Lecture 11

Agenda:

- Amplifier Basics
  - Device models
  - Current mirrors
  - Single-stage amplifiers
  - Operational amplifier configurations

Cross-section

- N/P Bipolar Junction Transistor (BJT)
- n-channel Metal Oxide Semiconductor Field-Effect Transistor (n-channel MOSFET)

MOSFET Small-signal Model

- MOSFET Small-signal Equivalent Circuit

Active Devices -- BJT & MOSFET

- N/P Bipolar Junction Transistor (BJT)
- n-channel MOSFET

Active region

Common-emitter configuration

- $I_C$ vs. $V_{CE}$ DC characteristics with base-emitter voltage (or base current) as parameter
- Other configurations are common-base and common-collector

Common-source configuration

- $I_D$ vs. $V_{DS}$ DC characteristics with gate-to-source voltage as parameter
- Other configurations are common-gate and common-drain
Device Model Summary

Constants

- $q = 1.602 \times 10^{-19}$ C
- $k = 1.38 \times 10^{-23}$ J K$^{-1}$
- $n_s = 1.1 \times 10^{10}$ carriers m$^{-2}$ at $T = 300$ K
- $s_p = 8.85 \times 10^{-10}$ F/m

Diode Equations

Reverse-Biased Diode ( abrupt junction)

- $C_i = \frac{\varepsilon_0 A}{q} \left( \frac{V_D}{q} + \frac{V_A}{q} \right)$
- $C_p = \frac{2kT \alpha \phi}{\varepsilon_0 A} \left( \frac{N_{A0} + N_{D0}}{N_{A0}^2 + N_{D0}^2} \right)

Forward-Biased Diode

- $I_0 = I_p e^{V_D / q}$
- $V_T = \frac{kT}{q}$

Small-Signal Model of Forward-Biased Diode

- $I_c = V_c / R_c$
- $V_c = I_c R_c$
- $I_c = 2g_m$

MOSFET Equations

The following equations are for PMOS devices. The equations do not account for drain-induced barrier lowering. The drain current $i_D = g_m V_{gs}^2 / 2l$.

Small-Signal Model (Active Region)

- $V_{ds} = V_{ds0} + \frac{g_m}{2l} V_{gs}^2 + \frac{1}{2} \frac{g_{m0}}{l} V_{gs0}^2$

- $g_{m0} = \frac{2

Device Model Summary
**Device Model Summary**

<table>
<thead>
<tr>
<th>Typical Values for a 0.5-μm Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{th} = 0.8$ V</td>
</tr>
<tr>
<td>$\mu_p C_{ox} = 99$ μA/V²</td>
</tr>
<tr>
<td>$C_{ox} = 1.9 \times 10^{-7}$ pF/μm²</td>
</tr>
<tr>
<td>$C_{ox} = 2.6 \times 10^{-6}$ pF/μm</td>
</tr>
<tr>
<td>$\Phi_p = 0.34$ V</td>
</tr>
<tr>
<td>$\gamma = 0.5$ V/μm</td>
</tr>
<tr>
<td>$N_{eq} = 6 \times 10^{11}$ impurities/m²</td>
</tr>
</tbody>
</table>

Johns and Martin, Analog Integrated Circuit Design, p.56-60

**Operating Point**

$$i_D = \frac{(v_D - v_{DS})}{R_L}$$

**Diode-connected Transistor**

- $i_D = \frac{(v_D - v_{DS})}{R_L}$
- Operating point
- Current can be adjusted by $R_L$
- Current can tune $V_{DS}$
- Sizing transistor to adjust $V_{DS}$ with $I_D$ fixed

**Basic Current Mirror**

- $Q_1$ and $Q_2$ are identical
- $I_{in}$ is set by $R_O$
- $V_{DS1}$ (and $V_{GS2}$) are set by $R_O$
- Thus $I_{out} = I_{in}$
- $I_{out}$ can exactly match $I_{in}$ or can be a fraction of it by adjusting the ratio between $(W_1/L_1)$ and $(W_2/L_2)$

$$I_D = \frac{\mu_C}{2} \left( \frac{W}{L} \right) (V_{GS} - V_T)^2$$
Basic Single-Stage Amplifiers

- **Common-source Amplifier**
  - High input impedance
  - Active load
  - Passive load for low-gain, high frequency
  - Most popular

\[ I_D = \frac{W}{L} C_C (V_{GS} - V_{TH})^2 \]

- **Common-drain Amplifier**
  - Source follower
  - Voltage buffer
  - Voltage gain ~ 1 but < 1
  - Current gain

- **Common-gate Amplifier**
  - Small input impedance
  - Active load
  - Current amplification

High-Quality Current Mirrors

- **Cascode Current Mirror**
  - High output impedance
  - \( r_{out} = \frac{r_{DS} g_{m4}}{2} \)
  - Impedance increased by 10x to 100x
  - Reduce output swings

- **Wilson Current Mirror**
  - High output impedance
  - Shunt-series feedback
  - \( r_{out} = \frac{r_{DS} g_{m4}}{2} \)
  - Reduce output swings
  - \( Q_3 \) is not required
Cascode Gain Stage

- **Telescopic-cascode Amplifier**
  - Allows same dc level for input and output signals
  - Slower due to p-channel

- **Folded-cascode Amplifier**
  - Common-source plus common-gate
  - High gain from single stage
  - Limit the voltage across the input transistor

Differential Pair

- \[ V_{out} = A_V z_{out} \]
- \[ z_{out} = r_{out} \parallel \frac{1}{sC_L} \]
- \[ r_{out} = r_{ds2} \parallel r_{ds4} \]

General Amplifiers

- **Amplifier Saturation**
  - hard limit at power supply limits
  - Jargon: “rail” = power supply
  - rail-to-rail

- **Amplifier Nonlinearity**

Operational Amplifiers

- **Operational Amplifiers**
  - Basic building block for analog signal processing circuits
    - First integrated circuit operational amplifier, \( \mu 709 \), made by Fairchild Semiconductor in 1960s followed by the \( \mu 741 \).
    - Consists of active transistors, resistors, and limited number of capacitors
    - Approximated by single-pole frequency response
  - Three stages
    - Differential amplifier stage
    - High-gain amplifier stage
    - Output amplifier stage

Ref. Sedra and Smith, Microelectronic Circuits, p. 16.
Operational Amplifiers

- Non-inverting Amplifier
  \[ \frac{V_o}{V_i} = 1 + \frac{R_1}{R_2} \]

- Inverting Amplifier
  \[ \frac{V_o}{V_i} = \frac{R_2}{R_1} \]

- Transimpedance Amplifier
  \[ V_o = -R_1 I_s \]

- Transimpedance Amplifier

- Integrator
  \[ v_o = -\frac{1}{RC} \int v_s(t) dt \]

- Differentiator
  \[ v_o = -RC \frac{dv_s}{dt} \]