Lecture 19

Transistor Amplifiers (I)
Common-Source Amplifier

Outline

• Amplifier fundamentals
• Common-source amplifier
• Common-source amplifier with current-source supply

Reading Assignment:
Howe and Sodini; Chapter 8, Sections 8.1-8.4

Announcement:
Amplifier Fundamentals

- Source resistance $R_S$ is associated *only* with small signal sources
- Choose $I_D = I_{SUP}$ --- DC output current
  - $I_{OUT} = 0$
  - $V_{OUT} = 0$

\[ v_{IN} = V_{BIAS} + v_s \]
\[ i_{IN} = I_{BIAS} + i_s \]

\[ v_{OUT} \]

\[ i_{OUT} = i_d \]
2. Common-Source Amplifier:

Consider the following circuit:

- Consider intrinsic voltage amplifier - no loading
  - $R_S = 0$
  - $R_L \rightarrow \infty$
  - $V_{GS} = V_{BIAS} - V_{SS}$

- $V_{BIAS}$, $R_D$ and W/L of MOSFET selected to bias transistor in saturation and obtain desired output bias point (i.e. $V_{OUT} = 0$).

Watch notation: $v_{OUT}(t) = V_{OUT} + v_{out}(t)$
Load line view of amplifier:

Transfer characteristics of amplifier:

Want:
- Bias point calculation;
- Limits to signal swing
- Small-signal gain;
- Frequency response [in a few days]
**Bias point:** choice of $V_{BIAS}$, $W/L$, and $R_D$ to keep transistor in saturation and to get proper quiescent $V_{OUT}$.

Assume MOSFET is in saturation:

\[ I_D = \frac{W}{2L} \mu_n C_{ox} (V_{BIAS} - V_{SS} - V_T)^2 \]

\[ I_R = \frac{V_{DD} - V_{OUT}}{R_D} \]

If we select $V_{OUT}=0$:

\[ I_D = I_R = \frac{W}{2L} \mu_n C_{ox} (V_{BIAS} - V_{SS} - V_T)^2 = \frac{V_{DD}}{R_D} \]

Then:

\[ V_{BIAS} = \sqrt{\frac{2I_D}{\frac{W}{L} \mu_n C_{ox}}} + V_{SS} + V_T \]

Equation that allows us to compute needed $V_{BIAS}$ given $R_D$ and $W/L$. 
Signal swing:

- Upswing: limited by MOSFET going into cut-off.

\[ v_{out,\text{max}} = V_{DD} \]

- Downswing: limited by MOSFET leaving saturation.

\[ V_{DS,\text{sat}} = V_{GS} - V_T = \sqrt{\frac{2I_D}{W/L} \mu_n C_{ox}} \]

or

\[ v_{out,\text{min}} - V_{SS} = V_{BIAS} - V_{SS} - V_T \]

Then:

\[ v_{out,\text{min}} = V_{BIAS} - V_T \]
Generic view of the effect of loading on small-signal operation

Two-port network view of small-signal equivalent circuit model of a voltage amplifier:

- $R_{\text{in}}$ is *input resistance*
- $R_{\text{out}}$ is *output resistance*
- $A_{\text{vo}}$ is *unloaded voltage gain*

![Diagram](image)

**Voltage divider at input:**

$$v_{\text{in}} = R_{\text{in}} \frac{v_s}{R_{\text{in}} + R_s}$$

**Voltage divider at output:**

$$v_{\text{out}} = R_L \frac{A_{\text{vo}} v_{\text{in}}}{R_{\text{out}} + R_L}$$

**Loaded voltage gain:**

$$\frac{v_{\text{out}}}{v_s} = \frac{R_{\text{in}}}{R_{\text{in}} + R_s} A_{\text{vo}} \frac{R_L}{R_L + R_{\text{out}}}$$
Small-signal voltage gain $A_{vo}$: draw small-signal equivalent circuit model: Remove $R_L$ and $R_S$

\[ v_{out} = -g_m v_t \left( r_o // R_D \right) \]

Then unloaded voltage gain:

\[ A_{vo} = \frac{v_{out}}{v_t} = -g_m \left( r_o // R_D \right) \]
Input Resistance

- Calculation of input resistance, $R_{in}$:
  - Load amplifier with $R_L$
  - Apply test voltage (or current) at input, measure test current (or voltage).

For common-source amplifier:

$$i_t = 0 \Rightarrow R_{in} = \frac{v_t}{i_t} = \infty$$

No effect of loading at input.
Output Resistance

- Calculation of output resistance, $R_{out}$:
  - Load amplifier with $R_S$
  - Apply test voltage (or current) at output, measure test current (or voltage).
  - Set input source equal zero

For common-source amplifier:

\[ v_{gs} = 0 \Rightarrow g_m v_{gs} = 0 \Rightarrow v_t = i_t \left( r_o // R_D \right) \]

\[ R_{out} = \frac{v_t}{i_t} = r_o // R_D \]
Two-port network view of common-source amplifier
Voltage Amplifier

\[
\frac{v_{out}}{v_s} = \frac{R_{in}}{R_{in} + R_S} A_{vo} \frac{R_L}{R_L + R_{out}}
\]

\[
\frac{v_{out}}{v_s} = -g_m \left( r_o \parallel R_D \right) \frac{R_L}{R_L + r_o \parallel R_D} = -g_m \left( r_o \parallel R_D \parallel R_L \right)
\]
Current Source Supply

I—V characteristics of current source:

\[ i_{SUP} = \begin{cases} 0 & \text{for } v_{SUP} \leq 0 \\ ISUP + \frac{v_{SUP}}{r_{oc}} & \text{for } v_{SUP} > 0 \end{cases} \]

High small-signal resistance \( r_{oc} \).

Equivalent circuit models:

- Large-signal model
- Small-signal model
3. Common-source amplifier with current-source supply

![Common-source amplifier with current-source supply diagram]

Loadline View

- $i_{SUP} = i_D$
- $V_{BIAS} - V_S = V_{DD} - V_{SS}$
- $V_{BIAS} = V_T$
- $0 = V_{SS}$
- $V_{OUT}$
- $V_{DD}$
- $R_S$
- $R_L$
- Signal source
- Signal load
Use PMOS for current source supply

Bias point: Assume both transistors in saturation
\( V_{OUT} = 0 \). Choose \( I_{SUP} \) and determine \( V_B \).

\[
I_{SUP} = -I_{Dp} = \left( \frac{W}{2L} \right)_p \mu_p C_{ox} \left( V_{DD} - V_B + V_{Tp} \right)^2
\]

Set \(-I_{Dp} = I_{Dn}\) for \( V_{OUT} \approx 0 \)

\[
I_{SUP} = I_{Dn} = \left( \frac{W}{2L} \right)_n \mu_n C_{ox} \left( V_{BIAS} - V_{SS} - V_{Tn} \right)^2
\]

\[
V_{BIAS} = \sqrt{\frac{2I_{SUP}}{\left( \frac{W}{L} \right)_n \mu_n C_{ox}}} + V_{SS} + V_T
\]
Signal swing:

- Upswing: limited by PMOS leaving saturation.

\[ V_{SD,sat} = V_{SG} + V_{Tp} = V_{DD} - V_B + V_{Tp} \]

\[ V_{DD} - v_{out,\text{max}} = V_{DD} - V_B + V_{Tp} \]

\[ v_{out,\text{max}} = V_B - V_{Tp} \]

- Downswing: limited by NMOS leaving saturation.
- Same result as with resistive supply current.

\[ v_{out,\text{min}} = V_{BIAS} - V_T \]
3. Common-source amplifier with current-source supply (contd.)

Current source characterized by high output resistance: $r_{oc}$. Significantly higher than amplifier with resistive supply.

p-channel MOSFET: $r_{oc} = 1/\lambda I_{Dp}$

- Voltage gain: $A_{vo} = -g_m (r_o//r_{oc})$.
- Input resistance: $R_{in} = \infty$
- Output resistance: $R_{out} = r_o//r_{oc}$.
Relationship between circuit figures of merit and device parameters

Remember:

$$g_m = \sqrt{2I_D \frac{W}{L} \mu_n C_{ox}}$$

$$r_o \approx \frac{1}{\lambda_n I_D} \propto \frac{L}{I_D}$$

Then:

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<tr>
<th>Device* Parameters</th>
<th>Circuit Parameters</th>
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<tr>
<td>$I_{SUP} \uparrow$</td>
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<td>$W \uparrow$</td>
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<td>$L \uparrow$</td>
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* adjustments are made to $V_{BIAS}$ so that none of the other parameters change

CS amplifier with current source supply is a good voltage amplifier ($R_{in}$ high and $|A_{vol}|$ high), but $R_{out}$ high too $\Rightarrow$ voltage gain degraded if $R_L << r_o//r_{oc}$. 
What did we learn today?

Summary of Key Concepts for CS amplifier

- Bias Calculations
- Signal Swing
- Small Signal Circuit Parameters
  - Voltage Gain - $A_{VO}$
  - Input Resistance - $R_{in}$
  - Output Resistance - $R_{out}$
- Relationship between small signal circuit and device parameters