Lecture 19 - Transistor Amplifiers (I)

COMMON-SOURCE AMPLIFIER

November 15, 2005

Contents:

1. Amplifier fundamentals
2. Common-source amplifier
3. Common-source amplifier with current-source supply

Reading assignment:

Howe and Sodini, Ch. 8, §§8.1-8.6

Announcements:

Quiz 2: 11/16, 7:30-9:30 PM, open book, must bring calculator; lectures #10-18.

Quiz 2 TA Review Session: 11/15, 7:30-9:30 PM,
Key questions

• What are the key figures of merit of an amplifier?

• How can one make a voltage amplifier with a single MOSFET and a resistor?

• How can this amplifier be improved?
1. Amplifier fundamentals

Goal of amplifiers: *signal amplification.*

Features of amplifier:

- *Output signal* is faithful replica of *input signal* but amplified in magnitude.
- *Active device* is at the heart of amplifier.
- Need *linear transfer characteristics* for distortion not to be introduced.
Signal could be represented by \textit{current} or \textit{voltage} \Rightarrow four broad types of amplifiers:

- **voltage amplifier**
  - Input: $v_s$
  - Output: $v_{out}$

- **transconductance amplifier**
  - Input: $i_{in}$
  - Output: $v_{out}$

- **transresistance amplifier**
  - Input: $i_{in}$
  - Output: $v_{out}$

- **current amplifier**
  - Input: $i_{in}$
  - Output: $v_{out}$
More realistic transfer characteristics:

- Transfer characteristics linear over limited range of voltages: *amplifier saturation*.
- Amplifier saturation limits *signal swing*.
- Signal swing also depends on choice of *bias point, Q* (also called *quiescent point* or *operating point*).

Other features desired in amplifiers:

- Low *power consumption*.
- Wide *frequency response* [will discuss in a few days].
- *Robust* to process and temperature variations.
- *Inexpensive*: must minimize use of unusual components, must be small (in Si area)

/ or exotic technology}/
2. Common-Source Amplifier

Consider the following circuit:

![Common-Source Amplifier Circuit Diagram]

Consider it first unloaded by $R_L$. How does it work?

- $V_{GG}$, $R_D$ and $W/L$ of MOSFET selected to bias transistor in saturation and obtain desired output bias point (i.e. $V_{OUT} = 0$).
- $v_{GS} \uparrow \Rightarrow i_D \uparrow \Rightarrow i_R \uparrow \Rightarrow v_{out} \downarrow$
- $A_v = \frac{v_{out}}{v_s} < 0$; output out of phase from input, but if amplifier well designed, $|A_v| > 1$.

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

Transfer characteristics of amplifier:

Want:

- Bias point calculation;
- small-signal gain;
- limits to signal swing
- frequency response [in a few days]
□ **Bias point:** choice of $V_{GG}$, $W/L$, and $R_D$ to keep transistor in saturation and to get proper quiescent $V_{OUT}$.

Assume MOSFET is in saturation:

$$I_D = \frac{W}{2L} \mu_n C_{ox} (V_{GG} - V_{SS} - V_T)^2$$

$$I_R = \frac{V_{DD} - V_{OUT}}{R_D}$$

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

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

Then:

$$V_{GG} = \sqrt{\frac{2V_{DD}}{R_D} \frac{W}{L} \mu_n C_{ox}} + V_{SS} + V_T$$
**Small-signal voltage gain:** draw small-signal equivalent circuit model:

![Circuit Diagram]

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

Then **unloaded voltage gain:**

\[ A_{vo} = \frac{v_{out}}{v_{in}} = -g_m \left( r_o / R_D \right) \]
**Signal swing:**

- **Upswing:** limited by transistor going into cut-off:
  
  \[ v_{out,max} = V_{DD} \]

- **Downswing:** limited by MOSFET entering linear regime:
  
  \[ V_{DS,sat} = V_{GS} - V_T \]

  or

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

  Then:

  \[ v_{out,min} = V_{GG} - V_T \]
Effect of input/output loading:

- Bias point not affected because selected $V_{OUT} = 0$. ($I_L = 0$)
- Signal swing:
  - Upswing limited by resistive divider: ($I_R = I_L$)
    \[
    v_{out,max} = V_{DD} \frac{R_L}{R_L + R_D}
    \]
  - Downswing not affected by loading
- Voltage gain:
  - Input loading ($R_S$): no effect because gate does not draw current;
  - Output loading ($R_L$): $R_L$ detracts from voltage gain because it draws current.
    \[
    |A_v| = g_m(r_o // R_D // R_L) < g_m(r_o // R_D)
    \]
Generic view of loading effect on small-signal operation:

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

\[
\begin{align*}
R_{in} & \text{ is input resistance} \\
R_{out} & \text{ is output resistance} \\
A_{vo} & \text{ is unloaded voltage gain}
\end{align*}
\]

Voltage divider at input: 
\[
v_{in} = R_{in} \frac{v_s}{R_{in} + R_S}
\]

Voltage divider at output: 
\[
v_{out} = R_L \frac{A_{vo} v_{in}}{R_{out} + R_L}
\]

Loaded voltage gain: 
\[
A_v = \frac{v_{out}}{v_s} = \frac{R_{in}}{R_{in} + R_S} A_{vo} \frac{R_L}{R_L + R_{out}}
\]
• 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:

\[ i_t = 0 \implies R_{in} = \frac{v_t}{i_t} = \infty \]

No effect of loading at input.
- Calculation of output resistance, $R_{out}$:
  
  - load amplifier at input with $R_S$
  - apply test voltage (or current) at output, measure test current (or voltage)

For common-source amplifier:

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

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

\[ A_v = \frac{v_{out}}{v_s} = \frac{R_{in}}{R_{in} + R_S} A_v o \frac{R_L}{R_L + R_{out}} = -g_m \left( \frac{r_o}{//R_D} \right) \frac{R_L}{R_L + r_o//R_D} \]

Or:

\[ A_v = -g_m \left( \frac{r_o}{//R_D//R_L} \right) \]

\( \uparrow \)

loaded voltage gain
Design issues of common-source amplifier (unloaded):

Examine bias dependence:

$$|A_{vo}| = g_m(r_o//R_D) \approx g_m R_D$$

Rewrite $|A_{vo}|$ in the following way:

$$|A_{vo}| \approx g_m R_D = \sqrt{\frac{2W}{L} \mu_n C_{ox} I_D \frac{V_{DD}}{I_D}} \propto \frac{V_{DD}}{\sqrt{I_D}}$$

Then, to get high $|A_{vo}|$:

$$\Rightarrow V_{DD} \uparrow$$
$$\Rightarrow I_D \downarrow$$

Both approaches imply $\Rightarrow R_D = \frac{V_{DD}}{I_D} \uparrow$

Consequences of high $R_D$:

- large $R_D$ consumes a lot of Si real state
- large $R_D$ eventually compromises frequency response

Also, it would be nice not to use any resistors at all!

$\Rightarrow$ Need better circuit.
3. Common-source amplifier with current-source supply

Loadline view:
Current source characterized by high output resistance: $r_{oc}$.

Then, unloaded voltage gain of common-source stage:

$$|A_{vo}| = g_m \left( \frac{r_o}{r_{oc}} \right)$$

significantly higher than amplifier with resistive supply.

Can implement current source supply by means of p-channel MOSFET:
• Relationship between circuit figures of merit and device parameters

Remember:

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

\[ r_o \approx \frac{1}{\lambda_n I_D} \propto \frac{L}{I_D} \]

Then:

<table>
<thead>
<tr>
<th>Device * Parameters</th>
<th>Circuit Parameters</th>
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<tbody>
<tr>
<td></td>
<td>(</td>
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<tr>
<td></td>
<td>( g_m(r_o//r_{oc}) )</td>
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<tr>
<td>( I_{SUP} \uparrow )</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( W \uparrow )</td>
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<tr>
<td>( \mu_n C_{ox} \uparrow )</td>
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* adjustments are made to \( V_{GG} \) so none of the other parameters change

CS amp with current supply source is good voltage amplifier \((R_{in} \text{ high and } |A_v| \text{ high})\), but \( R_{out} \text{ high too } \Rightarrow \) voltage gain degraded if \( R_L \ll r_o//r_{oc} \).
Key conclusions

- Figures of merit of an amplifier:
  - gain
  - signal swing
  - power consumption
  - frequency response
  - robustness to process and temperature variations

- Common-source amplifier with resistive supply: trade-off between gain and cost and frequency response.

- Trade-off resolved by using common-source amplifier with current source supply.

- Two-port network computation of voltage gain, input resistance and output resistance of amplifier.