EE 330
Lecture 31

• High-Gain Amplifiers
• Current Source Biasing
  – Current Sources and Sinks
  – Current Mirrors
# Basic Amplifier Gain Table

<table>
<thead>
<tr>
<th>Circuit</th>
<th>MOS</th>
<th>BJT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE/CS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC/CD</td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>CEwRE/CSwRS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Amplification Factor ($A_V$)

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<tr>
<th>Circuit</th>
<th>MOS</th>
<th>BJT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE/CS</td>
<td>(-g_mR_C)</td>
<td>(-\frac{R_C}{R_E})</td>
</tr>
<tr>
<td>CC/CD</td>
<td>(\frac{g_m}{g_m+g_E})</td>
<td>(\frac{2I_{DQ}R_C}{V_{EB}})</td>
</tr>
<tr>
<td>CB/CG</td>
<td>(\frac{I_{CQ}R_E}{V_{EB}})</td>
<td>(\frac{I_{CQ}R_C}{V_t})</td>
</tr>
<tr>
<td>CEwRE/CSwRS</td>
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### Input Resistance ($R_{in}$)

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<tr>
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<th>MOS</th>
<th>BJT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE/CS</td>
<td>(\infty)</td>
<td>(\frac{r_{TT}}{})</td>
</tr>
<tr>
<td>CC/CD</td>
<td>(\frac{\beta V_t}{I_{CQ}})</td>
<td>(\infty)</td>
</tr>
<tr>
<td>CB/CG</td>
<td>(\beta \left(\frac{V_t}{I_{CQ}}+R_E\right))</td>
<td>(\infty)</td>
</tr>
<tr>
<td>CEwRE/CSwRS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Output Resistance ($R_{out}$)

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<tr>
<th>Circuit</th>
<th>MOS</th>
<th>BJT</th>
</tr>
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<tbody>
<tr>
<td>CE/CS</td>
<td>(R_C)</td>
<td>(R_C)</td>
</tr>
<tr>
<td>CC/CD</td>
<td>(\frac{2I_{DQ}}{V_{EB}})</td>
<td>(\frac{I_{CQ}}{V_t})</td>
</tr>
<tr>
<td>CB/CG</td>
<td>(R_C)</td>
<td>(R_C)</td>
</tr>
<tr>
<td>CEwRE/CSwRS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Can use these equations only when circuit is EXACTLY like that shown above!!

Review from last lecture
Why are we focusing on these basic circuits?

1. So that we can develop analytical skills
2. So that we can design a circuit
3. So that we can get the insight needed to design a circuit

Which is the most important?

1. So that we can get the insight needed to design a circuit
2. So that we can design a circuit
3. So that we can develop analytical skills
Basic Amplifier Characteristics Summary

**CE/CS**
- Large noninverting gain
- Low input impedance
- Moderate (or high) output impedance
- Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode

**CC/CD**
- Gain very close to +1 (little less)
- High input impedance for BJT (high for MOS)
- Low output impedance
- Widely used as a buffer

**CB/CG**
- Large noninverting gain
- Low input impedance
- Moderate (or high) output impedance
- Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode

**CEwRE/CSwRS**
- Reasonably accurate but somewhat small gain (resistor ratio)
- High input impedance
- Moderate output impedance
- Used when more accurate gain is required
High-gain amplifier

This gain is very large!

Too good to be true!

Need better model of MOS device!
Review from last lecture

High-gain amplifier

\[ A_V = \frac{-g_m}{g_0} \]

\[ A_V = \frac{-I_{CQ}}{V_t |I_{CQ} - V_{AF}|} = -\frac{V_{AF}}{V_t} \]

\[ A_V = -\frac{V_{AF}}{V_t} \approx \frac{200V}{25mV} = -8000 \]

This gain is very large!

But how can we make a current source?
High-gain amplifier

\[ A_V \approx -8000 \]

How can we build the ideal current source?

What is the small-signal model of an actual current source?
Current Sources/Mirrors

If the base currents are neglected

\[ I_0 \approx \frac{(V_{CC} - 0.6V)}{R} \]
Current Sources/Mirrors

If the base currents are neglected:

\[ I_0 = \frac{(V_{CC} - 0.6V)}{R} \]

\[ I_1 = J_S A_{E1} e^{\frac{V_{BE1}}{V_i}} \]

since \( V_{BE1} = V_{BE2} \)

\[ I_1 = \left( \frac{A_{E1}}{A_{E0}} \right) I_0 \]

Behaves as a current source!

Actually termed a “sink” current since coming out of load.
Current Sources/Mirrors

- Multiple Outputs Possible
- Can be built at sourcing or sinking currents
- Also useful as a current amplifier
- MOS counterparts work very well and are not plagued by base current
Current Sources/Mirrors

Multiple-Output Bipolar Current Sink

\[ I_k = \left[ \frac{A_{E_k}}{A_{E_0}} \right] I_0 \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source

\[ I_k = \begin{bmatrix} A_{E_k} \\ A_{E_0} \end{bmatrix} I_0 \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source and Sink

\[ I_{nk} = ? \quad I_{pk} = ? \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source and Sink

I_{nk} = \left[ \frac{A_{Enk}}{A_{E0}} \right] I_0

I_{pk} = \left[ \frac{A_{En1}}{A_{E0}} \right] \left[ \frac{A_{Epk}}{A_{Ep0}} \right] I_0
Current Sources/Mirrors

- Termed a “current mirror”
- Output current linearly dependent on $I_{in}$
- Serves as a current amplifier
- Widely used circuit

\[ I_{out} = \left[ \frac{A_{E1}}{A_{E0}} \right] I_{in} \]
Current Sources/Mirrors

npn current mirror amplifier

\[ i_{\text{out}} = ? \]
Current Sources/Mirrors

\[ I_{BS} \quad \downarrow \quad i_{\text{in}} \quad i_{\text{out}} \quad M I_{BS} \]

\[ Q_0 \quad A_{E0} \quad Q_1 \quad A_{E1} \]

\[ M = \frac{A_{E1}}{A_{E0}} \]

npn current mirror amplifier

\[ i_{\text{out}} = \left[ \frac{A_{E1}}{A_{E0}} \right] i_{\text{in}} \]

Amplifiers both positive and negative currents
Current Sources/Mirrors

n-channel Current Mirror

I_{in}\rightarrow M_{0} \quad W_{0, L_{0}}

\rightarrow M_{1} \quad W_{1, L_{1}}

I_{out}\rightarrow

I_{out} = ?

npn Current Mirror

I_{0}\rightarrow Q_{0} \quad A_{E_{0}}

\rightarrow Q_{1} \quad A_{E_{1}}

I_{out}\rightarrow
Current Sources/Mirrors

If process parameters are matched, it follows that

\[
\begin{align*}
I_{in} &= \frac{\mu C_{OX} W_1}{2L_2} (V_{GS1} - V_{T1})^2 \\
I_{out} &= \frac{\mu C_{OX} W_2}{2L_2} (V_{GS2} - V_{T2})^2
\end{align*}
\]

Current mirror gain can be accurately controlled

Layout is important to get accurate gain (for both MOS and BJT)
Layout of Current Mirrors

Example with $M = 2$

Standard layout

Gate area after fabrication depicted

$$M = \begin{bmatrix} \frac{W_2}{W_1} & \frac{L_1}{L_2} \end{bmatrix}$$

$$M = \begin{bmatrix} \frac{W_2 + 2\Delta W}{W_1 + 2\Delta W} & \frac{L_1 + 2\Delta L}{L_2 + 2\Delta L} \end{bmatrix}$$

$$M = \begin{bmatrix} \frac{2W_1 + 2\Delta W}{W_1 + 2\Delta W} & \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \end{bmatrix} \neq 2$$
Layout of Current Mirrors

Example with $M = 2$

Standard layout

$$M = \begin{bmatrix} \frac{W_2}{W_1} & L_1 \\ L_1 & \frac{L_2}{L_1} \end{bmatrix}$$

Better Layout

$$M = \begin{bmatrix} \frac{2W_1 + 2\Delta W}{W_1 + 2\Delta W} & \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \end{bmatrix} \neq 2$$

$$M = \begin{bmatrix} \frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} & \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \end{bmatrix} = 2$$
Layout of Current Mirrors

Example with $M = 2$

Standard layout

Better Layout

Even Better Layout

\[ M = \begin{bmatrix} \frac{W_2}{W_1} & \frac{L_1}{L_2} \end{bmatrix} \]

\[ M = \begin{cases} \frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} \cdot \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} = 2 \end{cases} \]

This is termed a common-centroid layout
Current Sources/Mirrors

\[ i_{\text{out}} = \begin{bmatrix} \frac{W_2}{W_1} & \frac{L_1}{L_2} \end{bmatrix} i_{\text{in}} \]

Amplifiers both positive and negative currents
Current Sources/Mirrors

\[
I_k = \left[ \frac{W_k}{W_0} \frac{L_0}{L_k} \right] I_0
\]

multiple output n-channel current sink array

multiple output p-channel current source array
High-gain amplifier

\[ A_V \approx -8000 \]

How can we build the current source?

What is the small-signal model of an actual current source?
Basic Current Sources and Sinks

Basic Bipolar Current Sinks

\[ I_X = J_S A e^{V_t/V_{xx}} \]

Basic Bipolar Current Sources

\[ I_X \approx \frac{V_{CC} - 0.6V}{R} \]

Very practical methods for biasing the BJTs can be used

Current Mirrors often used for generating sourcing and sinking currents
Basic Current Sources and Sinks

Small-signal Model of BJT Current Sinks and Sources

Small-signal model of all other BJT Sinks and Sources are the same
Basic Current Sources and Sinks

Small-signal Model of BJT Current Sinks and Sources

Small-signal model of all other BJT Sinks and Sources are the same
Basic Current Sources and Sinks

Small-signal Model of BJT Current Sinks and Sources

Small-signal model of all other MOS Sinks and Sources are the same
High-gain amplifier

\[ A_V = \frac{-g_m}{g_0} \]

\[ A_V = \frac{-g_{m1}}{g_{01} + g_{02}} \approx \frac{-g_{m1}}{2g_{01}} \]
High-gain amplifier

\[ A_V = \frac{-g_m}{g_0} \]

- Nonideal current source decreased the gain by a factor of 2
- But the voltage gain is still quite large

Can the gain be made even larger?