Comparison of surface-potential-based and charge-based MOSFET core models

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Outline

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- $Q_I^{'}$ – based model
- Drain current calculation
- Comparison between $Q_I^{'}$ and ϕ_s models
- Conclusions

Introduction

$$I_{DS} = \frac{\mu W}{L}\int_{V_S}^{V_D}\left(-Q_I^{'}\right)dV_C$$

"exact" Pao and Sah current formula

- Classical (as opposed to QM) model
- Long channel device
- Constant mobility

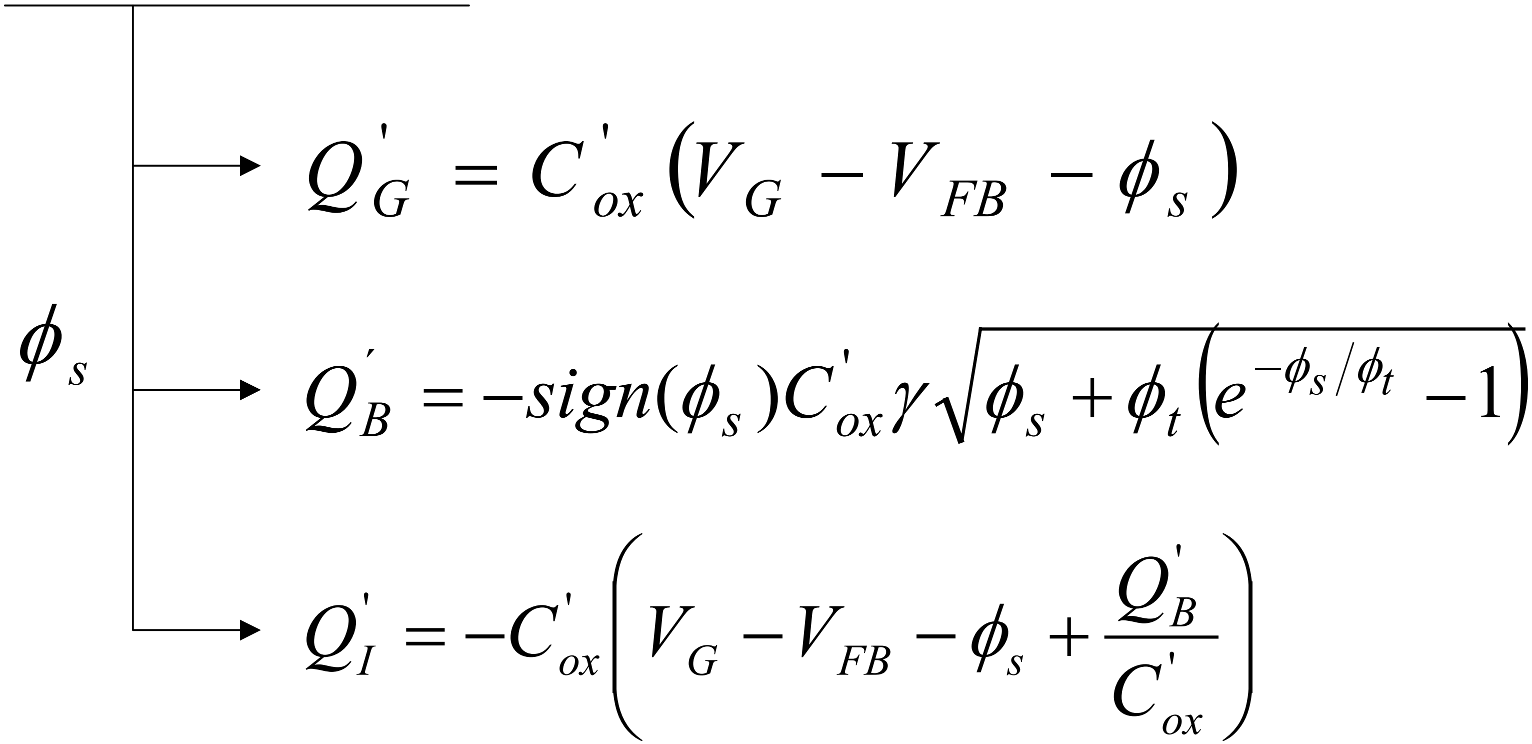
Compact Models

$Q_I^{'}$ based $$I_{DS} = -\mu\frac{W}{L}\int_{Q_{IS}^{'}}^{Q_{ID}^{'}} Q_I^{'}\overset{\overset{\text{Approximated using UCCM}}{\downarrow}}{\frac{dV_C}{dQ_I^{'}}}dQ_I^{'}$$

ϕ_s based $$I_{DS} = -\mu\frac{W}{L}\int_{\phi_{s0}}^{\phi_{sL}} \underset{\underset{\text{Charge sheet approximation}}{\uparrow}}{Q_I^{'}\left(\phi_s\right)}\frac{dV_C}{d\phi_s}d\phi_s$$

Surface potential model

$$\left(V_G - V_{FB} - \phi_s\right)^2 = \gamma^2 \phi_t e^{-\left(2\phi_F + V_C\right)/\phi_t}\left(e^{\phi_s/\phi_t} - 1\right) + \gamma^2\left(\phi_s + \phi_t\left(e^{-\phi_s/\phi_t} - 1\right)\right)$$



$$\phi_s$$

$$Q_G^{'} = C_{ox}^{'}\left(V_G - V_{FB} - \phi_s\right)$$

$$Q_B^{\prime} = -sign(\phi_s)C_{ox}^{'}\gamma\sqrt{\phi_s + \phi_t\left(e^{-\phi_s/\phi_t} - 1\right)}$$

$$Q_I^{'} = -C_{ox}^{'}\left(V_G - V_{FB} - \phi_s + \frac{Q_B^{'}}{C_{ox}^{'}}\right)$$

Charge – based model

Basic Approximations

- Charge sheet approximation

$$Q_I' = -C_{ox}'\left(V_G - V_{FB} - \phi_S - \gamma\sqrt{\phi_S - \underbrace{\phi_t}}\right)$$

Included in UCCM+

- C'_b **constant** along the channel $C_b' = \dfrac{\gamma C_{ox}'}{2\sqrt{\phi_{Sa} - \underbrace{\phi_t}}}$

ϕ_{Sa} : Value of surface potential disregading channel charge

$$Q_I' \cong \left(C_{ox}' + C_b'\right)\left(\phi_S - \phi_{Sa}\right) = n\,C_{ox}'\left(\phi_S - \phi_{Sa}\right)$$

Pinch-off Voltage

- Basic approximation: $Q_I' = nC_{ox}'(\phi_S - \phi_{Sa})$ (1)

pinch-off charge: $Q_{IP}' = -nC_{ox}'\phi_t$ (2)

- **Surface potential at pinch-off :** $\phi_{SP} = \phi_{Sa} - \phi_t$

- From (1), (2) and total charge expression $V_P = \phi_{Sa} - 2\phi_F - \phi_t\left[1 + \ln[\frac{n}{(n-1)}]\right]$

V_P: pinch-off potential

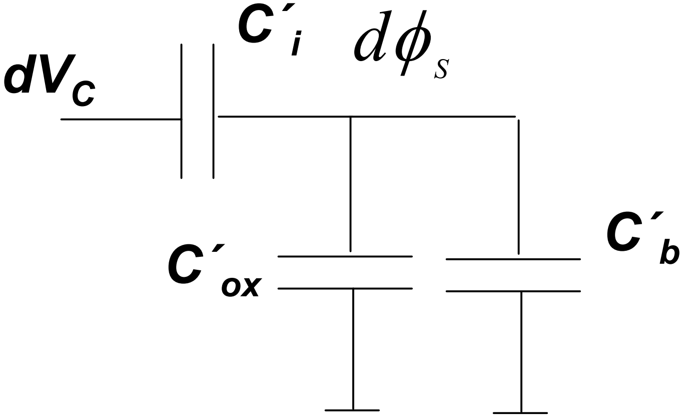
Capacitive model of the field - effect

- Potential Balance in Inversion $\left(\phi_s > 6\phi_t\right)$

$$V_G - V_{FB} = \phi_S + \gamma\sqrt{\phi_S + \phi_t e^{\left(\phi_S - 2\phi_F - V_C\right)/\phi_t} - \phi_t}$$

$$\Downarrow$$

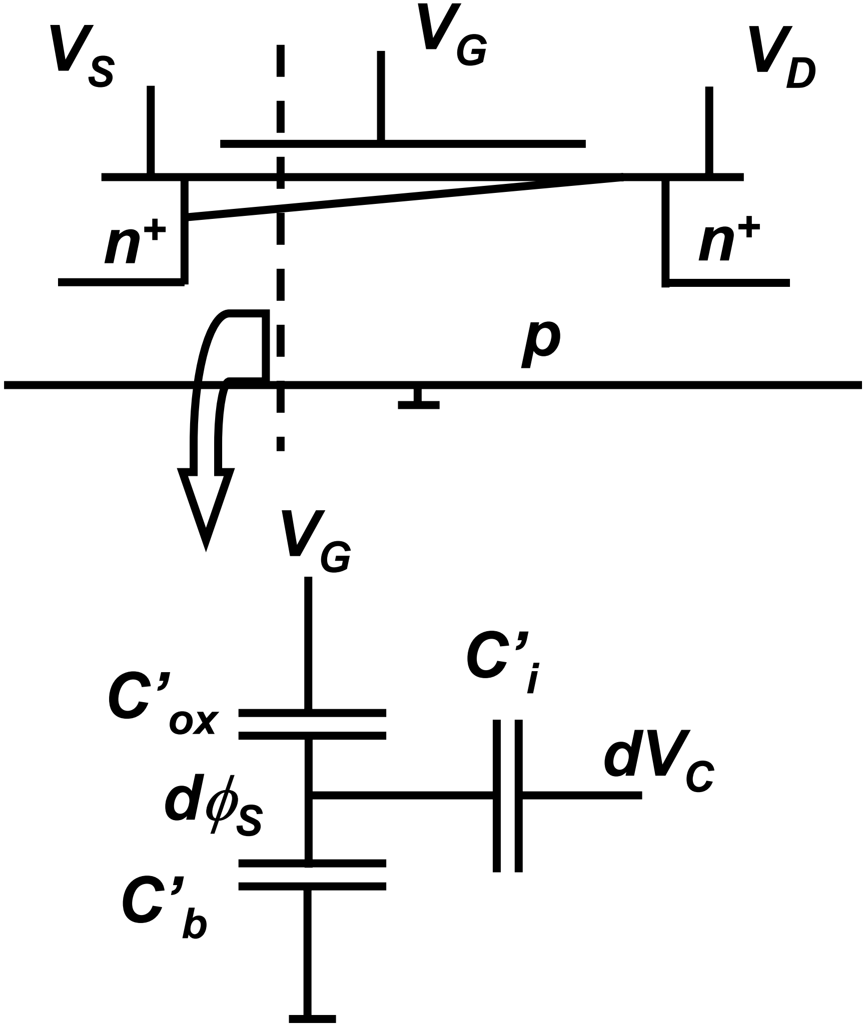
$$\left.\frac{d\phi_S}{dV_C}\right|_G = \frac{C_i^{'}}{C_i^{'} + C_b^{'} + C_{ox}^{'}}$$



$$C_i^{'} = -\frac{Q_I^{'}}{2\phi_t}\left(1 + \frac{Q_B^{'}}{Q_B^{'} + Q_I^{'}}\right) \longrightarrow C_i^{'} = -\frac{Q_I^{'}}{\phi_t}$$

Very accurate in WI and MI

The Unified Charge Control Model (1)



$$\left.\frac{dQ'_I}{dV_C}\right|_{V_G} = \frac{\left(C'_{ox} + C'_b\right)C'_i}{C'_{ox} + C'_b + C'_i}$$

Basic approximations:

$C'_{ox} + C'_b = nC'_{ox}$

$C'_i = - Q'_I/\phi_t$

⇓

$$dQ'_I\left(\frac{1}{nC'_{ox}} - \frac{\phi_t}{Q'_I}\right) = dV_C$$

The Unified Charge Control Model (2)

Integrating $dQ_I'\left(\frac{1}{nC_{ox}'}-\frac{\phi_t}{Q_I'}\right)=dV_C$ **between** $\boldsymbol{V_C}$ **and** $\boldsymbol{V_P}$**:**

$$\boxed{\frac{Q_{IP}'-Q_I'}{nC_{ox}'}+\phi_t\ln\left(\frac{Q_I'}{Q_{IP}'}\right)=V_P-V_C}$$

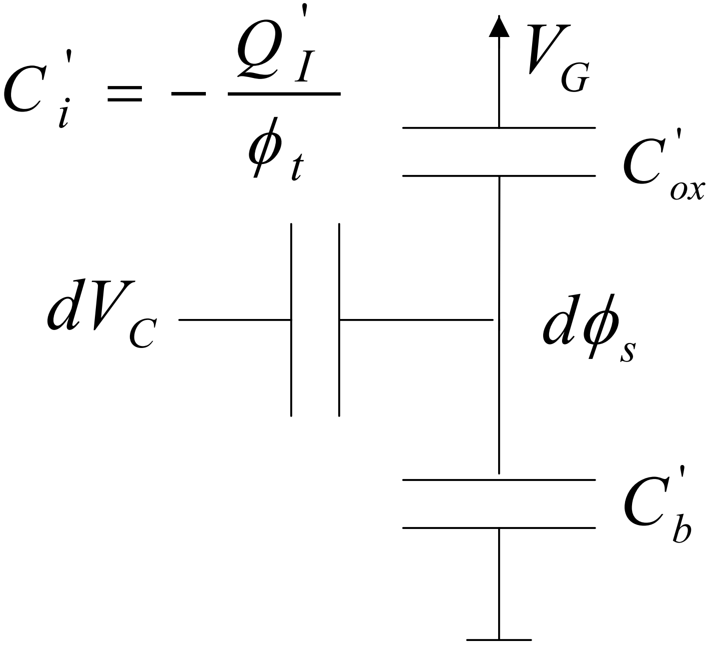
UCCM

$$\left|Q_I'\right|<<\left|Q_{IP}'\right|$$

$$Q_I'=-\frac{\sqrt{2q\varepsilon_s N_A}}{2\sqrt{\phi_{sa}-\phi_t}}e^{(\phi_{sa}-2\phi_F)/\phi_t}e^{-V_C/\phi_t}$$

Charge – sheet I-V Model

$$C_i^{'} = -\frac{Q_I^{'}}{\phi_t}$$



$$\longrightarrow \quad \frac{dV_C}{d\phi_s} = 1 - \frac{\phi_t}{Q_I^{'}} \frac{dQ_I^{'}}{d\phi_s}$$

$$I_{DS} = -\mu W Q_I^{'} \frac{dV_C}{dx} = -\mu W Q_I^{'} \left(1 - \frac{\phi_t}{Q_I^{'}} \frac{dQ_I^{'}}{d\phi_s} \right) \frac{d\phi_s}{dx}$$

$$= -\mu W Q_I^{'} \frac{d\phi_S}{dx} + \mu W \phi_t \frac{dQ_I^{'}}{dx}$$

$\downarrow$

Charge sheet (drift + diffusion) current expression

Equivalent Approximations

1. The Unified Charge Control Model

$$\boxed{\frac{Q'_{IP}-Q'_I}{nC'_{ox}}+\phi_t\ln\left(\frac{Q'_I}{Q'_{IP}}\right)=V_P-V_C}$$

2. $C'_{ox}+C'_b=nC'_{ox}$ & $C'_i=-Q'_I/\phi_t$ ⇒ $dQ'_I\left(\frac{1}{nC'_{ox}}-\frac{\phi_t}{Q'_I}\right)=dV_C$

3. drift + diffusion + charge linearization ⇔

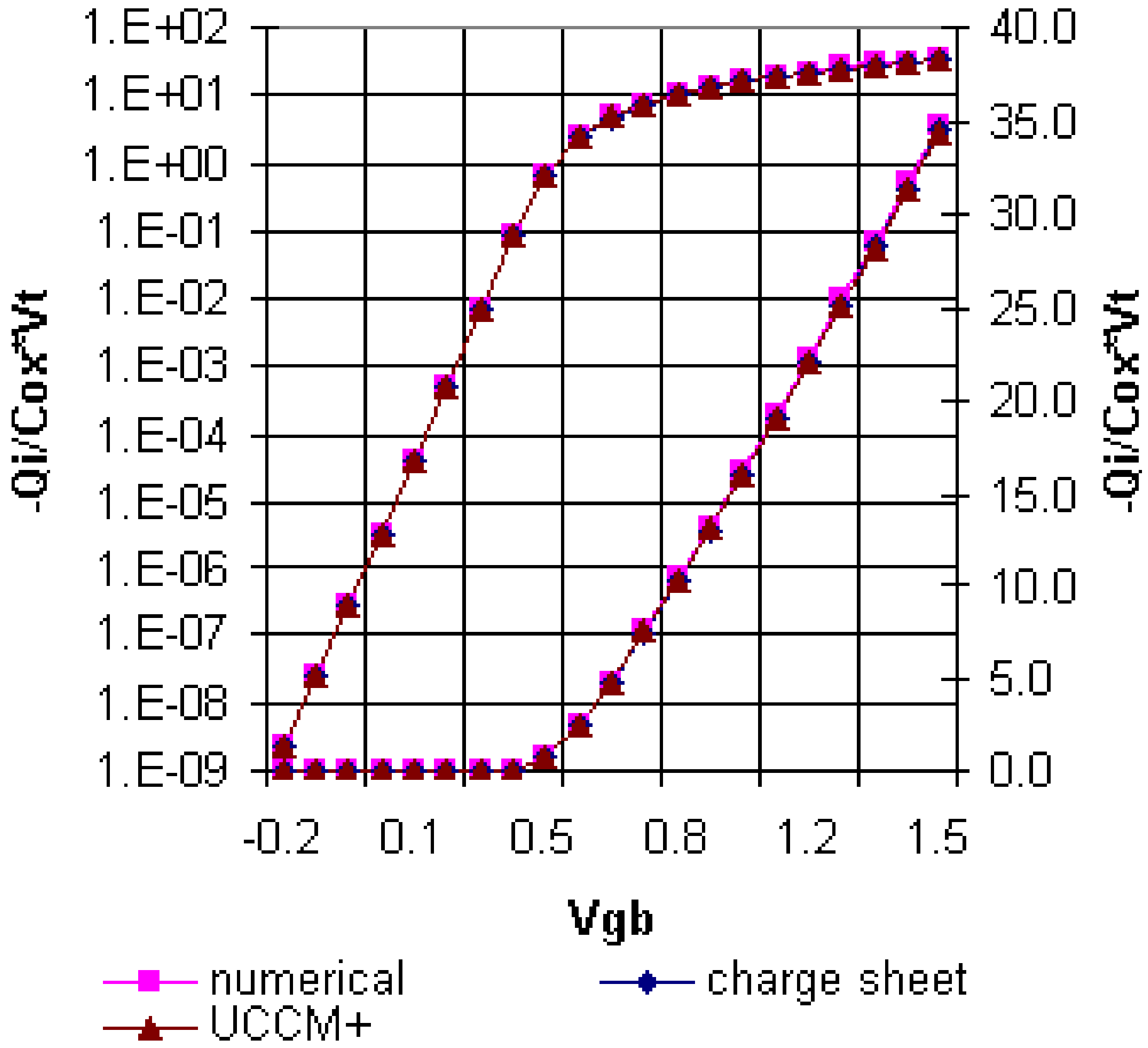
⇓

$$I_D=\frac{\mu W}{nC'_{ox}}\left(-Q'_I+nC'_{ox}\phi_t\right)\frac{dQ'_I}{dx}=-\mu W Q'_I\frac{dV_C}{dx}$$

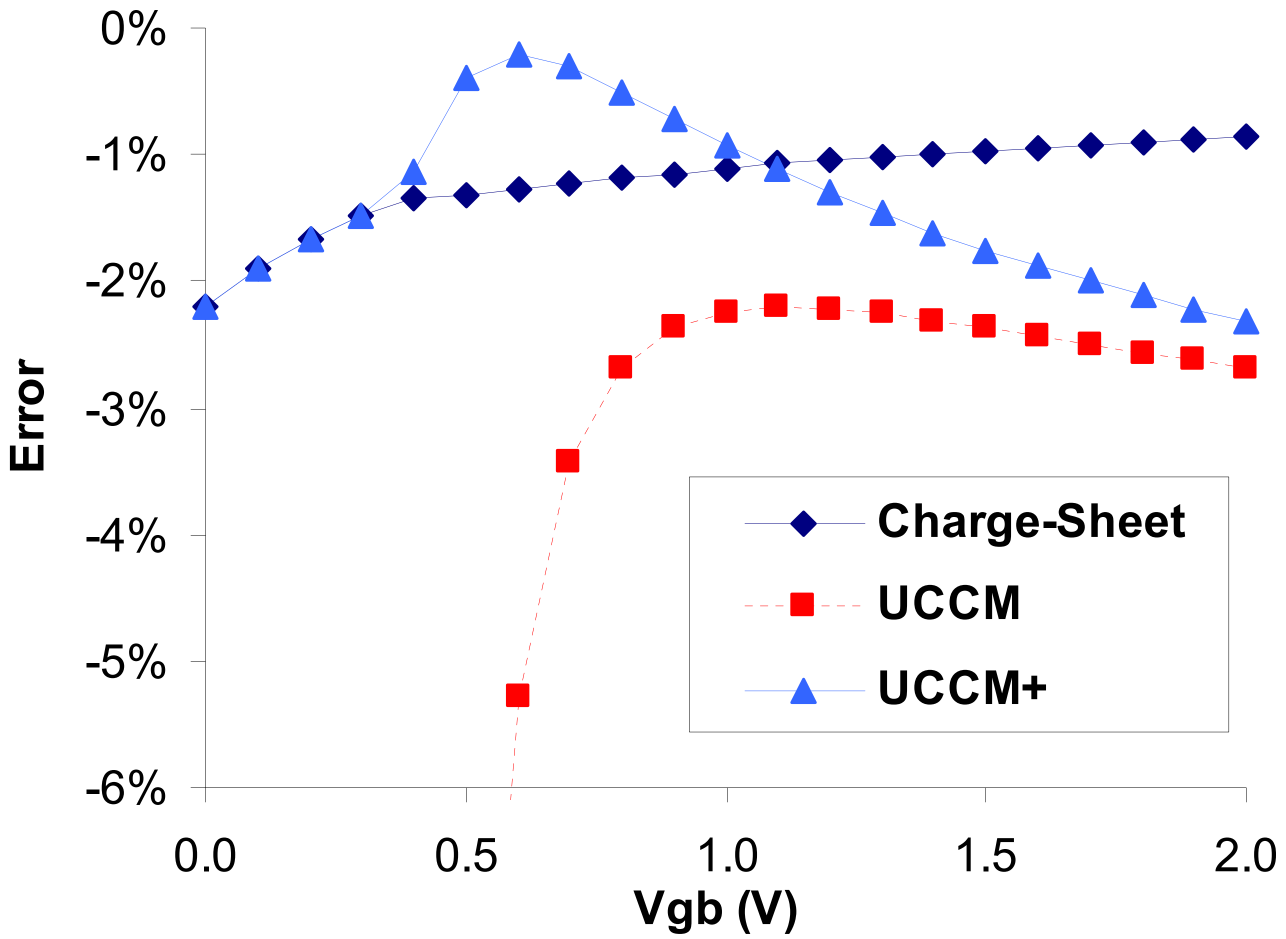
⇑

quasi-Fermi level formulation

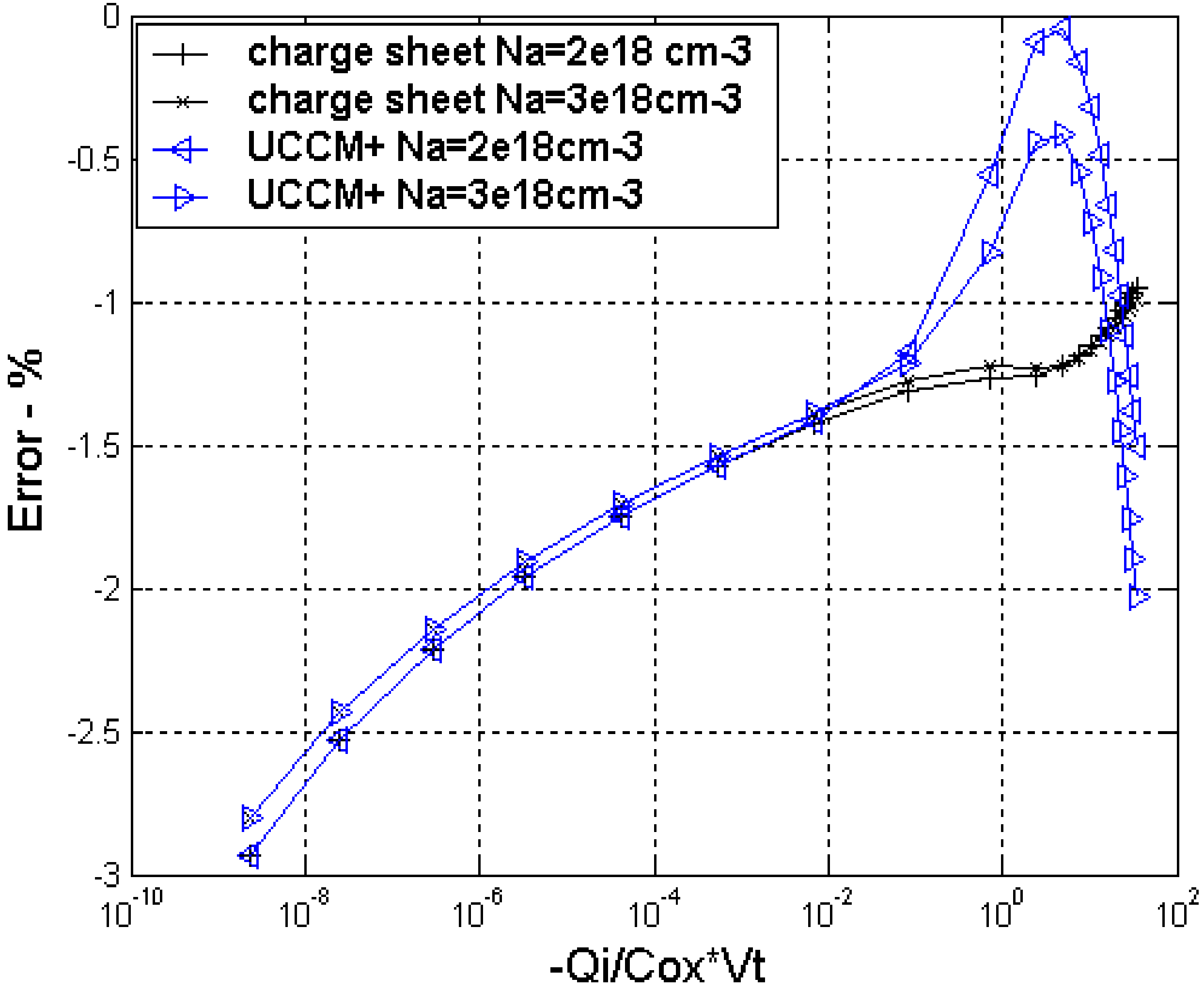
⇒ $dQ'_I\left(\frac{1}{nC'_{ox}}-\frac{\phi_t}{Q'_I}\right)=dV_C$



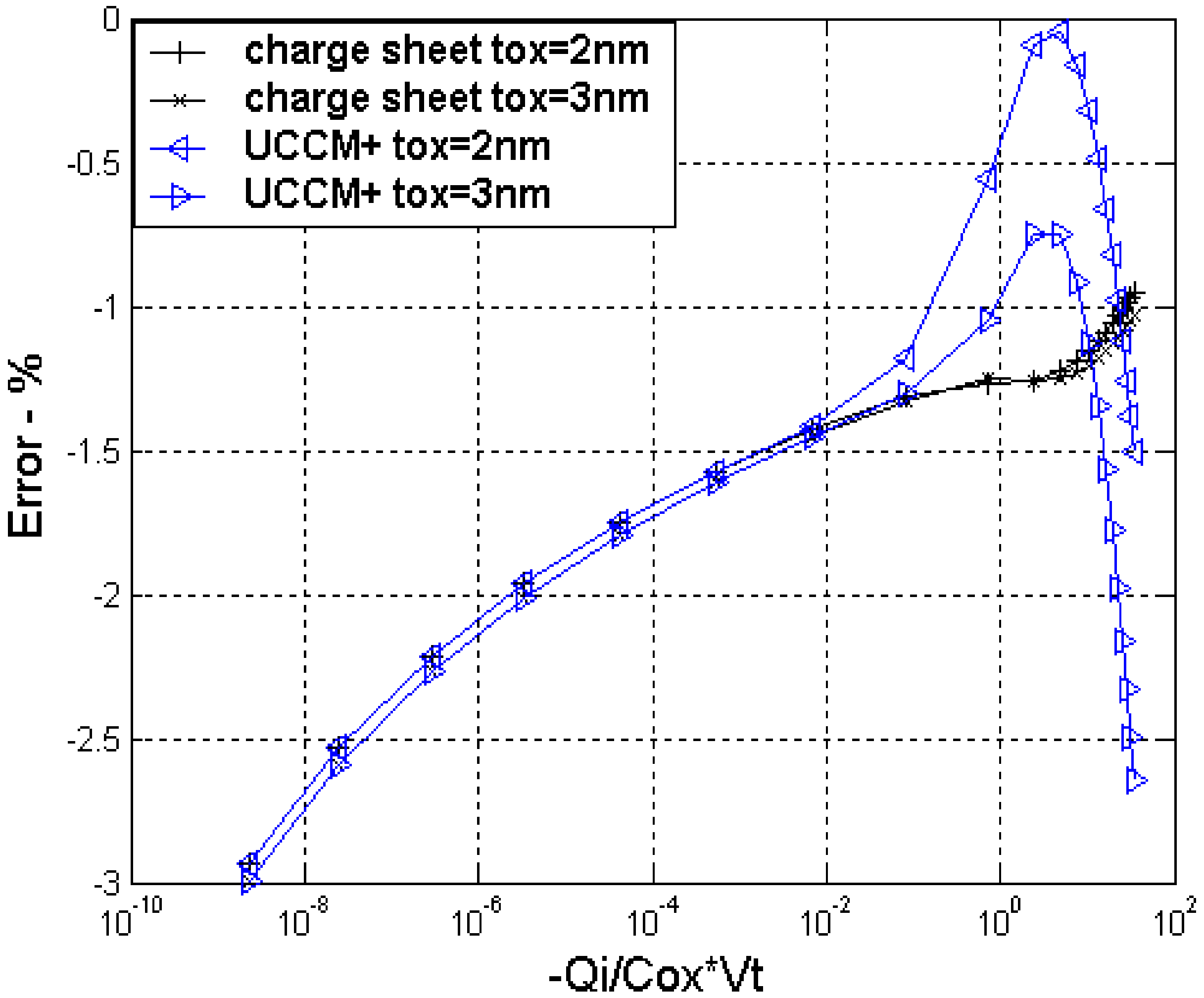
Inversion charge density



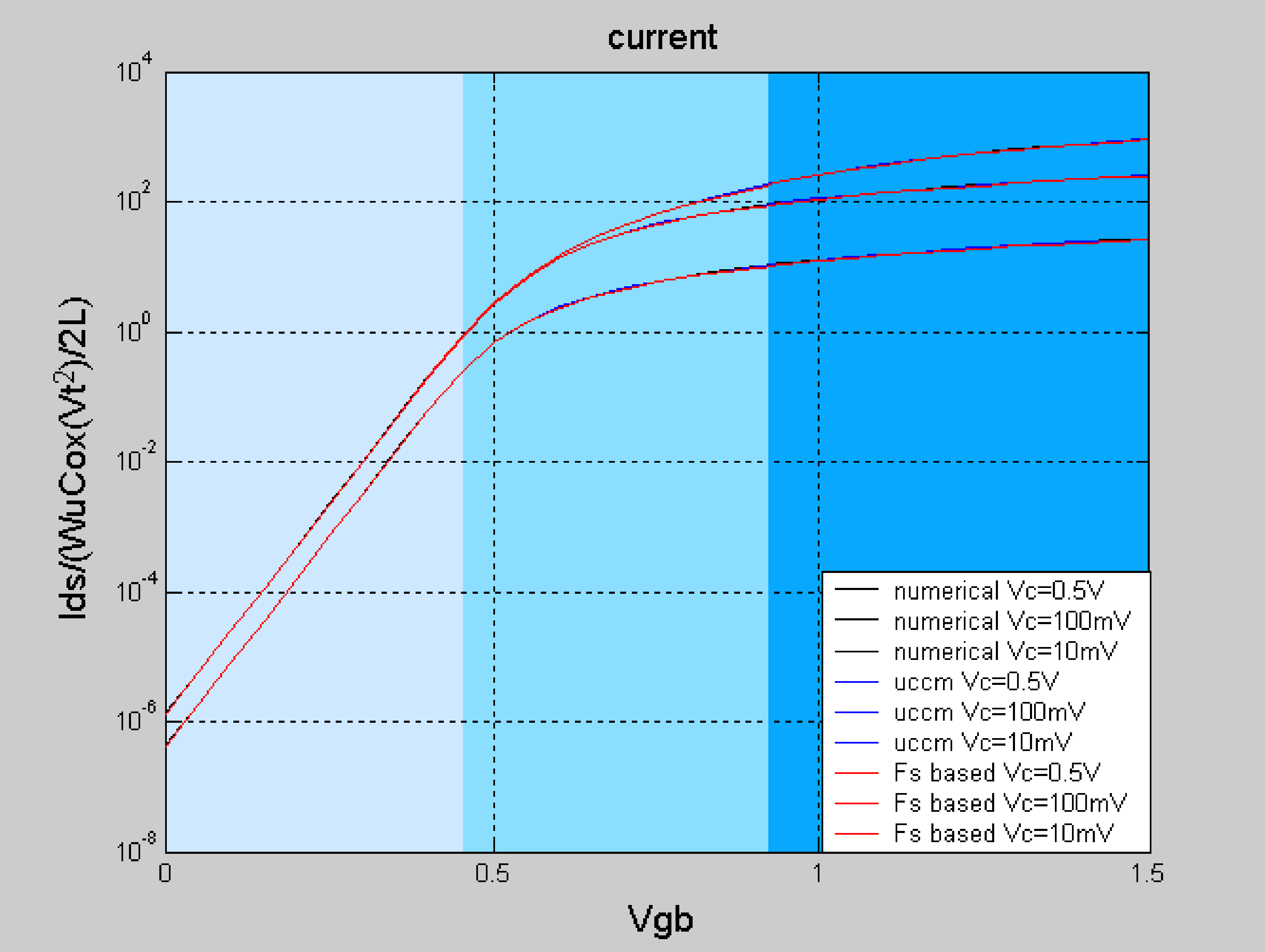
Error in inversion charge density relative to numerical solution

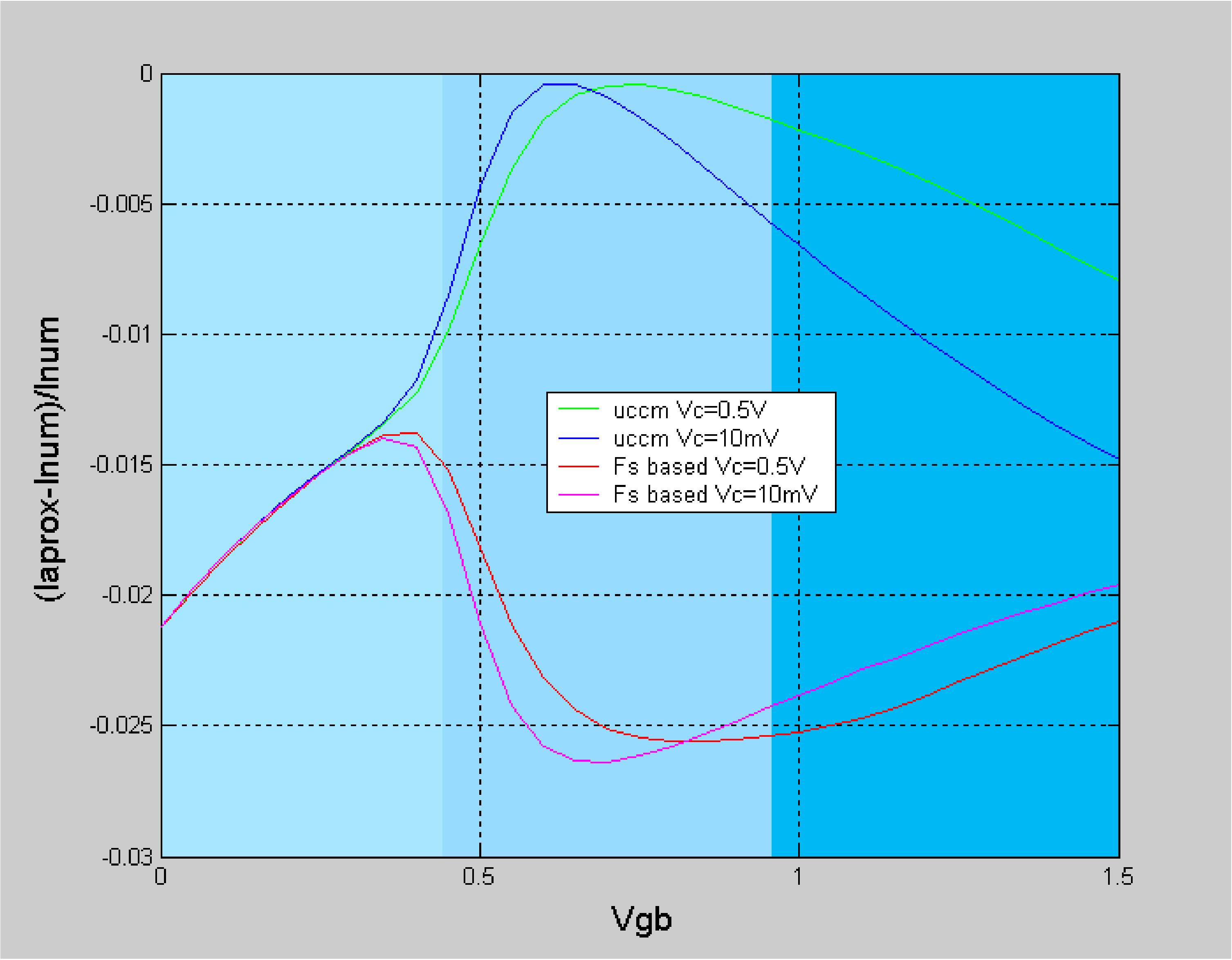


Error in inversion charge density for two doping concentrations



Error in inversion charge density for two oxide thicknesses


current
Ids/(WuCox(Vt^2)/2L)
10^4
10^2
10^0
10^-2
10^-4
10^-6
10^-8
0
0.5
1
1.5
Vgb
numerical Vc=0.5V
numerical Vc=100mV
numerical Vc=10mV
uccm Vc=0.5V
uccm Vc=100mV
uccm Vc=10mV
Fs based Vc=0.5V
Fs based Vc=100mV
Fs based Vc=10mV


0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
(Iaprox-Inum)/Inum
0
0.5
1
1.5
Vgb
uccm Vc=0.5V
uccm Vc=10mV
Fs based Vc=0.5V
Fs based Vc=10mV

Conclusions

- A new high accuracy charge model (UCCM$^+$) was achieved
- UCCM$^+$ and surface potential models give similar results for the inversion charge

	UCCM$^+$	**ϕ_s-model**
WI	=	=
MI	↑	**-**
SI	**-**	↑