Lecture 20 - Transistor Amplifiers (II)

OTHER AMPLIFIER STAGES

November 17, 2005

Contents:

1. Common-source amplifier (cont.)
2. Common-drain amplifier
3. Common-gate amplifier

Reading assignment:

Howe and Sodini, Ch. 8, §§8.7-8.9
Key questions

• What other amplifier stages can one build with a single MOSFET and a current source?
• What is the uniqueness of these other stages?
1. 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:

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

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

Then:

<table>
<thead>
<tr>
<th>Device Parameters</th>
<th>Circuit Parameters</th>
</tr>
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<tbody>
<tr>
<td>( I_{SUP} \uparrow )</td>
<td>(</td>
</tr>
<tr>
<td>( W \uparrow )</td>
<td>( g_m(r_o//r_{oc}) )</td>
</tr>
<tr>
<td>( \mu_n C_{ox} \uparrow )</td>
<td>( \uparrow )</td>
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<td>( L \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 (\( R_{in} \) high and \( |A_v| \) high), but \( R_{out} \) high too \( \Rightarrow \) voltage gain degraded if \( R_L \ll r_o//r_{oc} \).
Common-source amplifier is acceptable *voltage* amplifier (want high $R_{in}$, high $A_{vo}$, low $R_{out}$):

\[ \begin{align*}
&v_s \quad + \quad R_S \quad - \\
&v_{in} \quad + \quad R_{in} \quad - \\
+ &A_{vo}v_{in} \quad + \quad A_{vo}v_{in} \\
&v_{out} \quad + \quad R_L \quad - \\
&i_{out} \quad + \quad R_{out} \quad -
\end{align*} \]

... but excellent *transconductance* amplifier (want high $R_{in}$, high $G_{mo}$, high $R_{out}$):

\[ \begin{align*}
&v_s \quad + \quad R_S \quad - \\
&v_{in} \quad + \quad R_{in} \quad - \\
&G_{mo}v_{in} \quad + \quad G_{mo}v_{in} \\
&v_{out} \quad + \quad R_L \quad - \\
&i_{out} \quad + \quad R_{out} \quad -
\end{align*} \]

For common-source amplifier:

\[ G_{mo} = g_m \]
Common-source amplifier does not work as *transresistance* amplifier (want low $R_{in}$, high $R_{mo}$, low $R_{out}$):

nor as *current* amplifier
(want low $R_{in}$, high $A_{io}$, high $R_{out}$):

Need new amplifier configurations.
2. Common-drain amplifier

How does it work?

- $V_{GG}$, $I_{SUP}$, and $W/L$ selected to bias MOSFET in saturation, obtain desired output bias point, and desired output swing.

- $V_G \uparrow \Rightarrow i_D$ can’t change $\Rightarrow v_{OUT} \uparrow$ (source follower)

- to first order, no voltage gain: $v_{out} \simeq v_s$

- but $R_{out}$ small: effective voltage buffer stage (good for making voltage amp in combination with common-source stage).
\[ \text{Small-signal analysis} \]

Unloaded small-signal equivalent circuit model:

\[ v_{in} = v_{gs} + v_{out} \]

\[ v_{out} = g_m v_{gs} \left( \frac{r_o}{r_{oc}} \right) \]

Then:

\[ A_{vo} = \frac{g_m}{g_m + \frac{1}{\frac{r_o}{r_{oc}}}} \approx 1 \]
Input impedance: $R_{in} = \infty$

Output impedance:

\[
R_{out} = \frac{1}{g_m + \frac{1}{r_{o\parallel r_{oc}}}} \approx \frac{1}{g_m}
\]

small!

Loaded voltage gain:

\[
A_v = A_{vo} \frac{R_L}{R_L + R_{out}} \approx \frac{R_L}{R_L + \frac{1}{g_m}} \approx 1
\]
□ Effect of back bias:

If MOSFET not fabricated on isolated p-well, then body is tied up to wafer substrate (connected to $V_{SS}$):

Two consequences:

- Bias affected: $V_T$ depends on $V_{BS} = V_{SS} - V_{OUT} \neq 0$
- Small-signal figures of merit affected: signal shows up between B and S ($v_{bs} = -v_{out}$).
Small-signal equivalent circuit model:

\[ A_{vo} = \frac{g_m}{g_m + g_{mb} + \frac{1}{r_o//r_{oc}}} \approx \frac{g_m}{g_m + g_{mb}} < 1 \]

Also:

\[ R_{out} = \frac{1}{g_m + g_{mb} + \frac{1}{r_o//r_{oc}}} \approx \frac{1}{g_m + g_{mb}} \]
□ Relationship between circuit figures of merit and device parameters:

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

\[ g_{mb} = \frac{\gamma}{2\sqrt{-2\phi_p - V_{BS}}} g_m \]

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* adjustments are made to \( V_{GG} \) so none of the other parameters change

CD amp useful as a voltage buffer to drive small loads (in a multistage amp, other stages will be used to provide voltage gain).
3. Common-gate amplifier

Need to handle current-mode signal sources:

How does it work?

- since source is signal input terminal, body cannot be tied up to source ($C_{db}$ is significant)
- $i_{SUP}$, $I_{BIAS}$, and $W/L$ selected to bias MOSFET in saturation, obtain desired output bias point, and desired output swing
- $i_S \uparrow \Rightarrow i_D \downarrow \Rightarrow i_{OUT} \downarrow$
- no current gain: $i_s = -i_{out}$ (current buffer)
**Bias:** select $I_{SUP}$, $I_{BIAS}$, and $W/L$ to get proper quiescent $I_{OUT}$ and keep MOSFET in saturation.

![Diagram showing a MOSFET with $V_{DD}$, $I_{SUP}$, $I_{OUT}$, and $V_{SS}$ nodes]

\[ I_{SUP} + I_{OUT} + I_{BIAS} = 0 \]

Select bias so that $I_{OUT} = 0 \Rightarrow V_{OUT} = 0$.

Assume MOSFET in saturation (no channel modulation):

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

but $V_T$ depends on $V_{BS}$:

\[ V_T = V_{To} + \gamma_n (\sqrt{-2\phi_p - V_{BS}} - \sqrt{-2\phi_p}) \]

Must solve these two equations iteratively to get $V_S$. 
\[ \text{Small-signal circuit (unloaded)} \]

\[ i_s = -i_{out} \Rightarrow A_{io} = -\frac{i_{out}}{i_s} = -1 \]

Not surprising, since in a MOSFET: \( i_g = 0 \).
Input resistance:

\[ i_t - g_m v_t - g_{mb} v_t - \frac{v_t - (r_{oc} / R_L) i_t}{r_o} = 0 \]

Then:

\[ R_{in} = \frac{1 + \frac{r_{oc} / R_L}{r_o}}{g_m + g_{mb} + \frac{1}{r_o}} \approx \frac{1}{g_m + g_{mb}} \]

Very small.
Output resistance:

\[
\begin{align*}
\text{Do KCL on input node:} \\
i_t' - g_m v_{gs} - g_m b v_{gs} - \frac{v_t' + v_{gs}}{r_o} &= 0 \\
\text{Notice also:} \\
v_{gs} &= -i_t' R_S \\
\text{Then:} \\
R_{out} &= r_{oc} \left/ \left\{ r_o \left[ 1 + R_S \left( g_m + g_m b + \frac{1}{r_o} \right) \right] \right\} \\
&\approx r_{oc} \left/ \left[ r_o (1 + g_m R_S) \right] \right.
\end{align*}
\]

Very large, because of the feedback effect of \( R_S \).
Summary of MOSFET amplifier stages:

<table>
<thead>
<tr>
<th>stage</th>
<th>$A_{vo}$, $G_{mo}$, $A_{io}$</th>
<th>$R_{in}$</th>
<th>$R_{out}$</th>
<th>key function</th>
</tr>
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<tbody>
<tr>
<td>common source</td>
<td>$G_{mo} = g_m$</td>
<td>$\infty$</td>
<td>$r_o/r_{oc}$</td>
<td>transconductance amp.</td>
</tr>
<tr>
<td>common drain</td>
<td>$A_{vo} \approx \frac{g_m}{g_m+g_{mb}}$</td>
<td>$\infty$</td>
<td>$\frac{1}{g_m+g_{mb}}$</td>
<td>voltage buffer</td>
</tr>
<tr>
<td>common gate</td>
<td>$A_{io} \approx -1$</td>
<td>$\frac{1}{g_m+g_{mb}}$</td>
<td>$r_{oc}/[r_o(1 + g_m R_S)]$</td>
<td>current buffer</td>
</tr>
</tbody>
</table>

In order to design amplifiers with suitable performance, need to combine these stages ⇒ *multistage amplifiers*
Key conclusions

Different MOSFET stages designed to accomplish different goals:

- **Common-source stage:**
  - large voltage gain and transconductance, high input resistance, large output resistance
  - excellent transconductance amplifier, reasonable voltage amplifier

- **Common-drain stage:**
  - no voltage gain, but high input resistance and low output resistance
  - good voltage buffer

- **Common-gate stage:**
  - no current gain, but low input resistance and high output resistance
  - good current buffer