Fundamentals of Microelectronics

- CH1 Why Microelectronics?
- CH2 Basic Physics of Semiconductors
- CH3 Diode Circuits
- CH4 Physics of Bipolar Transistors
- CH5 Bipolar Amplifiers
- CH6 Physics of MOS Transistors
- CH7 CMOS Amplifiers
- CH8 Operational Amplifier As A Black Box

Chapter 7 CMOS Amplifiers

- 7.1 General Considerations
- 7.2 Common-Source Stage
- 7.3 Common-Gate Stage
- 7.4 Source Follower
- 7.5 Summary and Additional Examples
MOS Biasing

- Voltage at X is determined by $V_{DD}$, $R_1$, and $R_2$.
- $V_{GS}$ can be found using the equation above, and $I_D$ can be found by using the NMOS current equation.
Self-Biased MOS Stage

The circuit above is analyzed by noting M1 is in saturation and no potential drop appears across $R_g$.

\[ I_D R_D + V_{GS} + R_s I_D = V_{DD} \]

Current Sources

- When in saturation region, a MOSFET behaves as a current source.
- NMOS draws current from a point to ground (sinks current), whereas PMOS draws current from $V_{DD}$ to a point (sources current).
Common-Source Stage

\[ \lambda = 0 \]
\[ A_v = -g_m R_D \]
\[ A_v = -\sqrt{\frac{2\mu C_W}{L} I_D R_D} \]

Operation in Saturation

\[ R_D I_D < V_{DD} - (V_{GS} - V_{TH}) \]

- In order to maintain operation in saturation, \( V_{out} \) cannot fall below \( V_{in} \) by more than one threshold voltage.
- The condition above ensures operation in saturation.
CS Stage with $\lambda=0$

$A_v = -g_m R_L$

$R_{in} = \infty$

$R_{out} = R_L$

However, Early effect and channel length modulation affect CE and CS stages in a similar manner.
CS Gain Variation with Channel Length

\[ |A_v| = \frac{2 \mu \cdot C_{ox} \cdot W}{\lambda \cdot I_D} \propto \sqrt{\frac{2 \mu \cdot C_{ox} \cdot W \cdot L}{I_D}} \]

- Since \( \lambda \) is inversely proportional to \( L \), the voltage gain actually becomes proportional to the square root of \( L \).

CS Stage with Current-Source Load

\[ A_v = -g_{m1} \left( r_{O1} \parallel r_{O2} \right) \]
\[ R_{out} = r_{O1} \parallel r_{O2} \]

- To alleviate the headroom problem, an active current-source load is used.
- This is advantageous because a current-source has a high output resistance and can tolerate a small voltage drop across it.
Similarly, with PMOS as input stage and NMOS as the load, the voltage gain is the same as before.

\[ A_v = -g_{m2}(r_{o1} \parallel r_{o2}) \]

Lower gain, but less dependent on process parameters.
CS Stage with Diode-Connected PMOS Device

$$A_v = -g_{m2} \left( \frac{1}{g_{m1}} \| r_{o1} \| r_{o2} \right)$$

- Note that PMOS circuit symbol is usually drawn with the source on top of the drain.

CS Stage with Degeneration

$$A_i = -\frac{R_D}{\frac{1}{g_m} + R_S}$$

- Similar to bipolar counterpart, when a CS stage is degenerated, its gain, I/O impedances, and linearity change.
Example of CS Stage with Degeneration

A diode-connected device degrades a CS stage.

\[ A_y = -\frac{R_D}{1 + \frac{1}{g_{m1} g_{m2}}} \]

CS Stage with Gate Resistance

\[ V_{RG} = 0 \]

Since at low frequencies, the gate conducts no current, gate resistance does not affect the gain or I/O impedances.
Similar to the bipolar counterpart, degeneration boosts output impedance.

\[ r_{out} \approx g_m r_o R_s + r_O \]

Output Impedance Example (I)

When \( \frac{1}{g_m} \) is parallel with \( r_{o2} \), we often just consider \( \frac{1}{g_m} \).
In this example, the impedance that degenerates the CS stage is \( r_{o1} \), instead of \( 1/g_m \) in the previous example.

\[
R_{\text{out}} \approx g_m r_{o1} r_{o2} + r_{o1}
\]

Degeneration is used to stabilize bias point, and a bypass capacitor can be used to obtain a larger small-signal voltage gain at the frequency of interest.
Common-Gate Stage

- Common-gate stage is similar to common-base stage: a rise in input causes a rise in output. So the gain is positive.

\[ A_v = g_m R_D \]

Signal Levels in CG Stage

- In order to maintain M1 in saturation, the signal swing at \( V_{out} \) cannot fall below \( V_b - V_{TH} \).
The input and output impedances of CG stage are similar to those of CB stage.

\[ R_{in} = \frac{1}{g_m} \quad \lambda = 0 \quad R_{out} = R_D \]

- The input and output impedances of CG stage are similar to those of CB stage.

When a source resistance is present, the voltage gain is equal to that of a CS stage with degeneration, only positive.

\[ A_v = \frac{R_D}{\frac{1}{g_m} + R_S} \]
### Generalized CG Behavior

When a gate resistance is present it does not affect the gain and I/O impedances since there is no potential drop across it (at low frequencies).

The output impedance of a CG stage with source resistance is identical to that of CS stage with degeneration.

\[
R_{\text{out}} = (1 + g_m r_O) R_s + r_O
\]

### Example of CG Stage

Diode-connected \( M_2 \) acts as a resistor to provide the bias current.
CG Stage with Biasing

R1 and R2 provide gate bias voltage, and R3 provides a path for DC bias current of M1 to flow to ground.

\[
\frac{v_{out}}{v_{in}} = \frac{R_3 \parallel (1/g_m)}{R_3 \parallel (1/g_m) + R_3} \cdot g_m R_D
\]

Source Follower Stage

\[A_v < 1\]
Similar to the emitter follower, the source follower can be analyzed as a resistor divider.

In this example, $M_2$ acts as a current source.
The output impedance of a source follower is relatively low, whereas the input impedance is infinite (at low frequencies); thus, a good candidate as a buffer.

$R_{out} = \frac{1}{g_m} \parallel r_O \parallel R_L \approx \frac{1}{g_m} \parallel R_L$

- $R_G$ sets the gate voltage to $V_{DD}$, whereas $R_S$ sets the drain current.
- The quadratic equation above can be solved for $I_D$. 

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{DD} - I_D R_S - V_{TH})^2$$
If $R_g$ is replaced by a current source, drain current $I_D$ becomes independent of supply voltage.

Example of a CS Stage (I)

$A_v = -g_{m1} \left( \frac{1}{g_{m3}} \parallel \frac{r_{O1}}{r_{O2}} \parallel r_{O3} \right)$

$R_{out} = \frac{1}{g_{m3}} \parallel \frac{r_{O1}}{r_{O2}} \parallel r_{O3}$

$M_1$ acts as the input device and $M_2, M_3$ as the load.
Example of a CS Stage (II)

- $M_1$ acts as the input device, $M_3$ as the source resistance, and $M_2$ as the load.

\[
A_I = -\frac{r_{O2}}{\frac{1}{g_{m1}} + \frac{1}{g_{m3}} \parallel r_{O3}}
\]

Examples of CS and CG Stages

- With the input connected to different locations, the two circuits, although identical in other aspects, behave differently.

\[
A_{v,CS} = -g_{m2}[(1+g_{m1}r_{O1})R_S + r_{O1}] \parallel r_{O1}
\]

\[
A_{v,CG} = -\frac{r_{O2}}{\frac{1}{g_m} + R_S}
\]
Example of a Composite Stage (I)

By replacing the left side with a Thevenin equivalent, and recognizing the right side is actually a CG stage, the voltage gain can be easily obtained.

\[ A_v = \frac{R_D}{1 + \frac{1}{g_{m1} g_{m2}}} \]

Example of a Composite Stage (II)

This example shows that by probing different places in a circuit, different types of output can be obtained.

\[ v_{out2} = \frac{1}{g_{m3} \| r_{O3} \| r_{O4}} \]
\[ v_{in} = \frac{1}{g_{m2} \| r_{O2} + \frac{1}{g_{m1}}} \]

\( V_{out1} \) is a result of \( M_4 \) acting as a source follower whereas \( V_{out2} \) is a result of \( M_1 \) acting as a CS stage with degeneration.