Junctionless Nanowire Transistors Performance: Static and Dynamic Modeling

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Outline

Introduction & Motivation

The Junctionless Nanowire Transistor

Compact Modeling

Static Drain Current Model
Dynamic Model

Conclusion
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Conclusion
Moore’s Law: The number of devices per chip double each two years
Reduction on cost/function
Performance improvement

Cost / function

Scaling

Performance

ArF + RET
ArF immersion
NiSi
SiGe
Ge/IIIV
USJ
silicide
FUSI
HfO₂
high-k
Poly
metal gate
Ni
metal gate
FinFET
EUVL

Courtesy of Prof. Cor Claeyss
Evolution of Transistors

“1 Gate”

“2 Gates”

“3 Gates”

“Gate-all-Around”

Gate
Source
Drain
Buried oxide

Gate
Source
Drain

Gate
Source
Drain
Buried oxide

Polysilicon Gate
Silicon Fin

Buried Oxide

20 nm

Courtesy Dr. Jean-Pierre Colinge
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  Static Drain Current Model
  Dynamic Model

Conclusion
Introduction & Motivation

• The Junctionless Nanowire Transistor (JNT)
  ▸ Developed in 2009 by J.P. Colinge et al.[1].
  ▸ Absence of doping gradients;
  ▸ Avoids impurity diffusion into the channel region;
  ▸ Presents doping concentration in the order of $10^{19}$ cm$^{-3}$;

Introduction

• The Junctionless Nanowire Transistor

With respect to inversion mode devices:

Advantages

➢ Reduced electric field;
➢ Smaller mobility degradation;
➢ Better analog properties;
➢ Better DIBL;
➢ Reduced low frequency noise.

Drawbacks

➢ Strong dependence of $V_{TH}$ on the fin dimensions;
➢ Higher Series Resistance;
➢ Smaller low field mobility.
Junctionless nanowire transistor - (3 parallel nanowires)

Courtesy Dr. Jean-Pierre Colinge
Performance Comparison: Inversion-Mode and Junctionless nanowire transistors

- Common parameters in JNT and IM:
  - $\text{EOT}=1.3 \text{ nm}$
  - $t_{\text{Si}} = 10 \text{ nm}$
  - $W_{\text{fin}} > 10 \text{ nm}$
  - $L = \text{down to 10 nm}$

- JNT Characteristics:
  - $N_D = 1.10^{19} \text{ cm}^{-3}$

- IM Characteristics:
  - $N_A = 1.10^{15} \text{ cm}^{-3}$
Comparison between IM and Junctionless nanowire transistors of similar dimensions

**Drain current vs. \( V_{GT} \) - \( L \) down to 10 nm**

- **Junctionless Transistors**
  - Experimental Data
  - \( L = 100 \text{ nm} \)
  - \( L = 30 \text{ nm} \)
  - \( L = 10 \text{ nm} \)

- **Nanowire Transistors**
  - \( H_{\text{fin}} = 10 \text{ nm} \)
  - \( W_{\text{fin}} = 10 \text{ nm} \)
  - \( V_{DS} = 50 \text{ mV} \)

R. T. Doria *et al.*, IEEE S3S Conference, 2017

- Better Subthreshold Swing
- Higher \( I_{DS} \)
Comparison between IM and Junctionless nanowire transistors of similar dimensions

$V_{TH}$ and Subthreshold Swing (SS) vs. $L$

Junctionless Transistors

- $V_{TH}$ [V]
- SS [mV/dec]

Nanowire Transistors

- $V_{TH}$ [V]
- SS [mV/dec]

- $W_{fin} = 10$ nm
- $V_{DS} = 50$ mV

R. T. Doria et al., IEEE S3S Conference, 2017
Comparison between IM and Junctionless nanowire transistors of similar dimensions

Drain Induced Barrier Lowering (DIBL) vs. \( L \)

\[
\begin{align*}
V_{DS1} &= 50 \text{ mV} \\
V_{DS2} &= 1.0 \text{ V}
\end{align*}
\]

R. T. Doria \textit{et al.}, IEEE S3S Conference, 2017
Comparison between IM and Junctionless nanowire transistors of similar dimensions

**$I_{ON}$ and $I_{OFF}$ vs. $L$**

- Smaller $I_{ON}$
- Lower carrier mobility
- Smaller $I_{OFF}$
- Better electrostatic control
- Longer $L$ in subthreshold

$V_{DS} = 1$ V
$W_{fin} = 10$ nm
$H_{fin} = 10$ nm

$V_{GS} - V_{TH} = 0.5$ V

$V_{GS} - V_{TH} = -0.3$ V

R. T. Doria *et al.*, IEEE S3S Conference, 2017
Comparison between IM and Junctionless nanowire transistors of similar dimensions

**Comparison between ON/OFF current densities**

- **Larger** $I_{ON}/I_{OFF}$ at all $L$
- **Smaller** $I_{OFF}$

**Graph Details**
- $W_{fin} = 10$ nm
- $H_{fin} = 10$ nm
- Open Symbols - NWs
- Closed Symbols - JNTs
- $V_{DS} = 50$ mV
- $V_{DS} = 1$ V

**Reference**
R. T. Doria et al., IEEE S3S Conference, 2017
Comparison between IM and Junctionless nanowire transistors of similar dimensions

$g_{m\text{max}}$ and $R_S$ vs. $L$

Smaller $g_{m\text{max}}$ at all $L$

Lower carrier mobility

Larger $R_S$

Not optimized S/D extensions

$W_{\text{fin}} = 10 \text{ nm}$

$V_{DS} = 50 \text{ mV}$

R. T. Doria et al., IEEE S3S Conference, 2017
Comparison between IM and Junctionless nanowire transistors of similar dimensions

$I_{ON}, I_{OFF}$ and $I_{ON}/I_{OFF}$ vs. $W_{Fin}$

- Smaller $I_{ON}$
- Lower carrier mobility
- Smaller $I_{OFF}$
- Better electrostatic control
- Longer $L$ in subthreshold
- Larger $I_{ON}/I_{OFF}$ at all $W_{Fin}$

R. T. Doria et al., IEEE S3S Conference, 2017
Comparison between IM and Junctionless nanowire transistors of similar dimensions

SS and DIBL vs. $W_{\text{Fin}}$

Better Subthreshold Swing at all $W_{\text{Fin}}$

Better DIBL for $W_{\text{fin}}<60$ nm

R. T. Doria et al., IEEE S3S Conference, 2017
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Long Channel Drain Current Model

 Bulk conduction

- **2D Poisson equation** (considering only the depletion charge):

\[
\frac{d^2 \Phi}{dx^2} + \frac{d^2 \Phi}{dz^2} = -\frac{q N_D}{\varepsilon_{Si}}
\]

- Using the approximation:

\[
\frac{d \Phi}{dx} = \frac{d \Phi}{dz} \quad 2d \left(\frac{d \Phi}{dx}\right)^2 = -2 \frac{q N_D}{\varepsilon_{Si}} d \Phi
\]

and considering the **center potential as zero** at the source side

Poisson equation can be integrated, leading to:

\[
E_{S, depl} = \sqrt{q N_D \Phi_{S, depl} / \varepsilon_{Si}}
\]

Long Channel Drain Current Model

- **Approximation:**
  \[ \frac{d\Phi}{dx} = \frac{d\Phi}{dz} \]

**Potential [V]**

- \( \Phi(Z)_{x=0} \)
- \( \Phi(X)_{z=0} \)
- \( \Phi_{Right \ surface} = -0.11 \) V
- \( \Phi_{Top \ surface} = -0.12 \) V
- \( \Phi_{Left \ surface} = -0.11 \) V

**Electric field [x10^5 V/cm]**

- \( E_{Right \ surface} = 4.16 \times 10^5 \) V/cm
- \( E_{Top \ surface} = 4.04 \times 10^5 \) V/cm
- \( E_{Left \ surface} = 4.16 \times 10^5 \) V/cm
Long Channel Drain Current Model

**Bulk conduction**

- Relation between depletion charge and electric field:

\[ Q_{Depl} = \varepsilon_{Si} \ E_S (2H_{Fin} + W_{Fin}) \]

\[ E_S = \sqrt{qN_D \ \Phi_{S,depl} / \varepsilon_{Si}} \]

\[ \Phi_{S,depl} = V_G - V_{FB} - \frac{\alpha}{2C_{ox}} + \sqrt{\left(\frac{\alpha}{2C_{ox}}\right)^2 - \frac{\alpha}{C_{ox}} (V_G - V_{FB})} \]

**MOS capacitor:**

\[ (\Phi_{S,depl} + V_G - V_{FB})C_{ox} = Q_{Depl} \]

\[ \alpha = \varepsilon_{Si} q N_D (2H_{Fin} + W_{Fin})^2 \]
Long Channel Drain Current Model

Accumulation conduction

- **2D Poisson equation:**

\[
\frac{d^2 \Phi}{dx^2} + \frac{d^2 \Phi}{dz^2} = q \frac{N_D}{\varepsilon_{Si}} e^{\Phi/\Phi_t}
\]

Poisson equation can be integrated, leading to:

\[
E_{S,acc} = \sqrt{qN_D} \Phi_t \left( \exp(\Phi_{S,acc}/\Phi_t) - 1 \right) / \varepsilon_{Si}
\]

\[
\Phi_{S,acc} = \Phi_t \ln \left[ 1 + \frac{(V_G - V_{FB} - \Phi_{S,acc})^2}{\alpha \Phi_t} \frac{C_{ox}}{2} \right]
\]

An exact solution for \( \Phi_{S,acc} \) can be obtained by the use of the Lambert function. However, in order to obtain a simplified solution, as \( \Phi_{S,acc} \) values a few \( \Phi_t \) in strong accumulation, \( \Phi_{S,acc} \) can be neglected for \( V_G >> V_{FB} \) inside the logarithm term.
Long Channel Drain Current Model

- Transition between bulk and accumulation conduction

  to have a continuous transition between both conduction regimes (bulk conduction and both accumulation layer and bulk conductions), a smooth function has been used to $V_G$[24]:

$$V_{G2} = V_{FB} \left[1 - \frac{\ln[1 - \exp(A_1 (1 - (V_G - V_y)/V_{FB}))]}{\ln(1 + \exp(A_1))}\right]$$

where $A_1$ controls the smoothness and has been set to 12 and $V_y$ is the voltage at the point $y$ of the channel, i.e. $V_y = 0$ at source and $V_y = V_D$ at drain for the calculation of the source and drain surface potentials, respectively.

This equation is used to limit the maximum gate voltage in $V_{FB}$. This function is used inside the square root term of $\Phi_{s,depl}$ instead of $V_G$, so that the depletion charge smoothly tends to zero at the flatband condition.
Long Channel Drain Current Model

- Transition between subthreshold and above threshold regimes

This equation limits the minimum gate voltage in the threshold voltage, such that the conduction charge reduces exponentially.

\[
V_{G3} = V_T \left[ 1 + \frac{\ln[-1 + \exp(A_2 (1 - V_{G2}/V_T))]}{\ln(1 + \exp(A_2))} \right]
\]

where \( A_2 \) is related to the subthreshold slope, calculated as \( A_2 = V_T/(2.n.\phi_t) \), where \( n \) is the body factor which is close to the unity for these devices.
Long Channel Drain Current Model

- General solution

\[
\Phi_S = \Phi_{S,\text{depl}} + \Phi_{S,\text{acc}}
\]

\[
\Phi_{S,\text{depl}} = V_{G2} - V_{FB} + V_y - \frac{\alpha}{2C_{ox}^2} + \sqrt{\left(\frac{\alpha}{2C_{ox}^2}\right)^2 - \frac{\alpha}{C_{ox}^2}(V_{G3} - V_{FB})}
\]

\[
\Phi_{S,\text{acc}} = \phi_t \ln \left[ 1 + \frac{(V_G - V_{G2})^2 C_{ox}^2}{\frac{\alpha \phi_t}{\alpha \phi_t}} \right]
\]
Long Channel Drain Current Model

- The drain current can be obtained by:

\[ I_D = \mu_n Q_n \frac{dV_y}{dy} \]

\[ I_D = \frac{\mu_n}{L} \left[ \frac{(Q_{n,S}^2 - Q_{n,D}^2)}{2C_{ox}} \right] \]

\[ Q_n = Q_f + Q = qN_DWH - (V_{FB} - V_G + \Phi_S)C_{ox} \]
Long Channel Drain Current Model

**Saturation voltage**

\[ I_{D_{\text{sat}}} = Q_{\text{sat}} v_{\text{sat}} \]

The drain current \( I_{D_{\text{sat}}} \) is obtained by considering \( Q_{n,D} = Q_{\text{sat}} \). Therefore, \( Q_{\text{sat}} \) can be isolated, reaching:

\[
Q_{\text{sat}} = -v_{\text{sat}} \frac{L C_{\text{ox}}}{\mu_{n}} + \sqrt{v_{\text{sat}}^2 \left( \frac{L C_{\text{ox}}}{\mu_{n}} \right)^2 + Q_{n,S}^2}
\]

\[
V_{D_{\text{sat}}} = \alpha \left[ \left( -\frac{Q_{\text{sat}}}{2\alpha} + \frac{Q_{f}}{2\alpha} + \frac{1}{C_{\text{ox}}} \right)^2 - \left( \frac{1}{C_{\text{ox}}} \right)^2 \right] - V_{FB} + V_{G}
\]

\[
V_{D} = V_{D_{\text{sat}}} \left[ 1 - \ln[1 + \exp(A_{3}(1 - V_{D} / V_{D_{\text{sat}}}))] \right] / \ln(1 + \exp(A_{3}))
\]
Long Channel Drain Current Model

• Three-dimensional simulations were performed in Sentaurus
  ▪ channel length = 1 μm
  ▪ N+ polysilicon gate
    ▪ $t_{Si} = 10$ nm
  ▪ $N_D = 1 \times 10^{19}$ cm$^{-3}$
    ▪ $t_{ox} = 2$ nm
  ▪ $W = 10$ nm

• Device characteristics

• Low Field Mobility was considered as 100 cm$^2$/V.s
Long Channel Drain Current Model

N_D = 1 \times 10^{19} \text{ cm}^{-3}
H = 10 \text{ nm}
W = 10 \text{ nm}
t_{\text{ox}} = 2 \text{ nm}
L = 1 \mu\text{m}

Surface potential at drain for V_D = 0.1, 0.2 and 0.5V > V_D

Good Agreement between simulated and modeled data for various V_{DS}
Good Agreement between simulated and modeled data for various V_{DS}
Long Channel Drain Current Model

- Comparison of the curves $I_D \times V_G$ and $g_m \times V_G$:

\[ V_D = -0.05, -0.1, -0.2, -0.5 \text{ and } -1 \text{ V} \]

- $I_D$ and $g_m$ are correctly predicted by the model in both subthreshold and above threshold regions.

\[ L = 1 \mu m \]
\[ W = H = 10 \text{ nm} \]
\[ t_{ox} = 2 \text{ nm} \]
\[ N_A = 1 \times 10^{19} \text{ cm}^{-3} \]
Long Channel Drain Current Model

- Comparison of the curves $I_D \times V_D$ and $g_D \times V_D$:

![Graph A](image1)

![Graph B](image2)

- The dependence on $V_D$ is also adequately modeled.
Short Channel Effects

- To obtain an analytical expression for SCE, the 3D Poisson equation must be solved:

\[
\frac{d^2 \Phi}{dx^2} + \frac{d^2 \Phi}{dz^2} + \frac{d^2 \Phi}{dy^2} = \frac{q N_A}{\varepsilon_{Si}}
\]

- Using the superposition principle, the solution of the 2D Poisson equation can be added to the solution of the 3D Laplace equation for the minimum potential:

\[
\frac{d^2 \Phi}{dx^2} + \frac{d^2 \Phi}{dz^2} + \frac{d^2 \Phi}{dy^2} = 0
\]

which is given by:

\[
\Phi_{\text{min}} = \frac{V \sinh(y_{\text{min}}/\lambda) + U \sinh((L - y_{\text{min}})/\lambda)}{\sinh(L/\lambda)}
\]

\(y_{\text{min}}\) is point of the minimum potential given by:

\[
y_{\text{min}} = \frac{\lambda}{2} \ln \left[ \frac{U \exp(L/\lambda) - V}{V - U \exp(-L/\lambda)} \right]
\]

\(\lambda\) is the characteristic length
Short Channel Effects

- The minimum potential in the channel is obtained by:

\[
\Phi_{\text{min}} = \frac{V \sinh (\frac{y_{\text{min}}}{\lambda}) + U \sinh (\frac{L - y_{\text{min}}}{\lambda})}{\sinh (L/\lambda)}
\]

where:

\[
y_{\text{min}} = \frac{\lambda}{2} \ln \left[ \frac{U \exp (L/\lambda) - V}{V - U \exp (-L/\lambda)} \right]
\]

\[
\lambda = \left( \sqrt{\frac{1}{\lambda_1}} + \frac{1}{2\lambda_2} \right)^{-1}
\]

\[
\lambda_1 = \sqrt{\left( \frac{\varepsilon_{\text{Si}} W t_{\text{ox}}}{2 \varepsilon_{\text{ox}}} \right) \left( 1 + \frac{\varepsilon_{\text{ox}} W}{4 \varepsilon_{\text{Si}} t_{\text{ox}}} \right)^2}
\]

and

\[
\lambda_2 = \sqrt{\left( \frac{\varepsilon_{\text{Si}} H t_{\text{ox}}}{4 \varepsilon_{\text{ox}}} \right) \left( 1 + \frac{\varepsilon_{\text{ox}} H}{2 \varepsilon_{\text{Si}} t_{\text{ox}}} \right)^2}
\]

- To calculate the drain current with the short channel effects correction:

\[
V_G = V_G + \Phi_{\text{min}}
\]
Short Channel Effects

- $\Phi_{\text{min}}$ represents the variation of the minimum potential in the channel:

$$\begin{align*}
\Phi_{\text{min}} &\text{ represents the variation of the minimum potential in the channel:} \\
\text{Channel potential [V]} &\quad \text{Channel potential [V]} \\
y/L &\quad y/L \\
L = 20 \text{ nm} &\quad V_G = 1.2 \text{ V} \\
L = 1 \mu\text{m} &\quad V_G = 0.4 \text{ V} \\
V_G = 0 \text{ V} &\quad \text{variation of the minimum potential} \\
\end{align*}$$
Short Channel Effects

- Comparison of the curves $I_D \times V_G$ and $g_m \times V_G$ for a device with $L = 40$ nm:

- $I_D$ and $g_m$ are correctly predicted by the model in both subthreshold and above threshold regions.
Short Channel Effects

- Comparison of the curves $I_D \times V_D$ and $g_D \times V_D$ for a device with $L = 40 \text{ nm}$:

- The dependence on $V_D$ is also adequately modeled.
Short Channel Effects

- **Comparison of the curve** $g_m/I_D \times |I_D|$

- **The plateau in the weak inversion regime is inversely proportional to the subthreshold slope**

![Diagram showing the comparison of $g_m/I_D \times |I_D|$ for different channel lengths and drain voltages.](image)

- **Parameters**
  - $W = H = 10$ nm
  - $t_{ox} = 2$ nm
  - $N_A = 1 \times 10^{19}$ cm$^{-3}$
  - $V_D = -0.05$ and $-0.5$ V
  - $L = 40$ nm
  - $L = 1$ μm

- **Graphical representation**
  - Lines: Model
  - Symbols: Simulation
Drain Current Model – Devices with L=30 nm

Symbols - experimental
Lines - model

T = 300, 360 and 420 K

N_D = 1 \times 10^{19} \text{ cm}^{-3}
EOT = 1.5 \text{ nm}
W = 20 \text{ nm}
H = 12 \text{ nm}
L = 30 \text{ nm}
V_D = 40 \text{ mV}
50 fins
Drain Current Model – Devices with \( L = 30 \text{ nm} \)

Long Channel Drain Current Model

Substrate Bias Influence

- Relation between depletion charge and electric field:

\[ H_{\text{eff}} = H_{\text{Fin}} - \left( -\frac{\varepsilon_{\text{Si}} t_{\text{Box}}}{\varepsilon_{\text{ox}}} + \sqrt{\left(\frac{\varepsilon_{\text{Si}} t_{\text{Box}}}{\varepsilon_{\text{ox}}}\right)^2 + \frac{2\varepsilon_{\text{Si}}}{qN_D} (V_{\text{FBs}} - V_{\text{BS}})} \right) \]

\[ Q_{\text{Si}} = qN_D W_{\text{Fin}} H_{\text{Fin}} - C_{\text{Box}} (V_{\text{FBs}} - V_{\text{BS}}) \]

\[ E_S = \sqrt{qN_D \Phi_{\text{S,depl}} / \varepsilon_{\text{Si}}} \]

\[ \Phi_{\text{S,depl}} = V_G - V_{\text{FB}} - \frac{\alpha}{2C_{\text{ox}}} + \sqrt{\left(\frac{\alpha}{2C_{\text{ox}}}\right)^2 - \frac{\alpha}{C_{\text{ox}}} (V_G - V_{\text{FB}})} \]

This approximation neglects the cross-dependence between the gate and the substrate biases on the channel potential.

MOS capacitor:

\[ (\Phi_{\text{S,depl}} + V_G - V_{\text{FB}})C_{\text{ox}} = Q_{\text{Depl}} \]

\[ \alpha = \varepsilon_{\text{Si}} qN_D (2H_{\text{eff}} + W_{\text{Fin}})^2 \]
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Dynamic Model - Formulation

- Conduction charge density per unit of length:

\[
Q_C = qN_D W_{Fin} H_{Fin} - (V_{FBs} - V_B + \Phi_{SB}) C_{Box} - (V_{FB} - V_G + \Phi_S(V_G, V_y)) C_{ox}
\]
Dynamic Model - Formulation

- **Total Conduction charge at the channel:**

  - Integrating the conduction charge density:

    \[
    Q_t = \int_0^L Q_C \, dy = \frac{\mu}{I_D} \int_{V_S}^{V_D} Q_C^2 \, dV_y
    \]

    \[
    Q_t = -\frac{\mu}{C_{ox} I_D} \int_{Q_{c,s}}^{Q_{c,d}} Q_C^2 \, dQ_C = \frac{\mu}{3C_{ox} I_D} (Q_{c,s}^3 - Q_{c,d}^3)
    \]

  - Total charge at the gate:

    \[
    Q_G = Q_t - L(qN_D WH - C_{Box}(V_{FBs} - V_B + \Phi_{SB}))
    \]

    \[
    I_D = \frac{\mu}{L} \left[ \frac{(Q_{c,s}^2 - Q_{c,d}^2)}{2C_{ox}} \right]
    \]
Dynamic Model - Formulation

- **Total charge at drain node:**

  - Following Ward–Dutton scheme:

    \[
    Q_D = -\left[ \int_0^L \frac{y}{L} Q_C \, dy - \frac{L Q_f}{2} \right] = \frac{\mu^2}{2C_{ox} L I_D^2} \int_{V_s}^{V_p} Q_C^2 (Q_{C,S}^2 - Q_C^2) \, dV_y - \frac{L Q_f}{2}
    \]

    \[
    Q_D = \frac{\mu^2}{2 L (C_{ox} I_D)^2} \left[ \frac{Q_{C,S}^3}{3} - \frac{Q_{C,D}^3}{3} \right] - \frac{L Q_f}{2}
    \]

- **Total charge at source node:**

  \[
  Q_S = -Q_G - Q_D
  \]
Dynamic Model - Formulation

- Substituting the drain current into the charges equation:

\[ Q_G = \frac{2L}{3} \left( \frac{Q_{C,S}^2 + Q_{C,S} Q_{C,D} + Q_{C,D}^2}{Q_{C,S} + Q_{C,D}} \right) - LQ_f \]

\[ Q_D = -\frac{2L(2Q_{C,S}^3 + 4Q_{C,S}^2 Q_{C,D} + 6Q_{C,S} Q_{C,D}^2 + 3Q_{C,D}^3)}{15(Q_{C,S}^2 + 2Q_{C,S} Q_{C,D} + Q_{C,D}^2)} + \frac{LQ_f}{2} \]

\[ Q_S = -Q_G - Q_D \]

All charges are written in terms of the charge densities at source- and drain-side of the channel.
Dynamic Model - Formulation

**Transcapacitances:**

The transcapacitances are obtained by the node charges derivatives:

\[
C_{jk} = - \frac{\partial Q_j}{\partial V_k}
\]

\[
\frac{\partial Q_G}{\partial V_k} = \frac{2L}{3} \frac{\partial Q_{c,s}}{\partial V_k} \left( \frac{2Q_{c,s} + Q_{c,d}}{Q_{c,s} + Q_{c,d}} - \frac{Q_{c,s}^2 + Q_{c,s}Q_{c,d} + Q_{c,d}^2}{(Q_{c,s} + Q_{c,d})^2} \right) + \frac{2L}{3} \frac{\partial Q_{c,d}}{\partial V_k} \left( \frac{2Q_{c,d} + Q_{c,s}}{Q_{c,s} + Q_{c,d}} - \frac{Q_{c,s}^2 + Q_{c,s}Q_{c,d} + Q_{c,d}^2}{(Q_{c,s} + Q_{c,d})^2} \right)
\]

\[
\frac{\partial Q_D}{\partial V_k} = -\frac{4L}{15} \frac{\partial Q_{c,s}}{\partial V_k} \left( \frac{Q_{c,s}^3 + 3Q_{c,d}Q_{c,s}^2 + 3Q_{c,s}Q_{c,d}^2}{Q_{c,s}^3 + 3Q_{c,d}Q_{c,s}^2 + 3Q_{c,s}Q_{c,d}^2 + Q_{c,d}^3} \right) - \frac{2L}{15} \frac{\partial Q_{c,d}}{\partial V_k} \left( \frac{3Q_{c,d}^3 + 8Q_{c,d}Q_{c,s}^2 + 9Q_{c,s}Q_{c,d}^2}{Q_{c,s}^3 + 3Q_{c,d}Q_{c,s}^2 + 3Q_{c,s}Q_{c,d}^2 + Q_{c,d}^3} \right)
\]

\[
\frac{\partial Q_S}{\partial V_k} = -\frac{\partial Q_G}{\partial V_k} - \frac{\partial Q_D}{\partial V_k}
\]

All the transcapacitances are written in terms of \( Q_c \)

\[
\frac{\partial Q_C}{\partial V} = \left( \frac{\partial V_G}{\partial V_k} - \frac{\partial \Phi_S}{\partial V_k} \frac{(V_G, V_y)}{V_k} \right) C_{ox} + \left( \frac{\partial V_B}{\partial V_k} - \frac{\partial \Phi_{SB}}{\partial V_k} \right) C_{Box}
\]

As the surface potentials are obtained analytically, their derivatives are also analytical.
Dynamic Model - Formulation

- **Transconductances:**

  The transconductances are also written in terms of $Q_C$:

  \[
  \frac{\partial I_D}{\partial V_k} = -\frac{\mu}{2C_{ox}L} \left[ 2Q_{C,S} \frac{\partial Q_{C,S}}{\partial V_k} - 2Q_{C,D} \frac{\partial Q_{C,D}}{\partial V_k} \right]
  \]

- **Quantization:**

  QM effects are considered by the addition of $\Phi_{QM}$ to $\Phi_S$

  \[
  \Phi_{QM} = \frac{h^2}{8m_xW^2} + \frac{h^2}{8m_yH^2} + \beta(N_D) \left( \frac{\varepsilon_{Si}}{4qkT} \right)^{1/3} (E_S)^{0.63} + \delta(N_D)
  \]

  Accounts for electrical and structural confinements

  \[
  \frac{\partial \Phi_{QM}}{\partial V_k} = \beta(N_D) \left( \frac{\varepsilon_{Si}}{4qkT} \right)^{1/3} \frac{0.63}{E_S^{0.37}} \frac{\partial E_S}{\partial V_k}
  \]
Model Derivation

- **Short-Channel Effects:**

  SCE effects are considered by the addition of the minimum potential variation to $V_G$

  $\Phi_{\text{min}} = \frac{V \sinh(y_{\text{min}}/\lambda) + U \sinh((L - y_{\text{min}})/\lambda)}{\sinh(L/\lambda)}$

  $y_{\text{min}} = \frac{\lambda}{2} \ln \left[ \frac{U \exp(L/\lambda) - V}{V - U \exp(-L/\lambda)} \right]$

U and V are the surface potential at drain- and source-sides of the channel.
Dynamic Model – Comparison against 3D simulations

![Graph showing charge and conductance variations with gate voltage.]
Dynamic Model – Comparison against 3D simulations

\begin{align*}
C_{GG}, C_{GD}, C_{DS}, C_{SD} \\
N_d = 1 \times 10^{19} \text{ cm}^{-3} \\
W = 10 \text{ nm} \\
H = 10 \text{ nm} \\
t_{\text{ox}} = 2 \text{ nm}
\end{align*}

\begin{align*}
C_{GS}, C_{SG}, C_{DG} \\
L = 1 \mu\text{m} \\
V_{DS} = 1 \text{ V} \\
t_{\text{Box}} = 10 \text{ nm}
\end{align*}

\begin{align*}
C_{GB}, C_{SB}, C_{DB} \\
\text{Lines - Model} \\
\text{Symbols - Simulation}
\end{align*}
Dynamic Model – Comparison against 3D simulations

Symbols - Simulation
Lines - Model

$V_{DS} = 1 \text{ V}$
$L = 1 \mu\text{m}$

Capacitances [fF]
Gate voltage [V]

$N_D = 10^{19} \text{ cm}^{-3}$
$t_{Box} = 10 \text{ nm}$
$W = 15 \text{ nm}$
$H = 10 \text{ nm}$
$t_{ox} = 2 \text{ nm}$
$V_{BS} = 2, 0$ and $-2 \text{ V}$

VDS = 1 V
L = 1 μm

Capacitances [fF]
Gate voltage [V]
Dynamic Model – Comparison against 3D simulations

Dashed lines - Model neglecting SCEs
Solid lines - Model including SCEs
Symbols - Simulations

Capacitances [fF]
Gate voltage [V]

W = 10 nm
W = 20 nm

N_D = 1 x 10^{19} \text{ cm}^{-3}
t_{\text{box}} = 100 \text{ nm}
H = 10 \text{ nm}
t_{\text{ox}} = 2 \text{ nm}
L = 30 \text{ nm}
V_{\text{DS}} = 0.5 \text{ V}
Dynamic Model – Comparison against 3D simulations

Symbols - Simulation
Lines - Model

Capacitances [fF]
Gate voltage [V]

Neglecting QM - $t_{ox} = 2$ nm
Including QM - $t_{ox} = 2$ nm
Neglecting QM - $t_{ox} = 2.4$ nm

$N_o = 1 \times 10^{19}$ cm$^{-3}$
$W = 10$ nm
$H = 10$ nm
$L = 1 \mu$m
$V_{DS} = 1$ V
$t_{Box} = 100$ nm

$C_{GG}$
$C_{GD}$
$C_{GS}$

$C_{GS}$
$C_{GD}$
$C_{GG}$
Dynamic Model – Comparison against 3D simulations

(A) W = 5, 20 and 50 nm

(B) H = 5, 20 and 50 nm

(C) Opened symbols - $t_{ox} = 1$ nm
Closed symbols - $t_{ox} = 3$ nm

(D) $N_D = 0.5, 2$ and $3 \times 10^{19}$ cm$^{-3}$
Dynamic Model – Comparison against Experimental data

Outline

Introduction & Motivation

The Junctionless Nanowire Transistor

Compact Modeling

Static Drain Current Model

Dynamic Model

Conclusion
Conclusion

• The Junctionless Nanowire Transistor is an interesting alternative for MOSFET downscaling with respect to IM nanowires.
  • Smaller $I_{\text{OFF}}$ and higher $I_{\text{ON}}/I_{\text{OFF}}$ at similar $L$ (down to 10 nm).

• The analytical models presented show good agreement with experimental and simulated data.
  • Accounted for terminal voltages variations;
  • Symmetric in the vicinity of $V_{\text{DS}}=0$ V;
  • Transconductances and transcapacitances.
Tasks Ongoing

• Transfer the models to VERILOG-A

• Compact modeling of Low Frequency Noise
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