ECE606: Solid State Devices
Lecture 38: Modern MOSFET

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<th>Equilibrium</th>
<th><strong>DC</strong></th>
<th>Small signal</th>
<th>Large Signal</th>
<th>Circuits</th>
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<tr>
<td><strong>Diode</strong></td>
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<td><strong>Schottky</strong></td>
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<td><strong>BJT/HBT</strong></td>
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<td><strong>MOSFET</strong></td>
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Outline

1. Short channel effect

2. Control of threshold voltage

3. Mobility enhancement

4. Conclusion

\[ I_D = \frac{\mu C_{ox}}{L_{ch}} (V_G - V_{th}^*)^2 \]

REF: Chapter 19, SDF
Short Channel Effect: $V_{th}$ Roll-off

$$V_{th} = 2\phi_F - \frac{Q_B}{C_{ox}} = 2\phi_F + \frac{qN_A W_T}{C_{ox}}$$
Short Channel Effect: Punch-through

Recall similar problem with bipolar transistor
Physics of Short Channel Effect

\[ V_{th,\text{Short}} = 2\phi_F - \frac{Q_{B,\text{Short}}}{C_{ox}} \]

\[ Q_{B,\text{Short}} = -qN_A \times Z \times W_T \left( \frac{L + L'}{2} \right) \]

\[ = -qN_A W_T \left( \frac{L + L'}{2L} \right) \]

\[ V_{th,L} = 2\phi_F - \frac{Q_{B,\text{Long}}}{C_{ox}} \]

\[ Q_{B,\text{long}} \rightarrow -qN_A W_T \quad (L \approx L') \]

\[ \Delta V_{th} = -\frac{Q_{B,\text{Long}}}{C_{ox}} + \frac{Q_{B,\text{short}}}{C_{ox}} \]

\[ = -\frac{qN_A W_T}{C_{ox}} \left[ 1 - \frac{L' + L}{2L} \right] \]
Short Channel Effect

\[ (r_j + W_s)^2 = W_T^2 + \left( r_j + \frac{L - L'}{2} \right)^2 \]

\[ L' = L - 2r_j \left( \sqrt{1 + \frac{2W_T}{r_j}} - 1 \right) \]

\[ \Delta V_{th} = -qN_A W_T \left[ \frac{L' + L}{2L} \right] \]

\[ = -qN_A W_T \frac{r_j}{C_{ox}} \frac{r_j}{L} \left( \sqrt{1 + \frac{2W_T}{r_j}} - 1 \right) = \alpha_0 \quad \text{Minimum acceptable...} \]
How to reduce $V_{th}$ roll-off ...

Reduced substrate doping $N_A$
consider WT and junction breakdown

$$V_{th}$$

$$L_{min} = \frac{qN_A W_T}{C_{ox}} \left( \frac{r_J}{\alpha_0} \left( \sqrt{1 + \frac{2W_T}{r_J}} - 1 \right) \right)$$

Shallow junction/geometry of transistors
laser annealing of junctions, FINFETs

Thinner gate oxides
Consider tunneling current

Higher gate dielectric
Consider bulk traps
Outline

1. Short channel effect

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Solution: Ultra-thin Body SOI

\[ E_F \]
\[ V_G \]
\[ t_{Si} \]
\[ t_{ox} \]
\[ N_A \]
Example: FINFET, OmegaFET, X-FET

Source

Drain

Gate

Cross-section
Quantization and Control of Fin-width

\[ \varepsilon_n = \frac{\hbar^2 n^2 \pi^2}{2 m^* t_{Si}^2} \]

\[ E'_G = E_G + \varepsilon_1 + \varepsilon_{1h} \]

Band-gap widening
Fluctuation in thickness
Variability in Vth at Low Doping

\[ V_{th} = 2\phi_F - \frac{Q_B}{C_{ox}} = 2\phi_F - \frac{qN_D W_T}{C_{ox}} \]

\[ \sigma_{V_T} = 3.19 \times 10^{-8} \left( \frac{t_{ox} N_A^{0.4}}{\sqrt{L_{eff} W_{eff}}} \right) [V], \]

\[ \text{Figure 2} \]
Threshold voltage histogram for FETs in the 90-nm-technology node.

Variability in Threshold Voltage

\[ V_{th} = 2\phi_F - \frac{Q_B}{C_{ox}} = 2\phi_F - \frac{qN_A W_T}{C_{ox}} \]

\[ \sigma_{V_T} = 3.19 \times 10^{-8} \left( \frac{t_{ox} N_A^{0.4}}{\sqrt{L_{eff} W_{eff}}} \right) [V], \]

\[ I_D = \frac{\mu C_{ox}}{L_{ch}} (V_G - V_{th}^*)^2 \]

If every transistor has different \( V_{th} \) and therefore different current, circuit design becomes difficult.
V_{th} control by Substrate Bias

\[ V_{th} = \psi_s - \frac{Q_B}{C_{ox}} = \psi_s + B\sqrt{\psi_s} \]

\[ \psi_s = 2\phi_F \]

\[ \psi_s = 2\phi_F - V_{BS} \]
\( Q_i = C_{ox}(V_G - V_{th}) \)

\( V_{th} = -V_{FB} + \psi_s - \frac{Q_B}{C_{ox}} \)

\[
qV_{bi} = \left( \chi + E_g - \Delta_p \right) - \Phi_M
\]

= \( qV_{FB} \)
How to reduce $V_{th}$ roll-off ...

**Reduced substrate doping NA**
consider WT and junction breakdown

$$L_{\text{min}} = \frac{qN_A W_T}{C_{ox}} \frac{r_J}{\alpha_0} \left( \sqrt{1 + \frac{2W_T}{r_J}} - 1 \right)$$

**Shallow junction/geometry of transistors**
laser annealing of junctions, FINFETs

**Thinner gate oxides**
Consider tunneling current

**Higher gate dielectric**
Consider bulk traps
Tunneling Current

\[ J_T = \left( Q_i(V_G) - \frac{n_i^2}{N_A} e^{-qV_G \beta} \right) \nu_{th} \langle T(E) \rangle \]
How to make Vth Roll-off small ...

\[ L_{\text{min}} = \frac{qN_A W_T}{K_{ox} \varepsilon_0} r_J \left( \frac{2W_T}{r_J} \right) \left( \frac{1}{\alpha} \right) \]

High-k/metal gate MOSFET

- Shallow junction and geometry of transistors
- Laser annealing of junctions, FINFET
- Substrate doping NA
- Consider WT and junction breakdown
- Thinner gate oxides
- Consider tunneling current
- Higher gate dielectric
- Consider bulk traps
Advantages of High-k Dielectric ...

High-k/metal gate MOSFET

\[ L_c = \frac{qN_A W_T r_j}{\kappa_{ox} \varepsilon_0} \frac{r_j}{\alpha} \left( \sqrt{1 + \frac{2W_T}{r_j}} - 1 \right) \]

\[ I_D = \frac{\mu C_{ox}}{L_{ch}} \left( V_G - V_{th*} \right)^2 \]

Thicker oxide \( (x_0) \) for same capacitance ...

... ensures the drive-current is not reduced, but tunneling current is suppressed.
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\[ I_D = \frac{\mu C_{ox}}{L_{ch}} (V_G - V_{th}^*)^2 \]
Few words about universal Mobility ....

\[ \mu_{eff} = \frac{\mu_0}{1 + \theta(V_G - V_{th})} \]

Surface Roughness
Basics of Strain..

Compressive biaxial strain enhances mobility in the channel...
Biaxial Strain to Enhance Mobility
Biaxial Strain to Enhance Mobility

Adapted from Chang et. al, IEDM 2005.
Uniaxial Compressive Strain to Enhance Mobility
Orientation Dependent Mobility

Takagi, TED 52, p.367, 2005
New Channel Materials for improved Mobility

<table>
<thead>
<tr>
<th>Charges</th>
<th>Si</th>
<th>GaAs</th>
<th>In$<em>{0.53}$Ga$</em>{0.47}$As</th>
<th>InAs</th>
<th>InSb</th>
</tr>
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<tbody>
<tr>
<td>Electrons*</td>
<td>300</td>
<td>7000</td>
<td>10,000</td>
<td>15,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Holes*</td>
<td>450</td>
<td>400</td>
<td>200</td>
<td>460</td>
<td>1250</td>
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*Electron carrier mobilities measured in transistor channels with electron concentration of 1x10$^{12}$ cm$^{-2}$. Hole mobilities in bulk.

Ge in PNP transistors, bandgap too small, but now coming back for PMOS

Nature, 2009
Summary

1) Short channel effect is a serious concern for MOSFET scaling.

2) Many novel solutions at the material, device, circuit level have been proposed to reduce short channel effect.

3) The success of these efforts are now reflected in effective MOSFET channel lengths of 30 nm.