Lecture 10, February 7, 2001

EECS 105 Microelectronics Devices and Circuits, Spring 2001

Andrew R. Neureuther

Topics: More accurate gradual channel analysis; Physical effects including backgate, channel length modulation, mobility reduction by vertical field, and velocity saturation.

Reading: HS 4.4, Design problem D4.1

Version 2/ 8/ 01
NMOS Example

\[ Q_{B,\text{max}} = -\sqrt{2q\varepsilon_s N_a (-2\phi_p)} \]

Example pp. 139: \( N_a = 10^{17}; \ t_{ox} = 150\text{A} \)

\( \phi_{n+} = 550 \text{ mV} \quad \phi_p = -420 \text{ mV} \)

\[ Q_{B,\text{max}} = -\sqrt{2(1.6\times10^{-19})(11.7)(8.85\times10^{-14})(10^{17})(0.84)} = -1.67\times10^{-7} \text{ C / cm}^2 \]

\[ C_{ox} = \frac{3.9(8.85\times10^{-14} Fcm^{-1})}{150\times10^{-8} cm^1} = 2.3\times10^{-7} Fcm^{-2} = 230aF / \mu m^2 \]

\[ V_{\text{oxide}} = -\frac{1}{C_{ox}} \left( -\sqrt{2q\varepsilon_s N_A (-2\phi_p)} \right) = \frac{-1.67\times10^{-7}}{2.3\times10^{-7}} = 0.725V \]
NMOS Example cont.

\[ V_{Tn} = V_{FB} - 2\phi_p + \frac{1}{C_{ox}} \sqrt{2q\varepsilon_s N_A \left(-2\phi_p\right)} \]

\[ V_{Tn} = -970mV + 840mV + 725mV = 0.595V \]

Any excess gate voltage i.e. voltage above \( V_{Tn} \) creates additional mobile electrons.

For each volt excess gate voltage

\[ Q_{Mobile} = \left(2.3 \times 10^{-7} \text{ Fcm}^{-2}\right)(1V) = 2.3 \times 10^{-7} \text{ C / cm}^2 \]

This is \(1.4 \times 10^{12}\) electrons/cm\(^2\)
Threshold Voltage $V_{T_p}$

\[ V_{T_p} = V_{FB} - 2\phi_n - \frac{1}{C_{ox}} \sqrt{2q\varepsilon_s N_D (2\phi_n)} \]

**Example pp. 144:** \( N_d = 10^{17}; \) \( t_{ox} = 150\text{A} \)

\( \phi_{n+} = 550 \text{ mV} \quad \phi_n = 420 \text{ mV} \quad C_{OX} = 2.3 \times 10^{-7} \text{ F/cm}^2 \)

\[ Q_{B,\text{max}} = \sqrt{2q\varepsilon_s N_D (2\phi_n)} \]

\[ = \sqrt{2(1.6\times10^{-19})(11.7)(8.85\times10^{-14})(10^{17})(0.84)} = 1.67\times10^{-7} \text{ C/cm}^2 \]

\[ V_{T_p} = -(550 - (420)) - 2(420) - \frac{1.67\times10^{-7}(10^3)}{2.3\times10^{-7}} \text{ mV} = -1.695\text{V} \]
Load Line Solution

\[ V_{IN} \quad R_L = 10 \, k\Omega \quad V_{OUT} \]

\[ I_{SC} = 500 \, \mu A \]

\[ V_{OC} = 5V \]

\[ 5V \]

Analog Integrated Circuits

Overview and Circuit Value Added
Large current $k$ and $V_T$ from $I$ vs. $V$

\[ \text{Slope} = \sqrt{\frac{W}{2L}} \mu_n C_{OX} (1 + \lambda V_{DS}) \]

\[ = 20 \sqrt{\mu A / V} \]
Realistic $I_{DS}$ vs. $V_{DS}$

(a) $I_D$ as a function of $V_{DS}$

(b) $\sqrt{I_D}$ as a function of $V_{GS}$ (for $V_{DS} = 5V$).

NMOS Enhancement Transistor: $W = 100 \ \mu m$, $L = 20 \ \mu m$
2nd Order Physics

- Backgate bias
- Channel-length modulation
- Mobility degradation
- Velocity saturation
- Sub-threshold leakage

These are important topics in EE 130 and we will use a slightly patched model for EE 105.
Backgate bias

- When the source is not at the substrate (or well) voltage, an extra voltage source body voltage occurs that increases $x_{B,\text{max}}$ and $Q_{B,\text{max}}$ and this changes the threshold voltage.

\[ V_{Tn} = V_{FB} - 2\phi_p + \frac{1}{C_{ox}} \sqrt{2q\varepsilon_s N_A (-2\phi_p - V_{BS})} \]

**Or for convenience**

\[ V_{Tn} = V_{TON} + \gamma_n \left( \sqrt{-2\phi_p - V_{BS}} - \sqrt{-2\phi_p} \right) \]

\[ \gamma_n = \left( \sqrt{2qN_a \varepsilon_s} \right)/C_{OX} \]
Channel-length modulation

- The MOS transistor is not an ideal current source in that the current tends to increase with $V_{DS}$. This is due to the physics of the region between pinch-off of the current and the drain. There is no simple intuitive physical model and two-dimensional simulation is needed.

Length reduction model

$$\frac{\Delta L}{L} = \lambda_n V_{DS} \quad \lambda_n = \frac{0.1 \mu m V^{-1}}{L}$$

$$I_{DS} = \left( \frac{W}{2L} \right) \mu_n C_{OX} (V_{GS} - V_{Tn})^2 (1 + \lambda_n V_{DS})$$
Mobility Degradation

\[ \mu_n = \frac{c}{700 - 250} \]

Electron trajectories have collisions at the interface

Vertical electric field

Horizontal electric field
Velocity saturation

- The electron velocity no longer increases once the horizontal field reaches 1.5V/µm.
- This effect becomes noticeable for a 1 µm device at 2 volts $V_{DS}$.

\[ E_{sat} = 1.5 \]

\[ \nu_{sat} = 10^7 \]

Constant mobility (slope = $\mu$)

Constant velocity
**I_{DS} vs. V_{DS} with Velocity Saturation**

(a) $I_D$ as a function of $V_{DS}$

(b) $I_D$ as a function of $V_{GS}$ (for $V_{DS} = 5$ V).

**Linear Dependence on $V_{GS}$**

Analog Integrated Circuits

Overview and Circuit Value Added
Improved $I_{DS}$ vs. $V_{DS}$ Model

\[ V_{Tn} = V_{Ton} + \gamma_n \left( \sqrt{-2\Phi_p - V_{BS}} - \sqrt{-2\Phi_p} \right) \]

**cutoff**

\[ I_{DS} = 0 \]

**VGS ≤ VTn**

**triode**

\[ V_{GS} - V_{DS} \geq V_{Tn} \]

\[ I_{DS} = \left( \frac{W}{L} \right) \mu_n C_{OX} \left[ V_{GS} - V_{Tn} - \left( \frac{V_{DS}}{2} \right) \right] (1 + \lambda_n V_{DS}) V_{DS} \]

**saturation**

\[ V_{DS} \geq V_{GS} - V_{Tn} \]

\[ I_{DS} = \left( \frac{W}{2L} \right) \mu_n C_{OX} \left( V_{GS} - V_{Tn} \right)^2 (1 + \lambda_n V_{DS}) \]

**Typical values:**

- $V_{Tn} = 1V$
- $\mu_n C_{OX} = 50 \mu A/V^2$
- $W/L = 4$
- $\gamma_n = 0.8V^{-1/2}$
- $\lambda_n = 0.05V^{-1}$