MOSFET Overview

Paul Hasler
MOS Capacitor Picture

$\kappa = \frac{\psi}{V_g} = \frac{C_{ox}}{C_{ox} + C_d}$

$V = 0$

$L = $ Drawn Length

$I = $ Channel Length
MOS-Capacitor Regions

Surface potential moving from depletion to inversion

\[ Q_s = e^{(\Psi - V_s)/U_T} \quad \text{Depletion (}\kappa(V_g - V_T) - V_s < 0) \]

\[ Q_s = \ln(1 + e^{(\kappa(V_g - V_T) - V_s)/U_T}) \quad \text{Inversion (}\kappa(V_g - V_T) - V_s > 0) \]

\[ Q_s = e^{(\kappa(V_g - V_T) - V_s)/U_T} \]
MOSFET Channel Picture

Channel Current is constant

\[ I = I_0 \left( e^{\frac{\kappa V_g - V_S}{U_T}} \right) \]

\[ -e^{\frac{\kappa V_g - V_d}{U_T}} \]

Diffusion:
\[ J_n = q D_n \frac{dn}{dx} = q D_n \frac{n_{source} - n_{drain}}{l} \]

Channel Length:
\[ l = \text{Channel Length} \]

Drawn Length:
\[ L = \text{Drawn Length} \]
Subthreshold MOSFET Curves

\[ I_{ds} = I_0 e^{\kappa V_g / U_T} \left( e^{-V_s / U_T} - e^{-V_d / U_T} \right) \]

\[ = I_0 e^{(\kappa V_g - V_s) / U_T} \quad (V_{ds} > 4 U_T) \]

"Saturation"

\[ \kappa = 0.58680 \]

\[ I_0 = 1.2104 \text{fA} \]

\[ U_T = 25.84 \text{mV} \]
Above-Threshold MOSFET

Moving from subthreshold to above-threshold

Conduction band bends due to electrostatic force of the electrons moving through the channel.

Significant at channel current \( I_{th} \)

\[
I = \frac{K}{2\kappa} \left( \frac{\kappa(V_g - V_T) - V_s}{\varepsilon_s} \right)^2 - \left( \frac{\kappa(V_g - V_T) - V_d}{\varepsilon_s} \right)^2 \propto Q_s
\]

Saturation: \( Q_d = 0 \)

\[
I = \frac{K}{2\kappa} \left( \frac{\kappa(V_g - V_T) - V_s}{\varepsilon_s} \right)^2 \propto Q_s
\]
Drain Current - Gate/Source Voltage

\[ V_T = 0.806 \]

\[ K \kappa = 37.861 \, \mu A/V^2 \]

\[ K/\kappa = 74.585 \, \mu A/V^2 \]

\[ (\kappa = 0.7) \]
MOSFET Equations

Above-Threshold:

\[ I = \frac{K}{2\kappa} \left( (\kappa(V_g - V_T) - V_s)^2 - (\kappa(V_g - V_T) - V_d)^2 \right) \]

Saturation: \( Q_d = 0 \)

\[ I = \frac{K}{2} (\kappa(V_g - V_T) - V_s)^2 \]

\[ V_d > \kappa(V_g - V_T) \]

Subthreshold:

\[ I = I_s e^{\kappa V_g - V_s / U_T} (1 - e^{-V_{ds} / U_T}) \]

Saturation: \( V_{ds} > 4 U_T \)

\[ I = I_s e^{\kappa V_g - V_s / U_T} \]
Velocity Saturation

Si Crystal Velocity Limit

Ideal Drift (Ohm’s Law)

Square-law region

L = 76 nm MOSFET
Origin of Drain Dependencies

Increasing $V_d$ effects the drain-to-channel region:

- increases barrier height
- increases depletion width
Current versus Drain Voltage

Why is this not flat?

Effect is called the Early effect
(no, it does not come before something else)

First considered in BJT devices

Limits the gain of a Transistor

\[ I_d = I_{d(sat)} (1 + \left( \frac{V_d}{V_o} \right) ) \]

\[ I_d = I_{d(sat)} e^{\frac{V_d}{V_o}} \]

\[ V_o = 16.86 \text{ V} \]

\[ I_{ds} = I_o e^{\frac{\kappa V_g}{U_T} \left( e^{\frac{V_s}{U_T}} - e^{\frac{V_d}{U_T}} \right)} \]

\[ = I_o e^{\left( \frac{\kappa V_g - V_s}{U_T} \right)} \]

\( (V_{ds} > 4 U_T) \), "Saturation"
DC-Removed Modeling

Needed for nonlinear analysis; do not want to carry biasing details through the analysis

Formulating the Approach

Assume bias conditions, some set, some set by the circuit:

\[ V_{g0}, V_{d0}, V_{s0} \]

Resulting in a bias current = \( I_{\text{bias}} \)

We expand

\[ V_g = V_{g0} + \Delta V_g, \quad V_d = V_{d0} + \Delta V_d, \]
\[ V_s = V_{s0} + \Delta V_s \]

For MOSFET in saturation, we get

\[ I = I_0 \exp\left( \frac{\kappa \, V_g - V_s}{U_T} \right) \exp\left( \frac{V_d}{V_A} \right) \]
\[ = I_{\text{bias}} \exp\left( \frac{\kappa \, \Delta V_g - \Delta V_s}{U_T} \right) \exp\left( \frac{\Delta V_d}{V_A} \right) \]

\[ I_{\text{bias}} = I_0 \exp\left( \frac{\kappa \, V_{g0} - V_{s0}}{U_T} \right) \exp\left( \frac{V_{d0}}{V_A} \right) \]

Solving for Transistor Gain

input/output relationship?

- Transistor in saturation

\[ I_{\text{bias}} = I_{\text{bias}} \exp\left( \frac{\kappa \, \Delta V_{\text{in}}}{U_T} \right) \exp\left( \frac{\Delta V_{\text{out}}}{V_A} \right) \]

Gain = \( \frac{\Delta V_{\text{out}}}{\Delta V_{\text{in}}} = - \frac{\kappa \, V_A}{U_T} \)
Key parameters of EKV model

\[ K' \rightarrow K_p \]

\[ \kappa \rightarrow \frac{\gamma}{2\phi_f} \]
\[ \gamma = \frac{1}{2\kappa \sqrt{2\phi_f}} \]

\[ V_{T0} \rightarrow V_{T0} \] (not voltage dependant)

\[ V_A \rightarrow DL \]
\[ \lambda \]

and some short-channel parameters