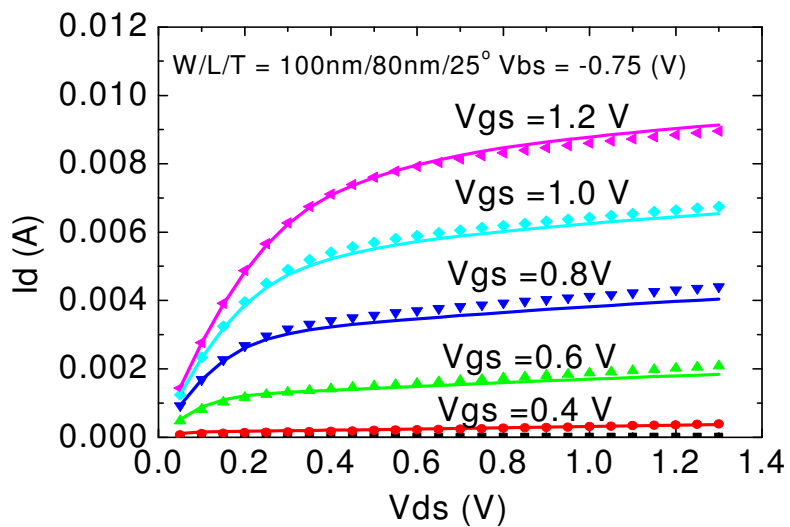
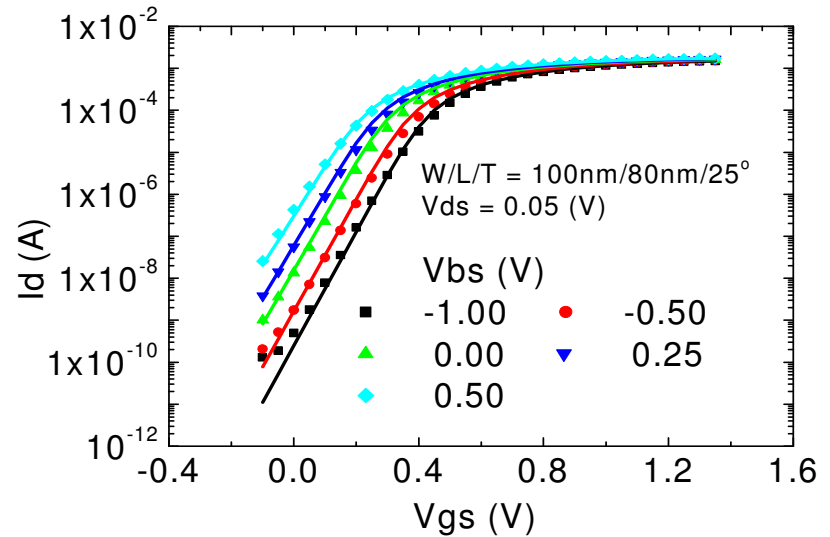
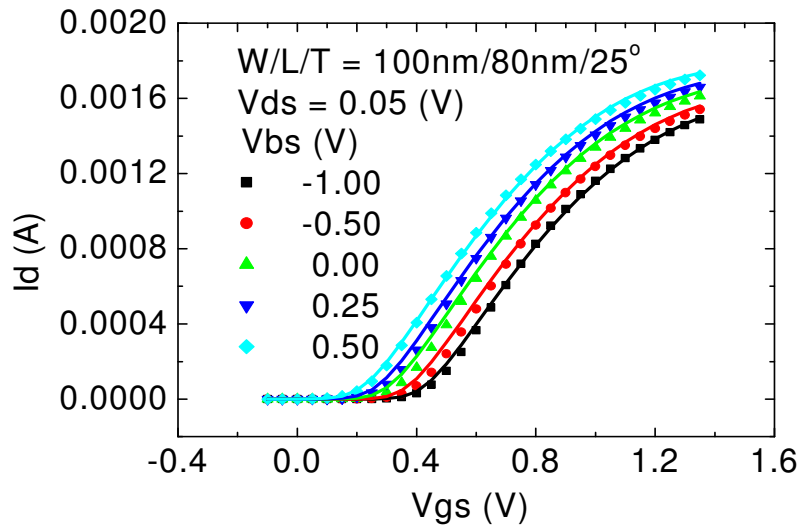
PUNSIM development
Primary
PUNSIM model results

W/L=10um/2um



PUNSIM development
Primary
PUNSIM model results

W/L=10um/80nm



Summary

- Compact modeling encounters great challenges
- Non-perfect approaches exist so far
- Charge-based and SP based models should take the advantages of the BSIM3/4, e.g. decoupling fitting
- Benchmark tests on Fashion SP models demonstrate SP model's issues neglected previously
- PUNSIM model is a young brother in this field
- Much effort needed for compact modeling community

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