Compact Modeling of Threshold Voltage in Double-Gate MOSFET including quantum mechanical and short channel effects


*L2MP, UMR CNRS 6137, Marseille, France
** Also with Institut Universitaire de France (IUF)
*** STMicroelectronics, Central R&D, Crolles, France

www.l2mp.fr
munteanu@up.univ-mrs.fr
Introduction

✧ Double-Gate threshold voltage modeling:
   ➢ $V_T$ definition: usual criterion does not apply

✧ Existing models:
   ➢ Short channel and quantum effects usually neglected

✧ This work:
   ➢ **Compact $V_T$ model for symmetric Double-Gate** structures, taking into account short-channel effects, carrier quantization and temperature dependence of $V_T$

   ➢ Model fully validated by 2D quantum numerical simulation and used to predict the threshold voltage roll-off in Double-Gate MOSFET with very short channel lengths and thin films

   ➢ The model reproduces with an excellent accuracy the experimental data

   ➢ The model can be directly implemented in a circuit simulator code and used for the simulation of DG MOSFET based-circuits.
Double-Gate MOSFETs: 2D modeling

\[ \Psi(x, y) = \Psi_s(x) - \alpha t_{Si} y + \alpha y^2 \]
Threshold voltage model

- Conventional MOSFET: band bending is $2 \times \phi_F$
- Double-Gate MOSFET: $\psi_S \neq 2 \times \phi_F$

**Threshold voltage definition:**

$V_T = V_G$ obtained by numerically solving eq. $Q_{\text{inv}} = \frac{kT}{q} C_{\text{ox}}$

$$Q_{\text{inv}} = \frac{qkT}{\pi \hbar^2} \sum_{l,t} \sum_{i} m_{2Dl,i}^t \ln \left[ 1 + \exp \left( -\beta \left( E_{l,t}^i + \frac{E_g}{2} - \psi_S(x_m) \right) \right) \right]$$

$$E_{l,t}^i = \frac{\hbar^2 \pi^2 i^2}{2 q m_{l,t}^* t_{Si}^2} + \frac{\alpha t_{Si}^2}{6} \left[ 1 + \frac{3}{\pi^2 i^2} \right]$$

Quantum effects

$$\psi_S(x_m) = C_1 \exp(m_1 x_m) + C_2 \exp(-m_1 x_m) - \frac{R}{m_1^2}$$

Short-channel
Quantum effects

- Inversion charge

\[ Q_{\text{inv}} = \frac{qkT}{\pi \hbar^2} \sum_{l,t} \sum_i m_{1d} g_{l,t} \ln \left( 1 + \exp \left( -\beta \left( E_{l,t} + \frac{E_g}{2} - \psi_S(x_m) \right) \right) \right) \]

- Energy levels – infinite rectangular well

\[ E_{l,t} = \frac{\hbar^2 \pi^2 i^2}{2 q m_{l,t}^* t_{Si}^2} \]

- Energy levels – first order perturbation method

\[ \Delta E^i = \langle \phi^i | H | \phi^i \rangle \]

\[ H = -q(-\alpha_{Si} y + \alpha y^2) \]

\[ \Delta E^i = \frac{\alpha t_{Si}^2}{6} \left[ 1 + \frac{3}{\pi^2 i^2} \right] \]
Short-channel effects

- **Surface potential calculation**

\[
\frac{d^2\psi_s}{dx^2} - \frac{2\eta C_{ox}}{\varepsilon_{Si}t_{Si}} \psi_s = \frac{\eta}{\varepsilon_{Si}t_{Si}} \left[ qN_A t_{Si} - 2C_{ox} (V_{GS} - V_{FB} - \phi_F) \right]
\]

\[
\psi_s(x) = C_1 \exp(m_1 x) + C_2 \exp(-m_1 x) - \frac{R}{m_1^2}
\]

- **Location of potential minimum**

(point which determines the \( V_T \))

\[
x_m = \frac{1}{2m_1} \ln \left( \frac{C_2}{C_1} \right)
\]

\[
C_{1,2} = \pm \frac{\phi_S [1 - \exp(\mp m_1 L)] + V_D + \frac{R[1 - \exp(\mp m_1 L)]}{m_1^2}}{2 \sinh(m_1 L)}
\]

\[
R = \frac{\eta}{\varepsilon_{Si}t_{Si}} \left[ qN_A t_{Si} - 2C_{ox} (V_G - V_{FB} - \phi_F) \right] \quad m_1 = \sqrt{\frac{2\eta C_{ox}}{\varepsilon_{Si}t_{Si}}}
\]
Results and model validation

$V_T$ predicted by the quantum short-channel model in excellent agreement with full 2-D QM numerical simulation data (BALMOS code*)

$V_T$ predicted by the quantum short-channel model reproduces very well the experimental data (different film thicknesses and channel lengths)