Drain current in Silicon-based Bulk and UTBB-FDSOI devices: what are the key ingredients?

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• What drives the Linear current in ultra-short MOSFETs?
  • NEGF vs Semi classical TCAD
  • A focus on the Near-LDD region
  • the link bw Access Resistance and the ‘Apparent’ Channel Mobility degradation.

• Investigation of the saturation regime
  • More NEGF simulations
  • Diffusive Model or Virtual Source Model?
  • Back to measurements
What drives the current reduction in Short Devices?

- Mobility Degradation
- Velocity Saturation
- Injection Velocity
- Pinch Off

Focus on Silicon-based Field effect transistors currently in production (2016)
What drives the Linear current in ultra-short MOSFETs?

Long Channel Length

- Total Device Resistance is dominated by the ‘Long channel’ Channel mobility

Short Channel Length (L\sim20\text{nm})

- The access Resistances reduce the current

Investigated:
- Do we have additional mechanisms in the channel?

Focus on:
- Planar MOSFETs with homogeneous channel (e.g. no pocket)

Total Device Resistance in the linear regime: 

\[ R_{on} = \frac{V_D}{I} \]

\[ R_{on} = L \cdot r(\mu_0) + R_1 \]

As e.g. [M. Zilli, et al., Electron Device Lett. 28, 1036 (2007).]
What drives the current in ultra-short MOSFETs?

Linear Channel Current:

\[ I \cdot L = C_{OX} \cdot \mu_0 \cdot (V_G - V_{TH} - V_D / 2)V_D \]

Access resistance: \( R_0 \)

\[ I \cdot L = \frac{C_{OX} \cdot \mu_0}{(1 + \left( \frac{\frac{2 \cdot R_0 \cdot C_{OX} \cdot \mu_0}{L} \cdot (V_G - V_{TH} - V_D / 2)}{L} \right))} \]

L-dependent Mobility degradation

Impact of \( R_0 \) only?

… or \( \mu_0(L) \) due to additional mechanisms?
Outlook

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The Channel Only: Quantum Resistance

Resistance calculated with NEGF in an ideal channel-device.

\[ R_{on} = L \cdot \left\{ \frac{1}{\mu_0 C_{OX} (V_G - V_{TH})} \right\} + \frac{1}{(V_G - V_{TH})} \cdot \{2 \cdot \sigma_B\} \]

Equation 1

Quantum resistance calculated with NEGF for various channel thicknesses.

\[ R_Q \approx \sqrt{2\pi \cdot m \cdot kT} / (q \cdot Cox \cdot (V_G - V_{TH})) \]

\( \Rightarrow \) NMOS: \( \sigma_B = 8.4 \ \Omega \cdot \text{mm.V} \)

\( \Rightarrow \) \( \mu_B = (2 \cdot \sigma_B \cdot C_{OX})^{-1} \) of 23.8 cm²/(V.s.nm)

**Simulation setups**

**TB_SIM**:  
- Self consistent NEGF  
- Local + remote coulomb  
- Band structure effects

**SYNOPSYS SDEVICE**:  
- Hydrodynamics with effective mobility  
- Density gradient quantum correction

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**Realistic Doping Profile from Process simulation**

**Varying channel length**

**Focus on**:  
- Planar MOSFETs with homogeneous channel (e.g. no pocket)

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http://inac.cea.fr/L_Sim/TB_Sim  
http://www.synopsys.com/Tools/TCAD/
Access Region: NEGF vs Semi classical

\[ R = 2 \cdot R_0 + 2 \cdot \sigma \cdot (V_G - V_{TH})^{-1} \]

- All scatterings (kp2): \( \sigma = 31 \)
- All scatterings (EMA): \( \sigma = 25 \)
- Phonon Only: \( \sigma = 11 \)
- Quantum (\( R_Q/2 \)): \( \sigma = 8.4 \)
- TCAD: \( \sigma = 33 \) \( R_0 = 18 \)
- NEGF(kp2): \( \sigma = 31 \) \( R_0 = 1.7 \)
- \( V_{GT} = 0.8 \text{V} \)

- All scatterings (kp2): \( \mu_0 = 0.028 \)
- All scatterings (EMA): \( \mu_0 = 0.04 \)
- PHONON Only: \( \mu_0 = 0.053 \)
- TCAD: \( \mu_0 = 0.025 \)
- NEGF(kp2): \( \mu_0 = 0.028 \)
How can we bridge Quantum transport to semi-classical transport?

Method 1: Current comparison

Method 2: Fermi level calculation assuming Fermi Dirac Distribution ➔ Localize the most resistive regions.
NEGFr: extraction of quasi Fermi level

- Occupied local density-of-states map in energy in linear regime ($V_{ds} = 50\text{mV}$)

Ballistic transport (no scattering)
Interferences of coherent waves

Fermi-Dirac distribution of occupied / unoccupied electrons

$$f = \frac{1}{1 + e^{E - E_F / k_B T}}$$

→ extraction of quasi-Fermi level $E_F$. 

Scattering with phonons. Incoherent transport
Access Region: Quasi-Fermi Level

- The Near-Spacer region exhibits a clear and large Quasi-Fermi-Level voltage drop.
- The diffusive part of the channel can be identified both in TCAD and NEGF simulations.
- Square resistance can be calculated from the derivative of the QLF vs position.
• What drives the Linear current in ultra-short MOSFETs?
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The theory of Access resistance involves understanding the resistance that affects the performance of transistors in integrated circuits. The figure illustrates a schematic of the drain, gate, and source regions, along with the BOX (boundary of the channel). The square resistance along the current path is shown, with positions marked as Drain, Corner, Spacer, and Channel, each with specific voltage conditions.

Mathematically, the Access resistance ($R_{acc}$) can be described by the equation:

$$R_{acc} = \frac{1}{(V_G - V_{TH})} \cdot \{2 \cdot (\sigma_{LDD} + \sigma_B)\} + 2 \cdot R_0$$

The graph shows extracted resistance data from TCAD simulations, with a peak at $R_0 = 18$ and a quantum resistance ($R_Q/2$) of $\sigma = 8.4$. The NFDSOI square resistance along the current path for $V_G - V_{TH} = 0.06V$ up to $V_G - V_{TH} = 0.6V$ and $V_{DS} = 0.05V$ is also depicted.
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Impact of $R_0$ on linear Drain current

Access resistance: $R_0$

Channel Mobility: $\mu_{\text{eff}} = \frac{\mu_0}{(1 + \theta \cdot (V_G - V_{\text{TH}} - V_D / 2))}$

$L$-dependent Mobility degradation

Impact of $R_0$ only? … or $\mu_0(L)$ due to additional mechanisms?
Y function$^{[1]}$: deembedding for $\theta$ and $R_0$

\[ Y = \frac{I_D}{\sqrt{g_m}} \]

\[ Y = \sqrt{\frac{\mu_0 C_{OX}}{L}} V_D \cdot (V_G - V_{TH}) \]

\[ \beta_{eff} = \frac{\mu_0 C_{OX}}{L} \]

Y-function slope

\[ I = \frac{C_{OX} \cdot \mu_0}{L \cdot (1 + (2 \cdot R_0 \cdot \frac{C_{OX} \cdot \mu}{L}) \cdot (V_G - V_{TH} - V_D / 2) V_D} \]

Y function measured in NFDSOI @ $V_D=50$ mV

From slope calculated at a given $V_G-V_{TH}$ overdrive, one can extract the mobility

Access Resistance:

\[ R = 2 \cdot R_0 + 2 \cdot \sigma \cdot (V_G - V_{TH})^{-1} \]

\[
I = \frac{C_{OX} \cdot \mu_0}{L \cdot (1 + \frac{2 \cdot \sigma \cdot C_{OX} \cdot \mu_0}{L}) + (\theta - \frac{2 \cdot R_0 \cdot C_{OX} \cdot \mu_0}{L}) \cdot (V_G - V_{TH} - V_D / 2))} \cdot (V_G - V_{TH} - V_D / 2) \cdot V_D
\]

\[ Y = I_D / \sqrt{gm} \]

\[
\frac{1}{\beta_Y} = L / \mu_0 C_{OX} + 2\sigma
\]

\[
\frac{1}{\mu_{eff}} = \frac{1}{\mu_0} + 2 \cdot \sigma \cdot C_{OX} / L
\]

or \[
\frac{1}{\mu_{eff}} = \frac{1}{\mu_0} + 1 / (L \cdot \mu_B)
\]

\[
\mu_B = (2 \cdot \sigma_B \cdot C_{OX})^{-1}
\]

The extracted mobility depends on L
An link bw Racc and Channel mobility?

Better to think with resistance than currents:

\[
R_{on} = L \left\{ \frac{1}{\mu_0 C_{OX} (V_G - V_{TH})} + \frac{\theta}{\mu_0 C_{OX}} \right\} + \frac{1}{(V_G - V_{TH})} \cdot \{2 \cdot \sigma\} + 2 \cdot R_0
\]

(Linear)

The apparent mobility degradation is linked to the access resistance \(V_G\) dependence.

\[
\frac{1}{\mu_{\text{eff}}} = \frac{1}{\mu_0} + 2 \cdot \sigma \cdot C_{OX} / L
\]
Apparent mobility degradation: Measurements

All Devices have homogenous channel processes (no pockets,...)

Bulk vs FD
- Bulk: $\sigma = 46$, $R_0 = 33$
- FD: $\sigma = 25$, $R_0 = 69$

NFD vs PFD
- NFD: $\sigma = 25$
- PFD: $\sigma = 58$, $R_0 = 1.6 \times 10^2$

NFD vs T
- T=25°C: $\sigma = 29$, $R_0 = 83$
- T=85°C: $\sigma = 25$, $R_0 = 69$
- T=-40°C: $\sigma = 24$, $R_0 = 66$

NFD vs Tox
- $C_{ox} = 0.01$: $\sigma = 67$, $R_0 = 1.3 \times 10^2$
- $C_{ox} = 0.025$: $\sigma = 25$, $R_0 = 69$
- $C_{ox} = 0.025$: $\sigma = 25$, $R_0 = 69$

Fit:
- $R = 2 \cdot R_0 + 2 \cdot \sigma \cdot (V_G - V_{TH})^{-1}$
- $1/\mu_{eff} = 1/\mu_0 + 2 \cdot \sigma \cdot C_{OX} / L$
- $1/\mu_{eff} = 1/\mu_0 + 1/(L \cdot \mu_B)$

Small Ballistic Mobility per unit length but in-line with other research group results
[e.g. $\mu_B \approx 1.8 - 9.9 \, \text{cm}^2/(\text{V.s.nm})$ in M. Zilli, et al., Electron Device Lett. 28, 1036 (2007).]
Key ingredients: a realistic picture for the Smaller Devices in Linear Regime

Access:
1. Contact Resistance ($R_0$)
2. Quantum Resistance
3. Near-Spacer-region Resistance

4/ No need for additional mechanisms in the Channel to account for the measurements:

$$R_{on} = R_{acc} + R_{CH} \cdot L$$

$R_{acc}$: Access Resistance

$R_{CH}$: Channel Resistance

In general in optimized technologies $L \sim L_{eff}$
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More NEGF simulations: Current

- $V_{DS} = 0.9 \text{ V}$
- $V_{DS} = 50 \text{ mV}$

- Effect of phonons
- Effect of scatterings

$L = 20\text{ nm}$
Saturation of velocity in long-channel FDSOI due to optical phonons is well described with NEGF.

### Graphical Representation

- **Graph Title:** More NEGF simulations: Velocity saturation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice parameter (nm)</td>
<td>ACELL = 0.5431 nm</td>
</tr>
<tr>
<td>Molar mass (g/mol)</td>
<td>MASS = 28.0855 g/mol</td>
</tr>
<tr>
<td>Longitudinal sound velocity (m/s)</td>
<td>VL = 9000 m/s</td>
</tr>
<tr>
<td>Transverse sound velocity (m/s)</td>
<td>VT = 5400 m/s</td>
</tr>
<tr>
<td>Conduction band acoustic deformation potential (eV)</td>
<td>DAC = 14.6 eV</td>
</tr>
<tr>
<td>Number of g-type phonons</td>
<td>NGTYP = 3</td>
</tr>
<tr>
<td>Energies of g-type phonons (eV)</td>
<td>EGTYP1 = 0.012 eV, EGTYP2 = 0.019 eV, EGTYP3 = 0.062 eV</td>
</tr>
<tr>
<td>Deformation potentials of g-type phonons (eV/Ang)</td>
<td>DGTYP1 = 0.5 eV/Ang, DGTYP2 = 0.8 eV/Ang, DGTYP3 = 11.0 eV/Ang</td>
</tr>
<tr>
<td>Number of f-type phonons</td>
<td>NFTYP = 3</td>
</tr>
<tr>
<td>Energies of f-type phonons (eV)</td>
<td>EFTYP1 = 0.019 eV, EFTYP2 = 0.047 eV, EFTYP3 = 0.059 eV</td>
</tr>
<tr>
<td>Deformation potentials of f-type phonons (eV/Ang)</td>
<td>DFTYP1 = 0.3 eV/Ang, DFTYP2 = 2.0 eV/Ang, DFTYP3 = 2.0 eV/Ang</td>
</tr>
</tbody>
</table>

#### Equations

- $\mu = 0.07 m^2/(Vs)$
- $\nu = 1.4 \times 10^5 m/s$
- $\mu = 0.055 m^2/(Vs)$
- $\nu = 1.1 \times 10^5 m/s$
More NEGF simulations: High VD

Occupied LDOS map in saturation regime ($V_{ds} = 0.9V$)

Ballistic (no scattering)

Scattering with phonons Incoherent transport

Opt Ph still play a role in 20nm FDSOI NFet
More NEGF simulations: details

### Quasi Fermi Level

- **50mV**
  - PH
  - PH + SR
  - BAL

- **0.9V**
  - PH
  - PH + SR
  - BAL

### Charge and velocity

- **50mV**
  - Linear
  - Velocity overshoot
  - Saturation

- **0.9V**
  - Saturation
  - Linear
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P&S in saturation

• Current without Resistance

\[ I = \frac{1}{L} \int_{s}^{d} dy (\mu_{\text{eff}} \cdot Q) \frac{\partial \phi}{\partial y} = \frac{1}{L} \int_{\varphi_{i}}^{\varphi_{D}} \partial \phi (\mu_{\text{eff}} \cdot Q) \]

\[ \mu_{\text{eff}} = \frac{\mu}{1 + \frac{\mu}{v^{*}} \cdot \frac{\partial \phi}{\partial y}} \]

\[ I = \frac{\mu_{0}C_{\text{ox}} \cdot (V_{G} - V_{TH} - \varphi / A) \cdot \frac{\partial \phi}{\partial y}}{(1 + \theta \cdot (V_{G} - V_{TH} - \varphi / A)) \cdot (1 + \frac{\mu}{v^{*}} \cdot \frac{\partial \phi}{\partial y})} \]

\[ \frac{1}{L} \int_{s}^{d} dy \cdot (1 + \frac{\mu}{v^{*}} \cdot \frac{\partial \phi}{\partial y}) = \frac{1}{L} \int_{s}^{d} dy \cdot \frac{\mu_{0}C_{\text{ox}} \cdot (V_{G} - V_{TH} - \varphi / A) \cdot \frac{\partial \phi}{\partial y}}{(1 + \theta \cdot (V_{G} - V_{TH} - \varphi / A))} \]

\[ I_{0} = \frac{\mu_{0}C_{\text{ox}}}{L} \int_{\varphi_{i}}^{\varphi_{D}} \partial \phi \cdot \frac{(V_{G} - V_{TH} - \varphi / A)}{(1 + \theta \cdot (V_{G} - V_{TH} - \varphi / A))} \]

\[ I_{0} = \frac{\mu_{0}C_{\text{ox}}}{L} \cdot \frac{V_{DS} (1 - \delta / V_{DS})}{\theta} \]

\[ \delta = \int_{\varphi_{i}}^{\varphi_{D}} \partial \phi / (1 + \theta \cdot (V_{G} - V_{TH} - \varphi / A)) \]

\[ \int_{\varphi_{i}}^{\varphi_{D}} \partial \phi / (1 + \theta \cdot (V_{G} - V_{TH} - \varphi / A)) = \frac{A}{\theta} \ln \left[ \frac{1 + \theta \cdot (V_{G} - V_{TH} - V_{S} / A)}{1 + \theta \cdot (V_{G} - V_{TH} - V_{D} / A)} \right] \]

Current accounting for theta, Vsat
P&S in saturation

Current with Resistance

\[ I = \frac{\mu_0 C_{ox}}{L} \cdot \frac{V_{DS} (1 - \delta/V_{DS})}{\theta (1 + \frac{\mu_0}{\nu^* L} \delta)} \]

and

\[ \delta = \frac{A}{\theta} \ln \left[ \frac{1 + \theta \cdot (V_G - V_{TH} - V_S / A)}{1 + \theta \cdot (V_G - V_{TH} - V_D / A)} \right] \]

\[ \begin{align*}
V_D &= V_D^{\text{ext}} - R \cdot I \\
V_S &= R \cdot I
\end{align*} \]

Calculation of \( V_{dsat} \) is numerical

\[ R=60*2, \ \sigma=30, \ \theta=0.1 \ \text{Vsats}=2.1 \times 10^5 \text{m/s} \]
Approximation on $V_{DSAT}$

- **Total Resistance @ low $V_D$**

$$R_{on} = L \left\{ \frac{1}{\mu_0 C_{OX} (V_G - V_{TH} - V_D/2)} + \frac{\theta}{\mu_0 C_{OX}} \right\} + \frac{1}{(V_G - V_{TH})} \left\{ 2 \cdot \sigma + \frac{V_D}{v^* C_{OX}} \right\} + 2 \cdot R_0$$

- **Total Resistance @ high $V_D$**

$$R_{on} = L \left\{ \frac{2 \cdot V_D}{\mu_0 C_{OX} (V_G - V_{TH}) \cdot (V_G - V_{TH})} + \frac{2 \cdot \theta \cdot V_D}{\mu_0 C_{OX} \cdot (V_G - V_{TH})} \right\} + \frac{2V_D}{(V_G - V_{TH})} \left\{ R_0 + \frac{\sigma}{(V_G - V_{TH})} + \frac{1}{v^* C_{OX}} \right\}$$

### Channel ‘current’

![Graph showing resistance vs. channel length for different $V_D$ values using P&S Model and Ron Approximation.](image-url)
Diffusive Model vs NEGF

$R(L = 0) = \frac{1}{(V_G - V_{TH})} \left\{ 2 \cdot \sigma + \frac{V_D}{v^*C_{OX}} \right\} + 2 \cdot R_0$

$R(L = 0) = \frac{2V_D}{(V_G - V_{TH})} \left\{ R_0 + \frac{\sigma}{(V_G - V_{TH})} + \frac{1}{v^*C_{OX}} \right\}$

Velocity overshoot (NEGF $V_{sat}$ (EMA) = $1.4e5$ m/s)

No L-dependence in $V_{sat}$ here

COX=0.025; $\mu_0$=0.069; $V_{sat}$=2.1e5; $R_0$; $\sigma$=13; $\theta$=.001;

Using P&S Model
Using Ron Approximation
NEGF

$V_D=0.8V$
$V_{GT}=0.15V$
$V_D=0.8V$
$V_{GT}=0.22V$
$V_D=0.8V$
$V_{GT}=0.41V$
$V_D=0.8V$
$V_{GT}=0.15V$

$V_{D}=10mV$

EXTRACTED RESISTANCE ($\Omega \cdot \mu m$)

$V_D=0.01V$: $\sigma = 13$
$R_0 = 4.9$

$V_D=0.8V$: $\sigma = 1.1e+002$
$R_0 = 19$

RESISTANCE ($\Omega \cdot \mu m$)

CHANNEL LENGH ($\mu m$)
Diffusive Model or Virtual Source Model*?

A fit with VSM seems not so easy:
⇒ Any suggestions?

- Injection velocity / Saturation velocity
- Virtual Source / Pinch Off

COX=0.025; MU0=0.06 ; vsat=1.2e5; R=0; sigma=13;

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• Total Resistance @ high $V_D$

Channel ‘current’

$$R_{on} = L \cdot \left\{ \frac{2 \cdot V_D}{\mu_0 C_{OX} (V_G - V_{TH}) \cdot (V_G - V_{TH})} + \frac{2 \cdot \theta \cdot V_D}{\mu_0 C_{OX} \cdot (V_G - V_{TH})} \right\} + \frac{2V_D}{(V_G - V_{TH})} \cdot \left\{ R_0 + \frac{\sigma}{(V_G - V_{TH})} + \frac{1}{\nu C_{OX}} \right\}$$

**Measurements**

$$2. \sigma_{eff}$$

EXTRACTED RESISTANCE [Ω . µm]

$$\text{EXTRACTED PARAMETER:} \, \sigma$$

**GO1 GO2**

FDSOI GO1
Current Break Down: GO1/GO2 25°C

GO1

GO2
Temperature

\[ V_D = 1 \text{V} \]

\[ \frac{2V_D}{(V_G - V_{TH})} \left\{ R_0 + \frac{\sigma}{(V_G - V_{TH})} + \frac{1}{v^* C_{OX}} \right\} \]

\[ L \cdot \left\{ \frac{2V_D}{\mu_0 C_{OX} (V_G - V_{TH}) (V_G - V_{TH})} + \frac{2 \cdot \theta \cdot V_D}{\mu_0 C_{OX}} \right\} \]
Velocity Saturation

EXTRACTED $\sigma$

DRAIN VOLTAGE (V)

T=40 °C
T=25 °C
T=125 °C

SATURATION VELOCITY (m/s)

TEMPERATURE (deg)

$2.2 \times 10^5$

$1.8$

$1.6$

$1.4$

$1.2$

$1.0$

$0.8$

$0.6$

0

-40

-20

0

20

40

60

80

100

120

140
Conclusions

1. TCAD and NEGF comparison with a focus on the LDD-region

2. Ron Resistance breakdown:
   • Ron = Raccess (50–70%) + Rch (30-50%)
   • Extraction methods should be interpreted with care

3. LDD-region drives a large part of Ron
   1. TCAD but also NEGF clear highlight the near LDD region on the total resistance of the device

4. Saturation Regime
   1. P&S or VS model?
   2. Velocity Saturation
   3. Not accounted for Velocity overshoot