3. Fundamental MOS Configurations and Discrete MOS Amplifiers

Reading: Sedra & Smith: Secs. 5.6 & 5.7
Voltage Amplifier Model
Voltage Amplifier Model

Input Resistance: \( R_i = \frac{v_i}{i_i} \)

Open-loop gain: \( A_{vo} = \frac{v_o}{v_i} \) with no load

Output resistance: \( R_o \) (resistance seen between output terminals with \( v_i = 0 \))

We focus on Unilateral amplifiers (i.e., \( R_i \) is independent of Load)

\[
\begin{align*}
\frac{v_i}{v_S} &= \frac{R_i}{R_i + R_{sig}} \\
\frac{v_o}{v_{in}} &= A_v = A_{vo} \cdot \frac{R_L}{R_L + R_o} \\
\frac{v_{out}}{v_S} &= \frac{R_i}{R_i + R_{sig}} \cdot A_{vo} \cdot \frac{R_L}{R_L + R_o}
\end{align*}
\]
Cascaded Amplifiers

\[
\frac{v_{i1}}{v_s} = \frac{R_{i1}}{R_{i1} + R_{sig}} = \frac{1\text{M}}{1\text{M}+100\text{k}} = 0.91
\]

\[
v_{o1} = v_{i2} \quad R_{L1} = R_{i2} = 100\text{k} \quad A_{v1} = \frac{v_{i2}}{v_{i1}} = A_{v_{o1}} \cdot \frac{R_{L1}}{R_{L1} + R_{o1}} = 10 \cdot \frac{100\text{k}}{100\text{k}+1\text{k}} = 9.9
\]

\[
v_{o2} = v_{i3} \quad R_{L2} = R_{i3} = 10\text{k} \quad A_{v2} = \frac{v_{i3}}{v_{i2}} = A_{v_{o2}} \cdot \frac{R_{L2}}{R_{L2} + R_{o2}} = 100 \cdot \frac{10\text{k}}{10\text{k}+1\text{k}} = 90.9
\]

\[
A_{v3} = \frac{v_L}{v_{i3}} = A_{v_{o3}} \cdot \frac{R_{L3}}{R_{L3} + R_{o3}} = 1 \cdot \frac{100}{100+10} = 0.909
\]

\[
A_v = \frac{v_L}{v_{i1}} = A_{v1} \cdot A_{v2} \cdot A_{v3} = 818
\]

\[
\frac{v_L}{v_s} = A_v \cdot \frac{v_{i1}}{v_s} = 818 \times 0.91 = 744
\]
MOS Fundamental Configurations
MOS fundamental amplifier configurations

Since PMOS has the same signal model, configurations and results are exactly the same
Common Source Configuration

Small Signal Circuit:

Small Signal Circuit with MOS SSM
Common Source Configuration (Gain)

Small Signal Circuit with MOS SSM

Relevant circuit for Gain calculation

\[ v_o = -g_m v_{gs} \left( r_o \parallel R_D \parallel R_L \right) \]

\[ A_v = \frac{v_o}{v_{in}} = -g_m \left( r_o \parallel R_D \parallel R_L \right) \]

\[ A_{vo} = -g_m \left( r_o \parallel R_D \right) \]
Common Source Configuration ($R_i$)

Small Signal Circuit with MOS SSM

Relevant circuit for $R_i$ calculation

$$i_i = 0$$

$$R_i = \frac{v_i}{i_i} = \infty$$
Common Source Configuration \((R_o)\)

Small Signal Circuit with MOS SSM

Relevant circuit for \(R_o\) calculation (set \(v_i = 0\))

Current source becomes open circuit
\[ R_o = r_o \parallel R_D \]
Common Source with Source Resistor

Small Signal Circuit:

Small Signal Circuit with MOS SSM

Input Resistance

\[ i_i = 0 \Rightarrow R_i = \frac{v_i}{i_i} = \infty \]
Common Source with Source Resistor (Gain*)

Node voltage method:

\[ v_{gs} = v_i - v_S \]

Node \( v_S \)

\[ \frac{v_S}{R_S} + \frac{v_S - v_o}{r_o} - g_m (v_i - v_S) = 0 \]

Node \( v_o \)

\[ \frac{v_o}{R_D \parallel R_L} + \frac{v_o - v_S}{r_o} + g_m (v_i - v_S) = 0 \]

Relevant circuit for Gain calculation

\[ A_v = \frac{v_o}{v_i} = -\frac{g_m r_o (R_D \parallel R_L)}{r_o + (1 + g_m r_o) R_S + (R_D \parallel R_L)} \]

\[ A_v \approx -\frac{g_m (R_D \parallel R_L)}{1 + g_m R_S + (R_D \parallel R_L) / r_o} \]

\[ A_{vo} = -\frac{g_m R_D}{1 + g_m R_S + R_D / r_o} \]

* Text book ignore \( r_o \)
Common Source with Source Resistor ($R_o^*$)

- set $v_i = 0$
- Attach $i_x$ and compute $v_x$

Node voltage method:

$$v_{gs} = -v_S$$

Node $v_s$

$$\frac{v_S}{R_S} + \frac{v_S - v_x}{r_o} - g_m(-v_S) = 0$$

$$\frac{v_s}{R_S} = \frac{v_x}{r_o + (1 + g_m r_o) R_S}$$

$$i_x = i_1 + i_2 = \frac{v_S}{R_S} + \frac{v_x}{R_D}$$

$$i_x = \frac{v_x}{R_o} + \frac{v_x}{r_o + (1 + g_m r_o) R_S} + \frac{v_x}{R_D}$$

Noting: $$\frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{R_1 \parallel R_2}$$

$$R_o = [r_o + (1 + g_m r_o) R_S] \parallel R_D$$

* Text book ignore $r_o$
Common Gate Configuration

Small Signal Circuit:

Small Signal Circuit with MOS SSM
Common Gate Configuration (Gain*)

Node voltage method:

\[ v_{gs} = -v_i \]

\[ \frac{v_o}{R_D \parallel R_L} + \frac{v_o - v_i}{r_o} + g_m(-v_i) = 0 \]

\[ \frac{v_o}{r_o \parallel R_D \parallel R_L} = \frac{1 + g_mr_o}{v_i} \]

Relevant circuit for Gain calculation

\[ A_v = \frac{v_o}{v_i} = \frac{1 + g_mr_o}{v_i} \]

\[ A_v \approx g_m(r_o \parallel R_D \parallel R_L) \]

\[ A_{vo} \approx g_m(r_o \parallel R_D) \]
Common Gate Configuration \((R_i \text{ and } R_o \ast)\)

**Input Resistance**

\[ R_i = \frac{v_i}{i_i} = \frac{r_o + R_D \parallel R_L}{1 + g_m r_o} \]

\[ R_i \approx \frac{1}{g_m} + \frac{R_D \parallel R_L}{g_m r_o} \]

**Output Resistance (set \(v_i = 0\))**

Current source becomes open circuit

\[ R_o = r_o \parallel R_D \]

\* Text book ignore \(r_o\)
Common Drain Configuration (Source Follower)

Note: This circuit needs a load as it is really a current amplifier.

Gain

Node voltage method:

\[ v_{gs} = v_i - v_o \]

Node \( v_s \)

\[ \frac{v_o}{R_L} + \frac{v_o}{r_o} - g_m(v_i - v_o) = 0 \]

\[ g_m v_i = \frac{v_o}{r_o || R_L} + g_m v_o \]

\[ A_v = \frac{g_m (r_o || R_L)}{1 + g_m (r_o || R_L)} \]

\[ A_{vo} = \frac{g_m r_o}{1 + g_m r_o} \approx 1 \]
**Common Drain Configuration (Source Follower)**

### Input Resistance

\[ i_i = 0 \]

\[ R_i = \frac{v_i}{i_i} = \infty \]

### Output Resistance (set \( v_i = 0 \))

\[ i_x = \frac{v_x}{r_o} - g_m v_{gs} = \frac{v_x}{r_o} + \frac{v_x}{1/g_m} \]

\[ R_o = \frac{1}{g_m} \parallel r_o \approx \frac{1}{g_m} \]
Summary of MOS Amp. Fundamental Forms
(PMOS circuits are identical)

**Common Source**

\[ A_v = -g_m \left( r_o \parallel R_D \parallel R_L \right) \]

**Common Gate**

\[ A_v = g_m \left( r_o \parallel R_D \parallel R_L \right) \]

**Common Source with RS**

\[ A_v = \frac{g_m (R_D \parallel R_L)}{1 + g_m R_S + (R_D \parallel R_L) / r_o} \]

**Common Drain/Source Follower**

\[ A_v = \frac{g_m (r_o \parallel R_L)}{1 + g_m (r_o \parallel R_L)} \]
Transistor can be configured to act as a resistor for small signals!

Ex: Output resistance of a CS Amplifier

Set $v_i = 0$, current source becomes open circuit

$$R_o = r_o \parallel R_D$$

- If we connect any two terminals of a MOS, we get a two-terminal device.
  - For Small Signals, this two terminal device can be replaced with its Thevenin equivalent circuit.
  - As there is NO independent sources present, the Thevenin equivalent circuit is reduced to a resistor.
Transistor can be configured to act as a resistor for small signals!

- But, MOS should be in saturation for small signal model to work!
  - Connection between MOS terminals are, therefore, made through ground for small signals.
  - In fact, one or both MOS terminals have to be connected to bias power supplies to ensure that MOS is in saturation.

Notation:

- $r_o$ is the small-signal resistance between the point and ground.

**Real Circuit**  
**Small Signal Circuit**

A)

B)

No Small Signal circuit
MOS is NOT in saturation
Elementary Configuration for MOS resistance
(PMOS circuits are identical)

\[ r_o (1 + g_m R) + R \approx r_o (1 + g_m R) \]

Output resistance of CS Amp with \( R_s \)

\[ \frac{r_o + R}{1 + g_m r_o} \approx \frac{1}{g_m} + \frac{R}{g_m r_o} \]

Input resistance of CG Amp

Input resistance of CS Amp

\[ \frac{1}{g_m} \parallel r_o \approx \frac{1}{g_m} \]

Diode-connected Transistor
Always in saturation!

Above configurations are for **Small Signal**. Typically one or both grounds are connected to bias voltage sources to ensure that MOS is in saturation!
Gain, input and output resistances of MOS amplifiers can be found using the fundamental amplifiers and elementary R configurations.
Discrete MOS Amplifiers

(Analysis using the fundamental Amplifiers and elementary R configurations)
Stable Bias circuits for discrete MOS amplifiers

One power supply

\[ V_{GS} = V_g - R_S I_D \]

Two power supplies

\[ V_{GS} = V_{SS} - R_S I_D \]

Identical small-signal circuit if

\[ R_G = R_1 \parallel R_2 \]

Drain Feedback

Will Discuss later

We will do analysis for this configuration
Signal is typically coupled to discrete amplifiers via coupling capacitors

- We assume that the small signals of interest are at sufficiently high frequencies, such that the (large) capacitors can be approximated as shorts.
  - A lower cut-off frequency for Amplifier

- These capacitors can be added at input, output, and between amplifier stages.

- These capacitor can also be used to "by-pass" resistors needed for bias but not for small-signal.
Discrete CS Amplifier

Real Circuit

Fundamental CS form

Test book uses current source for biasing (not a practical discrete circuit)
Derivation of small-signal circuit for Discrete CS Amplifier

Real Circuit

Short caps
Zero bias supplies

Rearrange
Fundamental CS form

Elementary R Configuration

\[ A_v = -g_m (r_o \parallel R_D \parallel R_L) \]

\[ R_i = R_G \]

\[ R_o = r_o \parallel R_D \]
Discrete CS Amplifier with $R_S$

Real Circuit

Small Signal Circuit
Discrete CS Amplifier with $R_S$

**Fundamental CS form with $R_S$**

**Elementary R Configuration**

**Elementary R Configuration**
Discrete CG Amplifier

Real Circuit

Small Signal Circuit
Discrete CG Amplifier

Fundamental CSGform

Elementary R Configuration

\[ A_v = g_m (r_o \parallel R_D \parallel R_L) \]

\[ R_i = R_S \parallel \left[ \frac{r_o + R_D \parallel R_L}{1 + g_m r_o} \right] \]

\[ R_o = r_o \parallel R_D \]
Discrete CD Amplifier (Source Follower)

Real Circuit

Small Signal Circuit
Discrete CD Amplifier (Source Follower)

**Fundamental CD form**

\[ A_v = \frac{g_m (r_o \parallel R_S \parallel R_L)}{1 + g_m (r_o \parallel R_S \parallel R_L)} \]

**Elementary R Configuration**

\[ R_i = R_G \]

\[ R_o = \frac{1}{g_m} \parallel R_S \]