ECE 255, MOSFET Basic Configurations

8 March 2018

In this lecture, we will go back to Section 7.3, and the basic configurations of MOSFET amplifiers will be studied similar to that of BJT. Previously, it has been shown that with the transistor DC biased at the appropriate point (Q point or operating point), linear relations can be derived between the small voltage signal and current signal. We will continue this analysis with MOSFETs, starting with the common-source amplifier.

1 Common-Source (CS) Amplifier

The common-source (CS) amplifier for MOSFET is the analogue of the common-emitter amplifier for BJT. Its popularity arises from its high gain, and that by cascading a number of them, larger amplification of the signal can be achieved.

1.1 Chararacteristic Parameters of the CS Amplifier

Figure 1(a) shows the small-signal model for the common-source amplifier. Here, R_D is considered part of the amplifier and is the resistance that one measures between the drain and the ground. The small-signal model can be replaced by its hybrid-π model as shown in Figure 1(b). Then the current induced in the output port is $i = -g_m v_{gs}$ as indicated by the current source. Thus

$$v_o = -g_m v_{gs} R_D \tag{1.1}$$

By inspection, one sees that

$$R_{\text{in}} = \infty, \quad v_i = v_{\text{sig}}, \quad v_{gs} = v_i \tag{1.2}$$

Thus the open-circuit voltage gain is

$$A_{vo} = \frac{v_o}{v_i} = -g_m R_D \tag{1.3}$$

Printed on March 14, 2018 at 10:48: W.C. Chew and S.K. Gupta.

One can replace a linear circuit driven by a source by its Thévenin equivalence. Then from the equivalent-circuit model in Figure 1(b), one can replace the output part of the circuit with a Thévenin or Norton equivalence. In this case, it is more convenient to use the Norton equivalence. To find the Norton equivalence resistance, one sets $v_i = 0$, which will make the current source an open circuit with zero current. And by the test-current method, the output resistance is

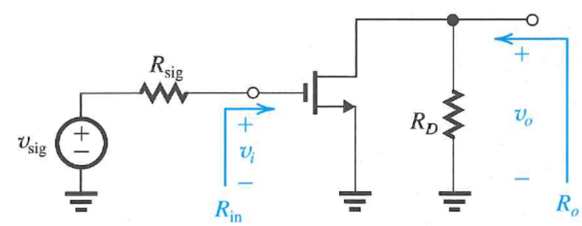
$$R_o = R_D \tag{1.4}$$

If now, a load resistor, R_L is connected to the output across R_D, then the voltage gain proper (also called terminal voltage gain), by the voltage divider formula, is

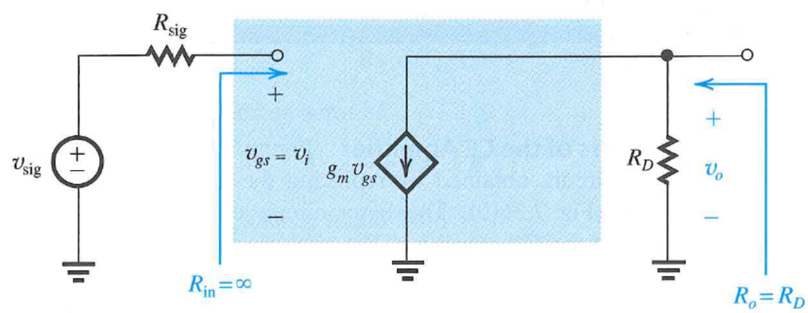
$$A_v = A_{vo}\frac{R_L}{R_L + R_o} = -g_m\frac{R_D R_L}{R_L + R_D} = -g_m(R_D \parallel R_L) \tag{1.5}$$

From the fact that $R_{\text{in}} = \infty$, then $v_i = v_{\text{sig}}$. The overall voltage gain, G_v, is the same as the voltage gain proper, A_v, namely

$$G_v = \frac{v_o}{v_{\text{sig}}} = -g_m(R_D \parallel R_L) \tag{1.6}$$



(a)



(b)

Figure 1: (a) Small-signal model for a common-source amplifier. (b) The hybrid-π model for the common-source amplifier (Courtesy of Sedra and Smith).

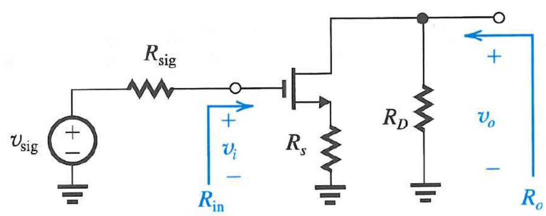
1.2 Final Remarks on CS Amplifier

1. The CS amplifiers has infinite input impedance (draws no current at DC), and a moderately high output resistance (easier to match for maximum power transfer), and a high voltage gain (a desirable feature of an amplifier).

2. Reducing R_D reduces the output resistance of a CS amplifier, but unfortunately, the voltage gain is also reduced. Alternate design can be employed to reduce the output resistance (to be discussed later).

3. A CS amplifier suffers from poor high frequency performance, as most transistor amplifiers do.

2 Common-Source Amplifier with a Source Resistance



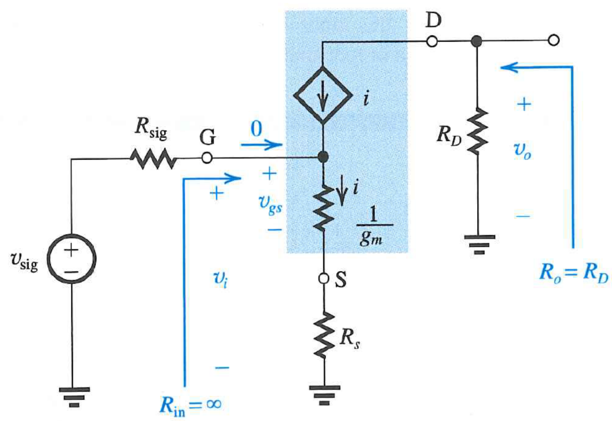


Figure 2: A CS amplifier with a source resistance: (top) detail circuit, and (bottom) equivalent circuit T model (Courtesy of Sedra and Smith).

As shown in Figure 2, a T model is used for the equivalent circuit for simplicity. It is seen that the input resistance of the circuit is infinite because no gate current flows. As a consequence, $v_i = v_{\text{sig}}$. However, because of the existence of the source resistance, less of the input voltage is divided to v_{gs}, by the voltage-divider formula. Thus

$$v_{gs} = v_i \frac{1/g_m}{1/g_m + R_s} = \frac{v_i}{1 + g_m R_s} \tag{2.1}$$

It is seen that R_s can be used to make v_{gs} small so that there is less nonlinear distortion as the small-signal approximations will become better. The output voltage is generated by the controlled current source yielding

$$v_o = -iR_D \tag{2.2}$$

The current i can be found by Ohm's law

$$i = \frac{v_i}{1/g_m + R_s} = \frac{g_m}{1 + g_m R_s} v_i \tag{2.3}$$

Thus the open-circuit voltage gain (assume that R_D is part of the amplifier) is

$$A_{vo} = \frac{v_o}{v_i} = -\frac{g_m R_D}{1 + g_m R_s} = -\frac{R_D}{1/g_m + R_s} \tag{2.4}$$

The above shows that including the source resistance reduces the amplifier gain by a factor of $1 + g_m R_s$, but linearity and bandwidth performance (to be shown later) will improve. This is called negative feedback because when the input voltage v_i or v_{gs} attempts to increase, the voltage drop across R_s increases reducing v_{gs}. The source resistance is also called **source-degeneration resistance**.

Since this is a linear circuit, the Thévenin equivalence of the amplifier looking in from the right can be easily found. The open-circuit voltage allows us to easily find the equivalent Thévenin voltage source. The equivalent Thévenin resistor is R_o which is just R_D in this case.

When a load resistor R_L is added, then the voltage gain proper (also called terminal voltage gain) is

$$A_v = -\frac{g_m (R_D \parallel R_L)}{1 + g_m R_s} = -\frac{R_D \parallel R_L}{1/g_m + R_s} \tag{2.5}$$

Because the input resistance is infinite, hence $v_i = v_{\mathrm{sig}}$ and the overall voltage gain $G_v = A_v$.

2.1 Summary of the CS Amplifier with Source Resistance

1. The input resistance R_{in} is infinite.
2. The open-circuit voltage gain, A_{vo}, is reduced by a factor of $1 + g_m R_s$ as seen in (2.4).
3. For the same nonlinear distortion, the input signal can be increased by a factor of $1 + g_m R_s$ compared to without R_s.
4. As shall be shown later, the high-frequency response of this design is improved.

In general, the addition of the source resistance R_s gives rise to a "negative" feedback factor $1 + g_m R_s$ that reduces voltage gain, but improves linearity, and high-frequency response. Because of the negative-feedback action of R_s, it is also called the **source-degenerate resistance.**

3 Common-Gate (CG) Amplifier

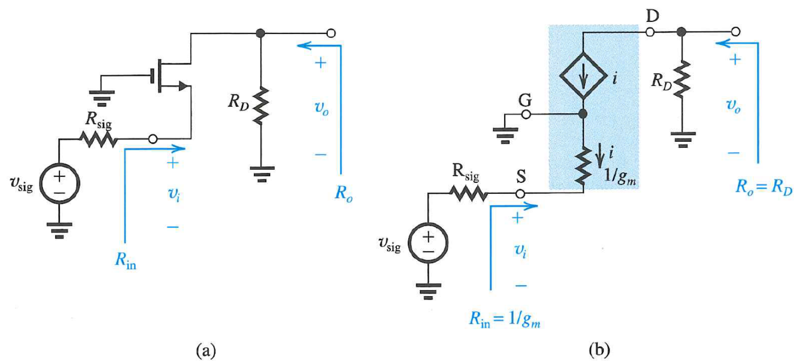


Figure 3: (a) Small-signal model for a common-gate amplifier. (b) The T model equivalent circuit for the common-gate amplifier. Note that the gate current is always zero in the T model (Courtesy of Sedra and Smith).

The small-signal and a T-model equivalent-circuit common-gate (CG) amplifier is shown in Figure 3. By inspection, the input resistance R_{in} is given by

$$R_{\text{in}} = \frac{1}{g_m} \tag{3.1}$$

which is typically a few hundred ohms, a low input impedance. The output voltage is

$$v_o = -iR_D, \text{ where } i = -\frac{v_i}{1/g_m} = -g_m v_i \tag{3.2}$$

Hence the open-circuit voltage gain is

$$A_{vo} = \frac{v_o}{v_i} = g_m R_D \tag{3.3}$$

which is similar to that of the CS amplifier save for a sign change. The output resistance (or the Thévenin equivalent resistor) of the circuit is

$$R_o = R_D \tag{3.4}$$

The smaller input impedance is deleterious to the amplifier gain, as by the voltage divider formula, one gets

$$\frac{v_i}{v_{\text{sig}}} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} = \frac{1/g_m}{1/g_m + R_{\text{sig}}} \tag{3.5}$$

meaning that the v_i is attenuated compared to v_{sig}, since R_{sig} is typically larger than $1/g_m$.

When a load resistor R_L is connected to the output, the voltage gain proper (terminal voltage gain) is then

$$A_v = g_m R_D \parallel R_L \tag{3.6}$$

Thus the overall voltage gain is

$$G_v = \frac{1/g_m}{R_{\text{sig}} + 1/g_m} g_m (R_D \parallel R_L) = \frac{R_D \parallel R_L}{R_{\text{sig}} + 1/g_m} \tag{3.7}$$

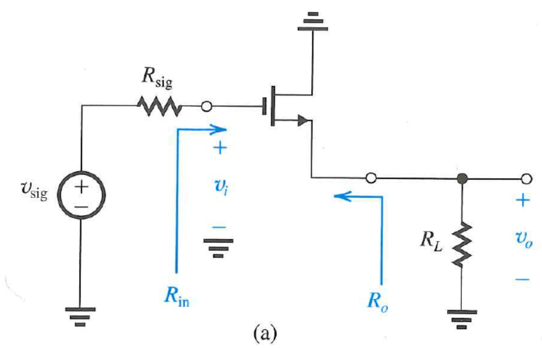
As the input impedance is low, it is good for matching sources with a low input impedance due the the maximum power theorem, but it draws more current, implying high power consumption from the signal source.

3.1 Summary of the CG Amplifier

1. The CG amplifier has a low input resistance $1/g_m$. This is undesirable as it will draw large current when driven by a voltage input.
2. The voltage gain of the CG amplifier can be made similar in magnitude to that of the CS amplifier if $R_D || R_L$ can be made large compared to $R_{\text{sig}} + 1/g_m$.
3. The output resistance can be made large since $R_o = R_D$.
4. The CG amplifier has good high frequency performance as shall be shown later.

4 The Source Follower (Common Drain Amplifier)

This is similar to the emitter follower for the BJT, which is used as a voltage buffer. It is a unit-gain amplifier with a very large input impedance but a smaller output impedance. Therefore it is good for matching a high-impedance circuit to a low-impedance circuit or to a circuit that needs a larger supply of current.



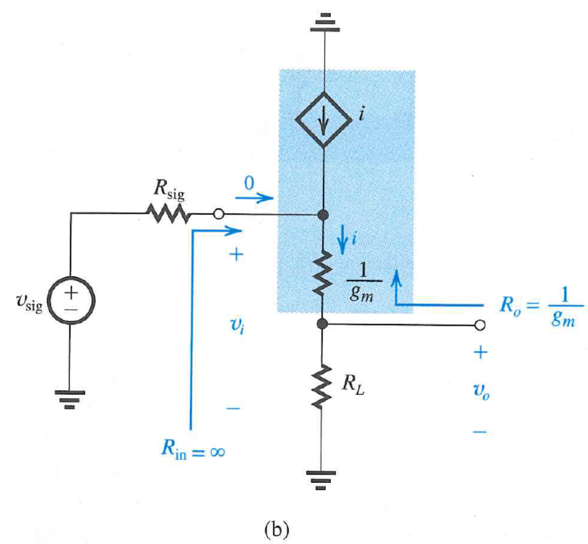


Figure 4: (a) Common-drain MOSFET amplifier or source follower for small signals. (b) The T model equivalent circuit for the common-drain or source follower amplifier. Note that the gate current is always zero in this model (Courtesy of Sedra and Smith).

4.1 Characteristics of a Source Follower

Figure 4 shows the small-signal circuit and a T-model equivalent circuit diagram for a source follower. The input source is represented by a Thévenin equivalent voltage v_{sig} and resistor R_{sig}. A load resistor is connected to the output between the source and ground.

Since the gate current is zero for this circuit,

$$R_{\text{in}} = \infty \tag{4.1}$$

Using the voltage divider formula, it is seen that voltage gain proper or terminal voltage gain is

$$A_v = \frac{v_o}{v_i} = \frac{R_L}{R_L + 1/g_m} \tag{4.2}$$

For the open-circuit voltage gain, $R_L = \infty$ and

$$A_{vo} = 1 \tag{4.3}$$

The output resistance is obtained by replacing the proper part of the amplifier with a Thévenin equivalence. To this end, with the use of the test-current method, one sets the value of $v_i = 0$, and thus

$$R_o = 1/g_m \tag{4.4}$$

Because of the infinite input impedance R_{in}, then $v_i = v_{\text{sig}}$, and the overall voltage gain G_v (also called the total voltage gain) is the same as the voltage gain proper A_v (also called terminal voltage gain)

$$G_v = A_v = \frac{R_L}{R_L + 1/g_m} \tag{4.5}$$

Since $1/g_m$ is typically small, with large R_L, the gain is less than unity, but is close to unity. Hence, this is a *source follower*, because the source voltage follows the input voltage, but yet, it can provide a larger current to the output than the input current.

5 Summary Table and Comparisons

The following concluding points are in order for the MOSFET and BJT amplifiers.

1. MOS amplifiers have high input impedance (except for CG amplifiers). This is an advantage over BJT amplifiers.

2. BJT's have higher transconductance g_m than MOSFET's giving BJT amplifiers higher gains.

3. Discrete-circuit amplifiers, e.g., circuits assembled on printed-circuit board (PCB), BJT's are prevalent because of their longer history and wider commercial availability.

4. Because of easier fabrication, integrated circuit (IC) amplifiers are dominated by MOSFET's.

5. The CS and CE configurations are best suited for gain amplifiers because of their larger than unity gain. A cascade of them can be used to increase the gain.

6. The addition of R_s in a CS amplifier and R_e in a CE amplifier improves the linearity of the circuit and better high frequency performance.

7. The CE and CS designs have both high voltage and current gains. The CB and CG designs have low current gain, but still high voltage gain. The CC and CD designs (emitter and source followers) have low voltage gain, but high current gain.

Table 7.4 from Sedra and Smith summarizes the characteristics of the MOSFET amplifiers.

Table 7.4 Characteristics of MOSFET Amplifiers

	Characteristics[a]				
Amplifier type	R_{in}	A_{vo}	R_o	A_v	G_v
Common source (Fig. 7.35)	∞	$-g_m R_D$	R_D	$-g_m(R_D \parallel R_L)$	$-g_m(R_D \parallel R_L)$
Common source with R_s (Fig. 7.37)	∞	$-\dfrac{g_m R_D}{1+g_m R_s}$	R_D	$\dfrac{-g_m(R_D \parallel R_L)}{1+g_m R_s}$ $-\dfrac{R_D \parallel R_L}{1/g_m + R_s}$	$-\dfrac{g_m(R_D \parallel R_L)}{1+g_m R_s}$ $-\dfrac{R_D \parallel R_L}{1/g_m + R_s}$
Common gate (Fig. 7.39)	$\dfrac{1}{g_m}$	$g_m R_D$	R_D	$g_m(R_D \parallel R_L)$	$\dfrac{R_D \parallel R_L}{R_{sig} + 1/g_m}$
Source follower (Fig. 7.42)	∞	1	$\dfrac{1}{g_m}$	$\dfrac{R_L}{R_L + 1/g_m}$	$\dfrac{R_L}{R_L + 1/g_m}$

[a] For the interpretation of R_{in}, A_{vo}, and R_o, refer to Fig. 7.34(b).