Physics-based compact model for ultimate FinFETs

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Outline

1. Introduction
2. Short-channel effects modeling
3. Mobility modeling
4. Quantum mechanical effect modeling
5. Transcapacitance modeling
6. Doped DG MOSFET modeling
FinFET transistor

- One of the best candidates to extend the CMOS technology.

- Needs of designers for advanced circuit simulation:
  (COMON European project)
  • a physics-based FinFET compact model
  • a parameter extraction methodology

L: channel length

$W_{Si}$: silicon width

$H_{Si}$: silicon height

t$_{ox}$: oxide thickness
Physics-based FinFET compact model

✓ Physics-based long-channel DG MOSFET model [1]
  • Extension of the undoped model to high doping [2]

✓ Model accounts for small-geometry effects [3]:
  • Short-channel effects (SCE), drain-induced barrier lowering (DIBL)
  • Subthreshold swing degradation
  • Drain saturation voltage and channel length modulation (CLM)
  • Mobility degradation
  • Quantum mechanical effects (QME)

✓ Transcapacitance modeling for small-geometry [3]


Range of validity

- Gate length \((L)\) : down to 25 nm
- Silicon width \((W_{Si})\) : down to 3 nm
- Silicon height \((H_{Si})\) : down to 50 nm
- Gate oxide thickness \((t_{ox})\) : 1.5 nm
- Top oxide thickness \((t_{top})\) : 50 nm
- Channel doping \((N_{ch})\) : intrinsic to \(10^{17} \text{ cm}^{-3}\) and high doping*
- Source/Drain doping \((N_{sd})\) : \(5 \times 10^{21} \text{ cm}^{-3}\)

*: only for long channel devices
Normalized charge-potentials relationship:

\[ v_p - v_{ch} = 4q_g + \ln q_g + \ln\left(1 + \alpha q_g\right) \]

with \( \alpha = \frac{C_{ox}}{C_{Si}} \)

\[ q_g = f(v_p - v_{ch}) \] \[ \text{[2]} \]

Normalized drain current:

\[ i = -q_m^2 + 2q_m + \frac{2}{\alpha} \ln\left(1 - \frac{\alpha}{2} q_m\right) \bigg|_{q_{mS}}^{q_{mD}} \]

with \( q_m = -2q_g \)


Study of the minimum surface potential

Cross-section of FinFET

Study in:
- classic physics
- weak inversion
Correction of the gate voltage:

\[ v_{gN} = v_g + \Delta \psi_{Smin} \]

Drain current model:

\[ i = -q_m (v_{gN})^2 + 2q_m (v_{gN}) + \frac{2}{\alpha} \ln \left( 1 - \frac{\alpha}{2} q_m (v_{gN}) \right) \left. \frac{q_{mD}}{q_{mS}} \right|_{\text{source}} \]

Potential Expression in the channel in the subthreshold region [1]:

$$\psi_S(x) = \nu_g + \Delta \psi_S(x)$$

valid for \( L > 1.5 \lambda (W_{Si}) \)

- General scaling length

- In weak inversion:
  - in the long-channel case, \( \Delta \psi_{Smin} = 0 \)
  - in the short-channel case, \( \Delta \psi_{Smin} > 0 \)

- In strong inversion, \( \Delta \psi_{Smin} \) analytical expression is negligible w.r.t \( \nu_g \),

⇒ No need of smoothing function between weak and strong inversion.

Mobility model \[1\]

- Total mobility model and channel length modulation model taken from \[2\]

- Transversal mobility:

\[
\mu_{\perp} = \frac{\mu_0}{1 + \frac{E_{\perp WI}}{e_0} + \frac{E_{\perp SI}}{e_1} + \frac{E_{\perp SI}^2}{e_2}}
\]

Term of mobility degradation for the short channels in weak inversion

Terms of mobility degradation in strong inversion

- \(\mu_0\): long-channel low field mobility
- \(E_{\perp WI}\): transversal electric field in weak inversion
- \(E_{\perp SI}\): transversal electric field in high inversion
- \(e_0\): normalizing factor \((= 1 \text{ V.nm}^{-1})\)
- \(e_1, e_2\): parameters to be extracted


Quantum mechanical effects \[1\] (1/3)

Principle of the quantum mechanical effects modeling

Quantum shift of the first energy level:

\[
\Delta E_0^{QM} = \Delta E_{Str}^{QM} + \Delta E_{Elec}^{QM}
\]

Quantum mechanical effects (2/3)

Modeling of the quantum shift as a correction to surface potential:

Inclusion of the term of **structural confinement** in the charge-potential relationship

\[ v_{gN}^{QM} = v_{gN} - \Delta \psi_{Str}^{QM} \quad \text{with} \quad \Delta \psi_{Str}^{QM} = \frac{\Delta E_{Str}^{QM}}{q \cdot U_T} \]

Inclusion of the term of **electrical confinement** in the charge-potential relationship

\[ \Delta \psi_{Elec}^{QM} = \frac{\Delta E_{Elec}^{QM}}{q \cdot U_T} = A^{QM} \cdot q^{2/3} \quad \text{with} \quad A^{QM} = \frac{3}{2} \cdot \left( \frac{\bar{h} \cdot C_{ox}}{(q \cdot m_x \cdot U_T)^{1/2} \cdot \varepsilon_{Si}} \right)^{2/3} \]

\[ q \quad : \text{elementary electronic charge} \]
\[ U_T \quad : \text{thermal voltage} \]
\[ m_x \quad : \text{effective mass of electrons in the channel length direction} \]
Quantum mechanical effects (3/3)

New charge-potentials relationship:

\[ v_{gN}^{QM} - v_{to} - v_{ch} = 4 \cdot q_g + \ln q_g + \ln(1 + \alpha \cdot q_g) + A_{QM} \cdot q_m^{2/3} \]

Normalized drain current expression:

\[ i = -q_m^2 + 2 \cdot q_m + \frac{2}{\alpha} \cdot \ln \left( 1 - \frac{\alpha}{2} \cdot q_m \right) + \frac{2}{5} \cdot A_{QM} \cdot q_m^{5/3} \]

Addition of a term in the drain current expression by taking into account the QMEs.
Results of the static model

Id(Vg) current curves

Id(Vd) current curves

Symbols: Quantum 3D simulations with CVT mobility model

Lines: Compact model
Transcapacitance modeling \[1\]

Transcapacitance definitions:

\[ C_{ij} = \pm \frac{\partial Q_i}{\partial V_j} \text{ where } i,j = D, G, S \]

Normalized total charge calculation according to the channel charge partition proposed by Ward

\[ q_G = -H_{Si} \cdot \int_0^L q_m dx \quad q_D = H_{Si} \cdot \int_0^L q_m \cdot \frac{x}{L} dx \quad q_S = -q_G - q_D \]

Charge-based expressions for the transcapacitances

Transcapacitance modeling \[1\]

Modeling of the **structural confinement** by $\Delta \psi_{Str}^{QM}$ in the calculation of the charge density $q_m(v_{gN}^{QM})$.

Modeling of the **electrical confinement** by $\Delta \psi_{Elec}^{QM}$ approximated according to a taylor series,

\[
\Delta \psi_{EC}^{QM} = A^{QM} \cdot q_m^{2/3} \approx A^{QM} \cdot q_{mo}^{2/3} + A^{QM} \cdot \frac{2}{3} \cdot q_{mo}^{-1/3} \cdot q_m
\]

within a new definition of the gate oxide capacitance $C_{ox}^*$

\[
C_{ox}^* = \frac{C_{ox}}{1 + A^{QM} \cdot \frac{2}{3} \cdot q_{mo}^{-1/3}}
\]

Results of the dynamic model

Cgg(Vg) of long channel

Symbols: Quantum 3D simulations with constant mobility
Lines: Compact model

Cgg(Vg) of short channel
Doped DG MOSFET model \[1\]

The equivalent-thickness concept

Including the doping $N_a$ in the Poisson’s equation,

$$\frac{d^2 \psi}{dx^2} = \frac{q}{\varepsilon_{Si}} \cdot \left( n_i \cdot e \frac{\psi - V}{U_T} + N_a \right)$$

we obtain a similar model than the one for the undoped DG MOSFET \[2\].

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Doped DG MOSFET model [1]

The equivalent-thickness concept

Charge-potentials relationship

\[ v_g - v_{ch} - v_{to\_doped} = 4q_g + \ln q_g + \ln \left(1 + q_g \frac{C_{ox}}{C_{eq}}\right) \]

with \( v_{to\_doped} = 2 \cdot q_{depl} - \ln \left(\frac{q_{int\_eq}}{2}\right) \) and \( C_{eq} = \frac{T_{eq}}{\varepsilon_{Si}} \)

where \( q_{depl} = \frac{q \cdot N_a \cdot T_{Si}}{4 \cdot C_{ox} \cdot U_T} \) and \( q_{int\_eq} = \frac{q \cdot n_i \cdot T_{eq}}{4 \cdot C_{ox} \cdot U_T} \)

\( T_{Si} \): real thickness \hspace{1cm} \( T_{eq} \): equivalent thickness

Doped DG MOSFET results

Exact analytical relationship between the equivalent thickness and the doping:

\[
\frac{1}{T_{eq} \over 2} = \frac{1}{\int_{-T_{Si}/2}^{0} e^{\frac{T_{Si}}{\varepsilon_{Si} U_T} x} x^2 \, dx} + \frac{X}{\varepsilon_{Si} U_T}
\]

with

\[
X = \frac{q \cdot N_a \cdot T_{Si}}{2}
\]

Equivalent thickness \( T_{eq} \)

Mobile charge density

- Equivalent silicon thickness (nm)
  - \( T_{Si} = 40 \text{ nm} \)
  - 40 nm
  - 35 nm
  - 30 nm
  - 25 nm
  - 20 nm
  - 15 nm
  - 10 nm
  - 5 nm
  - 0 nm

- Silicon doping (cm\(^{-3}\))
  - \( 10^{15} \)
  - \( 10^{16} \)
  - \( 10^{17} \)
  - \( 10^{18} \)

- Mobile charge density (abs. val.) (C/m\(^2\))
  - \( T_{Si} = 20 \text{ nm} \)
  - \( 10^{17} \)
  - \( 10^{18} \)
  - \( 10^{19} \)

- Gate Voltage (V)
  - 0
  - 1
  - 1.5
  - 2
Doped DG MOSFET results

Normalized drain current

\[ i = -q_m^2 + 2 \cdot q_m + 2 \cdot \frac{C_{ox}}{C_{eq}} \ln \left( 1 - q_m \cdot \frac{C_{ox}}{2 \cdot C_{eq}} \right) \]

Drain current versus gate voltage

![Graph showing drain current versus gate voltage for different gate voltages and a fixed channel length.](image)
### Electrical parameter number of the model

<table>
<thead>
<tr>
<th>Effect</th>
<th>Previous model [1,2]</th>
<th>Present model [3]</th>
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<tbody>
<tr>
<td>Roll-off (SCE), DIBL</td>
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<td>Subthreshold Slope (SS)</td>
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Conclusion

Included effects

- SCE & DIBL
- Sub-threshold Slope degradation
- Drain saturation voltage
- Channel length modulation (CLM)
- Mobility degradation
- Quantum mechanical effects
- Extrinsic capacitances

Validity range

- $I_D(V_{GS})$ & $I_D(V_{DS})$, small-signal parameters ($g_m$, $g_{ds}$, ...)
- $L \geq 25$nm
- $W_{Si} \geq 3$ nm
- $H_{Si}= 50$nm
- $t_{ox}= 1.5$nm

Perspectives

- Physic-based modeling of the temperature dependence
- 3D modeling: consideration of the triple-gate FinFET
- Extension of the doped model to short-channel devices
- Parameter extraction methodology associated with an automated extraction procedure
Thank You!

Major publications:

