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Surface-Potential versus Inversion-Charge Based Approaches to MOSFET Modeling

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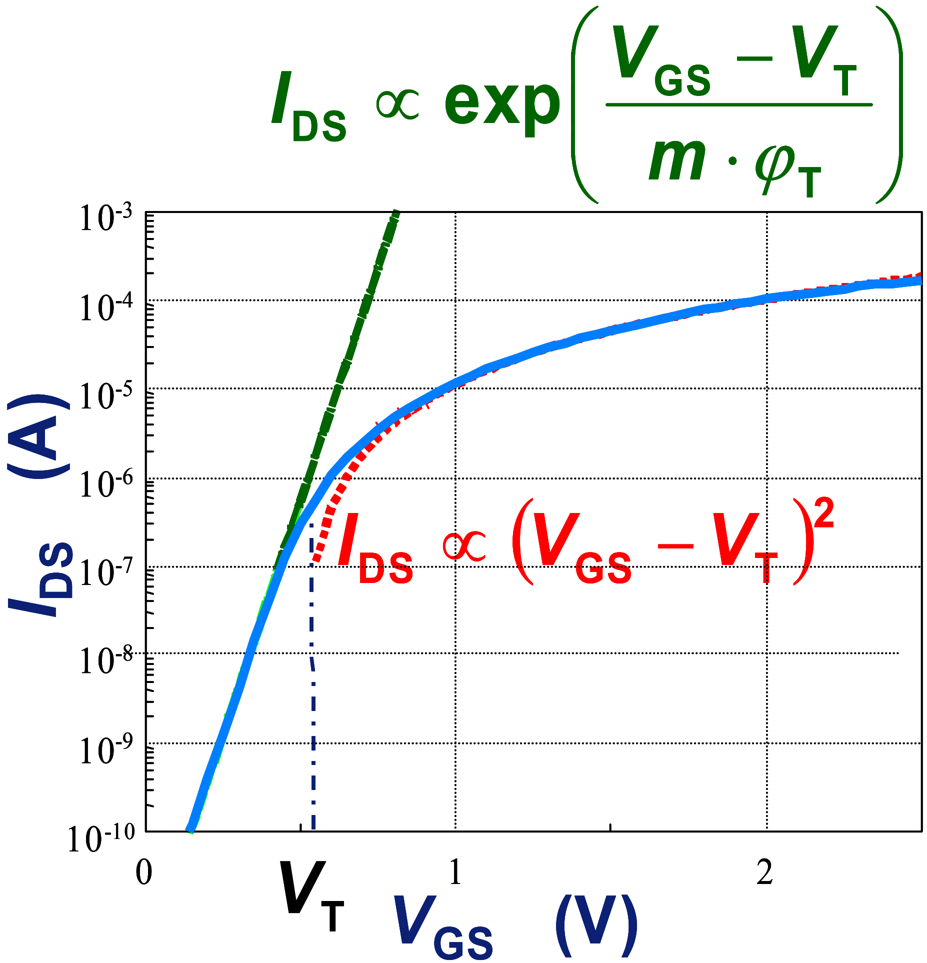
limitations V_T-based models (BSIM3/4, MM9)



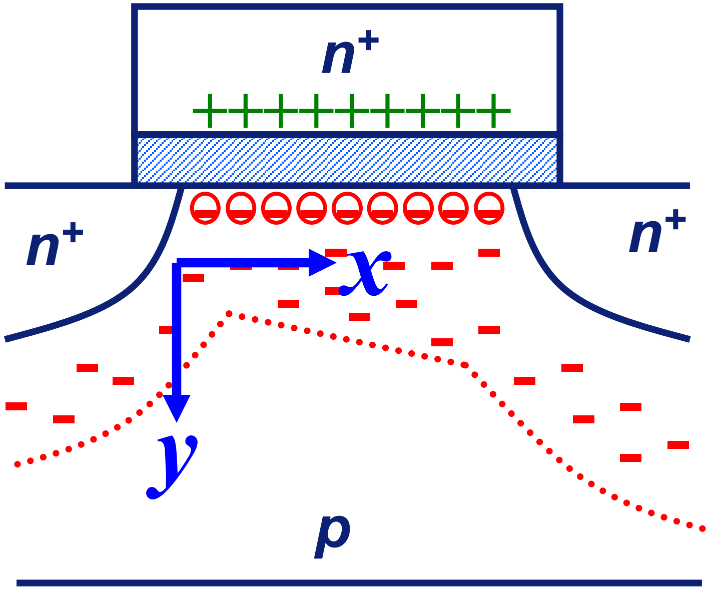
V_T-based models give inaccurate description of:

- moderate inversion
- drain/source symmetry
- accumulation

alternatives:

- ψ_s-based model
- Q_{inv}-based model

basis of MOSFET models: GCA



Poisson equation:

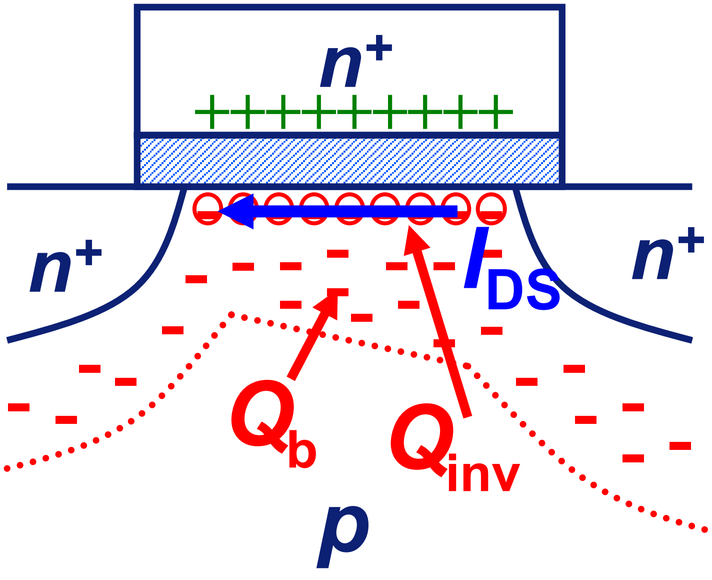
$$\frac{\partial^2 \psi}{\partial y^2} \approx -\frac{\rho}{\varepsilon_{Si}}$$

all MOS models based on Gradual Channel Approximation (GCA)

➡ equation in terms of surface potential ψ_s:

$$\left(\frac{V_{GB} - V_{FB} - \psi_s}{\gamma}\right)^2 = \psi_s + \varphi_T \cdot e^{\frac{-\varphi_B - V}{\varphi_T}} \cdot \left(e^{\frac{\psi_s}{\varphi_T}} - \frac{\psi_s}{\varphi_T} - 1\right) + \varphi_T \cdot \left(e^{-\frac{\psi_s}{\varphi_T}} - 1\right)$$

basis of MOSFET models: CSA



drain-source current:

$$I_{DS} = -\mu \cdot \frac{W}{L} \cdot \int_{V_{SB}}^{V_{DB}} Q_{inv} \cdot dV$$

Charge Sheet Approximation (CSA):

$$Q_{inv} = Q_{inv}(V_{GB}, \psi_s)$$

$$I_{DS} = I_{DS}(V_{GB}, \psi_{s0}, \psi_{sL})$$

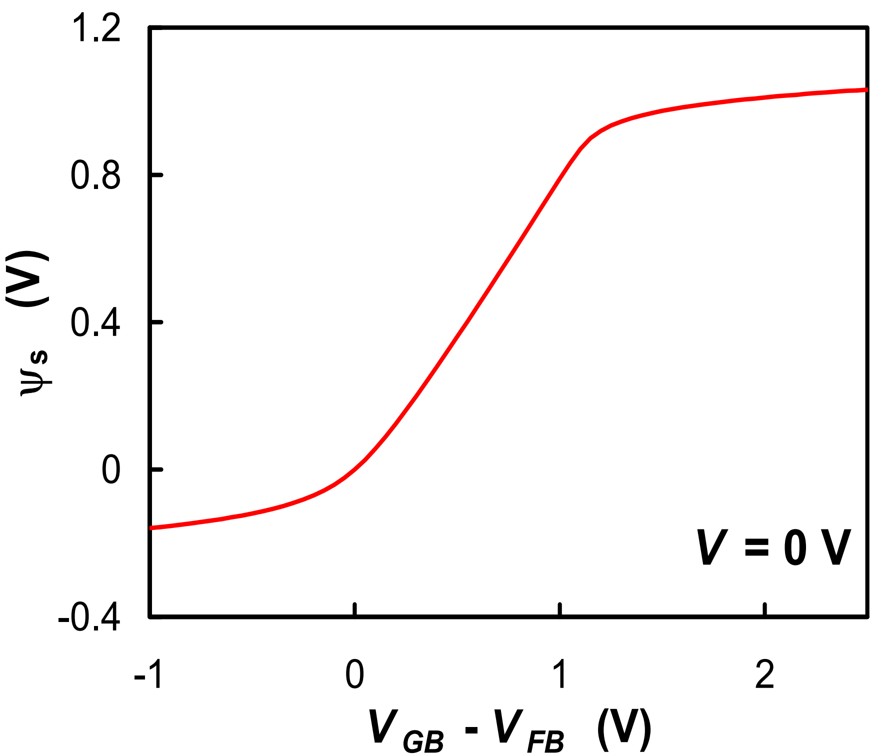
➡ **surface-potential-based models**

- **further simplification by linearizing Q_{inv} w.r.t. ψ_s (leads to simple and robust equations)**

surface-potential-based models

implicit equation for surface potential ψ_s (SPE):

$$\left(\frac{V_{GB}-V_{FB}-\psi_s}{\gamma}\right)^2=\psi_s+\varphi_T\cdot e^{\frac{-\varphi_B-V}{\varphi_T}}\cdot\left(e^{\frac{\psi_s}{\varphi_T}}-\frac{\psi_s}{\varphi_T}-1\right)+\varphi_T\cdot\left(e^{-\frac{\psi_s}{\varphi_T}}-1\right)$$



extremely efficient calculation of ψ_s:

- analytical approximation
- iterative solution

How to get to Q_{inv}-based models?

inversion-charge-based models: derivation

implicit equation for surface potential ψ_s (SPE):

$$\left(\frac{V_{GB}-V_{FB}-\psi_s}{\gamma}\right)^2=\psi_s+\varphi_T\cdot e^{\frac{-\varphi_B-V}{\varphi_T}}\cdot\left(e^{\frac{\psi_s}{\varphi_T}}-\frac{\psi_s}{\varphi_T}-1\right)+\varphi_T\cdot\left(e^{-\frac{\psi_s}{\varphi_T}}-1\right)$$

Q_{inv}–based models:

Q_{inv}-based models: derivation

implicit equation for surface potential ψ_s (SPE):

$$\left(\frac{V_{GB}-V_{FB}-\psi_s}{\gamma}\right)^2=\psi_s+\varphi_T\cdot e^{\frac{\psi_s-\varphi_B-V}{\varphi_T}}$$

Q_{inv}–based models:

- neglect accumulation

Q_{inv}-based models: derivation

implicit equation for surface potential ψ_s (SPE):

$$V_{GB} - V_{FB} - \varphi_B - V = -\frac{Q_{inv} + Q_b}{C_{ox}} + \varphi_T \cdot \ln\left[\frac{Q_{inv} \cdot (Q_{inv} + 2 \cdot Q_b)}{\gamma^2 \cdot C_{ox}^2 \cdot \varphi_T}\right]$$

Q_{inv}–based models:

- neglect accumulation
- rewrite to Q_{inv} and Q_b (using CSA)

Q_{inv}-based models: derivation

implicit relation for inversion charge Q_{inv} :

$$\frac{V_{GB} - V_{FB}}{n} - \varphi_B - V - n_1 \approx -\frac{Q_{inv}}{n \cdot C_{ox}} + \varphi_T \cdot \ln\left[\frac{-Q_{inv}}{n \cdot C_{ox} \cdot \varphi_T}\right]$$

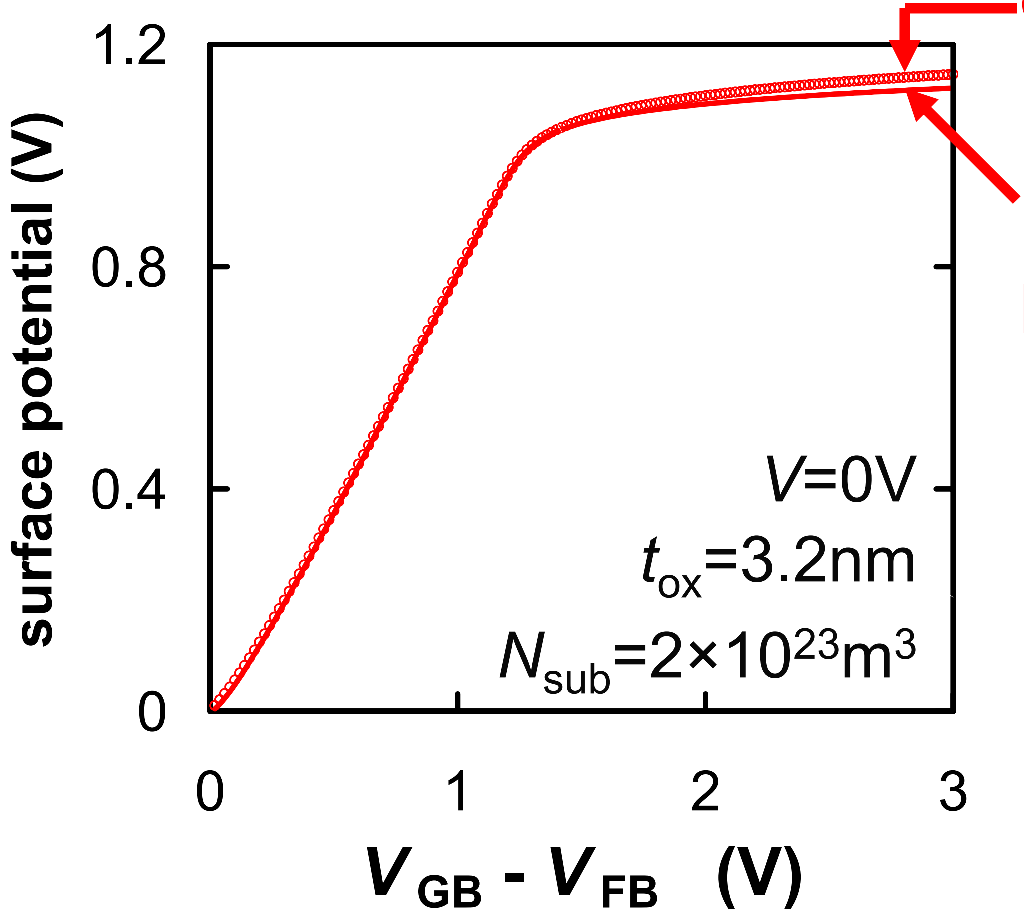
Q_{inv}–based models:

- neglect accumulation
- rewrite to Q_{inv} and Q_b (using CSA)
- linearize/approximate (use n and n_1: functions of V_{GB} and V)

simplifications at the expense of accuracy!

Q_{inv}-based models: calculation of ψ_s

surface potential calculated from Q_{inv}–based relation



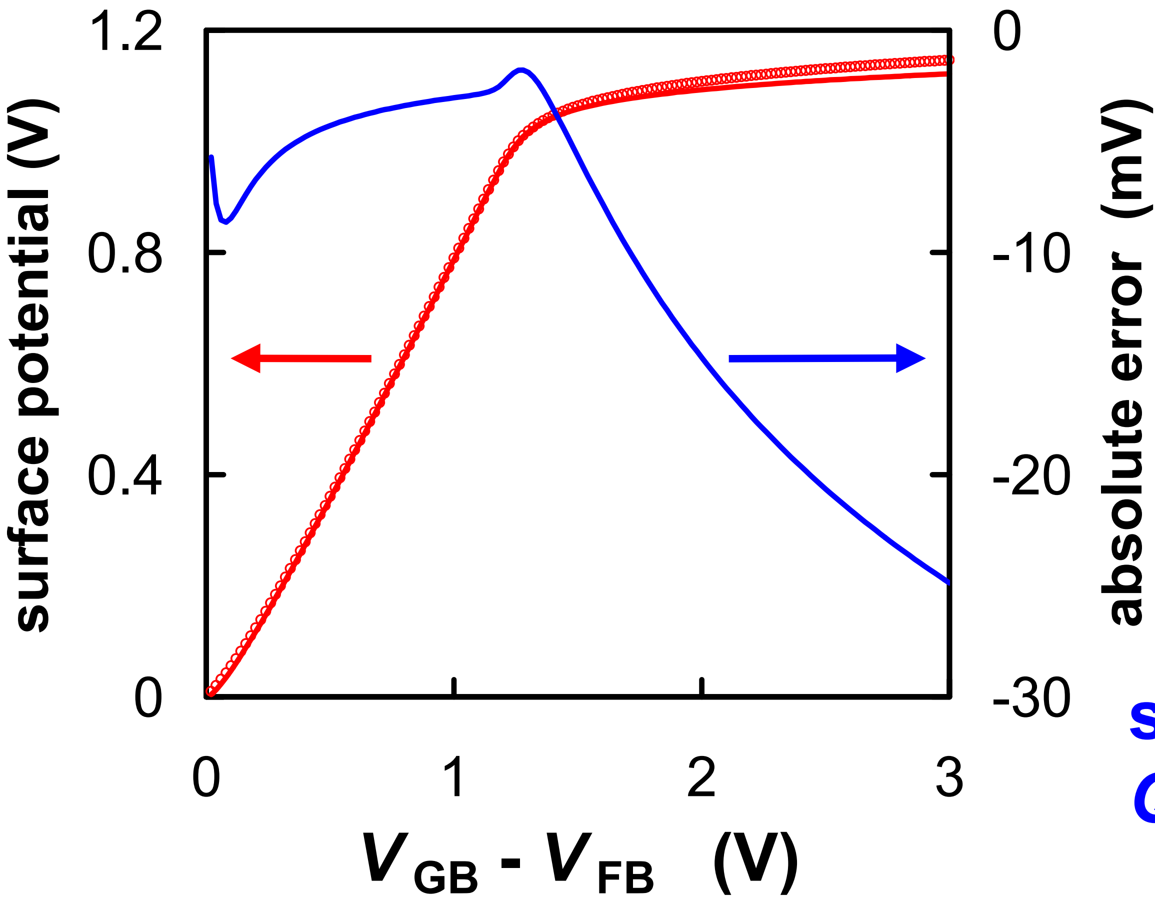
exact SPE solution

based on Q_{inv} approach

[J.M. Sallese *et al*., Solid-State Electron., V. 47, p. 677, 2003]

Q_{inv}-based models: calculation of ψ_s

surface potential calculated from Q_{inv}–based relation



significant error in Q_{inv}-based solution

Q_{inv}-based models: reduction to V_T-based model

implicit relation for inversion charge Q_{inv} :

$$\frac{V_{GB}-V_{FB}}{n}-\varphi_B-V-n_1\approx-\frac{Q_{inv}}{n\cdot C_{ox}}+\varphi_T\cdot\ln\left[\frac{-Q_{inv}}{n\cdot C_{ox}\cdot\varphi_T}\right]$$

Q_{inv}–based models:

- **neglect accumulation**
- **rewrite to Q_{inv} and Q_b (using CSA)**
- **linearize/approximate (use n and n_1)**

Q_{inv}-based models: reduction to V_T-based model

implicit relation for inversion charge Q_{inv} :

$$Q_{inv} = -n \cdot C_{ox} \cdot \varphi_T \cdot W\left[\frac{V_{GB} - V_{FB} - n \cdot (\varphi_B + V + n_1)}{n \cdot \varphi_T}\right]$$

Q_{inv}–based models:

- neglect accumulation
- rewrite to Q_{inv} and Q_b (using CSA)
- linearize/approximate (use n and n_1)
- Lambert W function W[x]: $w + \ln(w) = x$

Q_{inv}-based models: reduction to V_T-based model

implicit relation for inversion charge Q_{inv} :

$$Q_{inv} = -n \cdot C_{ox} \cdot \varphi_T \cdot W\left[\frac{V_{GB} - V_T - V}{n \cdot \varphi_T}\right]$$

Q_{inv}–based models:

- neglect accumulation
- rewrite to Q_{inv} and Q_b
- linearize/approximate
- Lambert W function $W(.)$
- insert threshold voltage V_T

Q_{inv}-based models: reduction to V_T-based model

explicit relation for inversion charge Q_{inv} :

$$Q_{inv} = -n \cdot C_{ox} \cdot \varphi_T \cdot \ln\left[1 + \exp\left(\frac{V_{GB} - V_T - V}{n \cdot \varphi_T}\right)\right]$$

Q_{inv}–based models:

- neglect accumulation
- rewrite to Q_{inv} and Q_b
- linearize/approximate
- Lambert W function $W(.)$
- insert threshold voltage V_T
- replace $W(.)$ by smoothing function

ψ_s-based versus Q_{inv}-based models

ψ_s-based model:

Poisson eq. + Gauss' law

↓ GCA

surface potential equation

↓ SCA (linearize Q_{inv})

terminal currents & charges

Q_{inv}-based model:

Poisson eq. + Gauss' law

↓ GCA

surface potential equation

↓ accumulation, SCA, linearize Q_{inv}, approximate

inversion charge equation

↓

terminal currents & charges

ψ_s-based versus Q_{inv}-based models

computational complexity:

ψ_s-based model: $(a - b \cdot x)^2 = x + c \cdot (e^x - x - 1) + e^{-x} - 1$

↕

Q_{inv}-based model: $a = x + \ln(x)$

Q_{inv}-based eq. looks simpler than ψ_s-based eq., however:

- Q_{inv}-based eq. is not sufficient, needs to be extended to accumulation region (increasing complexity)
- calculation time of ψ_s or Q_{inv} small fraction of total calculation time

conclusions

- Q_{inv}-based model is an approximation of ψ_s-based model
- drawbacks of Q_{inv}-based models:
  - less physical than ψ_s-based models
  - no accumulation included (varactor, overlap regions)
  - ψ_s is needed for gate current & charge

ψ_s-based model is best choice for a compact MOSFET model

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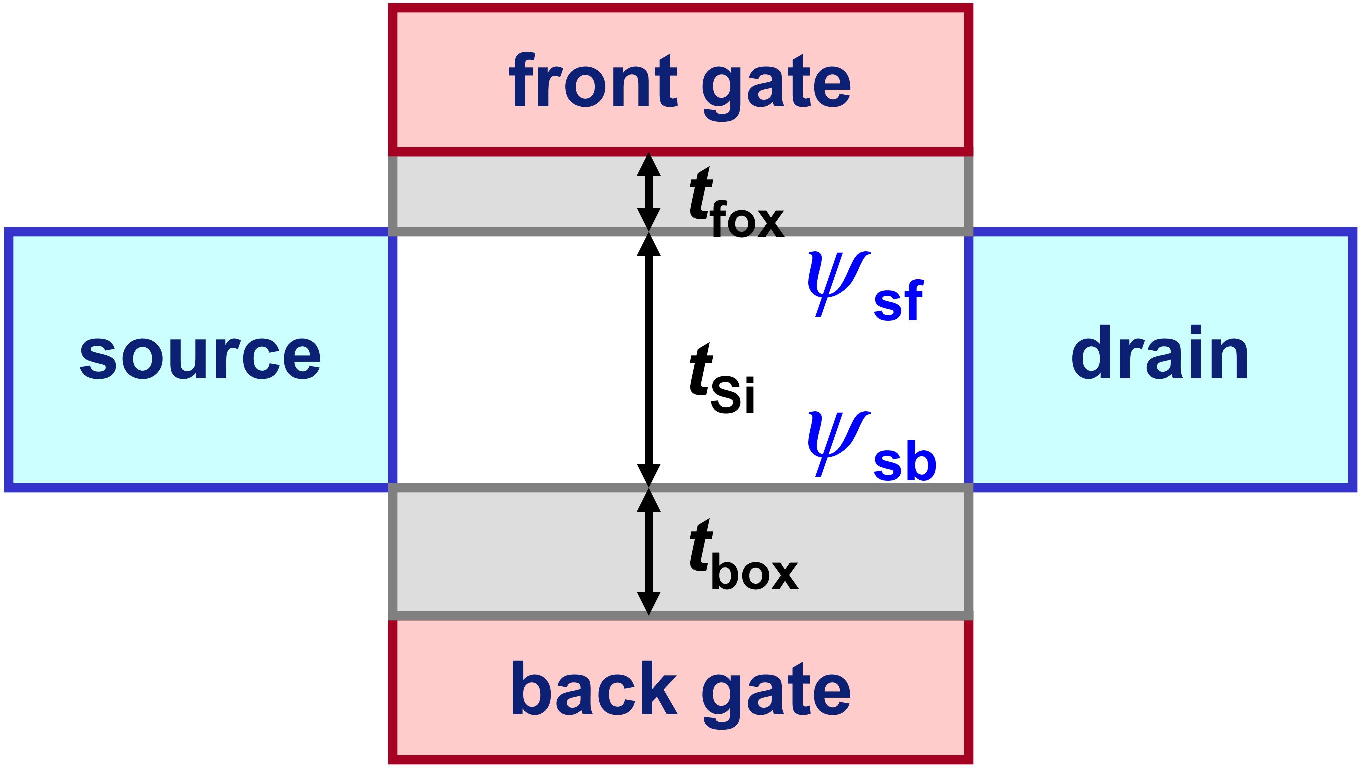
multiple-gate (MG) devices

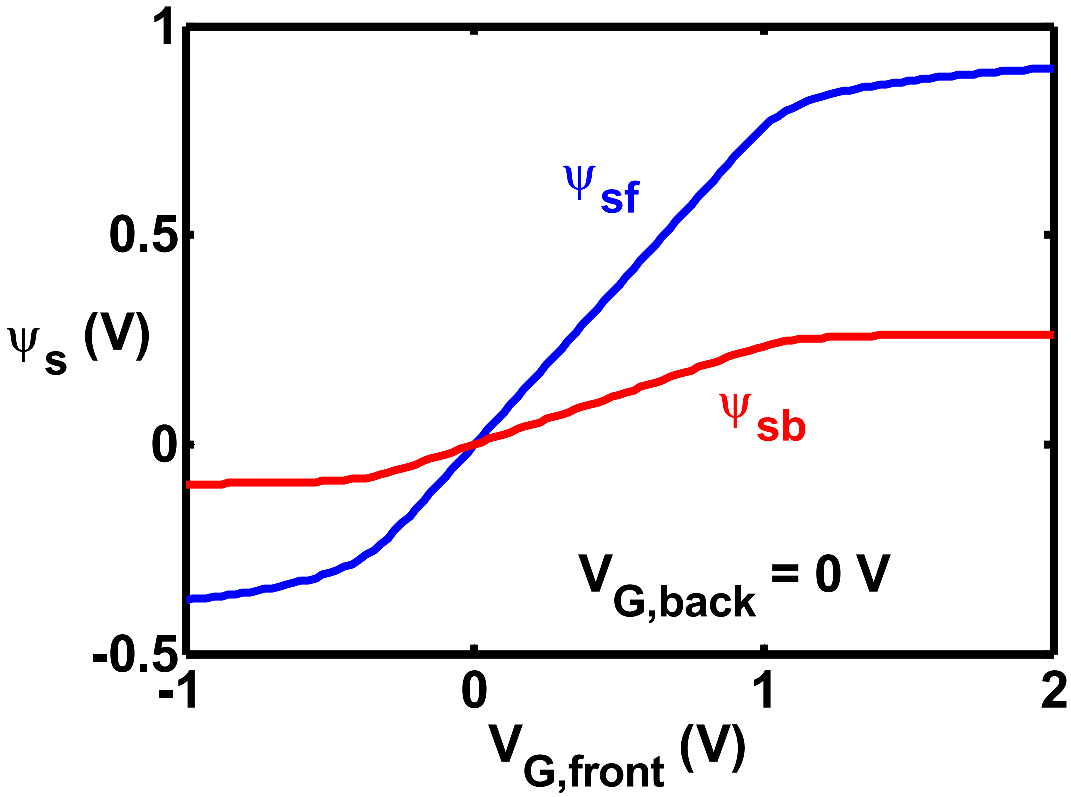
compact model for MG devices should be based on ψ_s

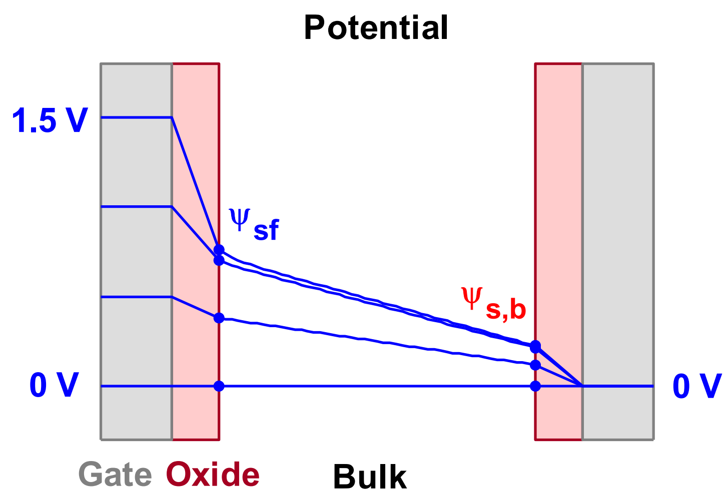


ψ_s-based model for double gate devices

MG devices: ψ_s-based model

surface potential is key to compact model





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