ECE 255, MOSFET Amplifiers

26 October 2017

In this lecture, 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

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

One can replace a linear circuit driven by a source by its Thévenin equivalence. Then from the equivalent-circuit model in Figure 1(b) and the test-current method by setting $v_i = 0$, the output resistance, which is the Thévenin resistor is

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

Printed on October 26, 2017 at 15:23: W.C. Chew and Z.H. Chen.

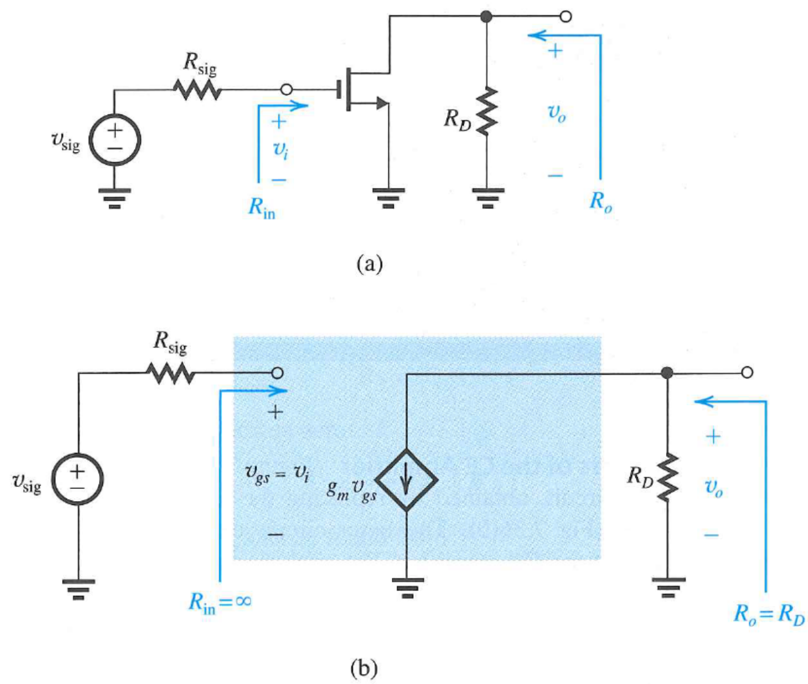

Figure 1: (a) Small-signal model for a common-source amplifier. (b) The hybrid-π model for the common-source amplifier (Courtesy of Sedra and Smith).

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

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

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), and a high voltage gain (a desirable feature of an amplifier).

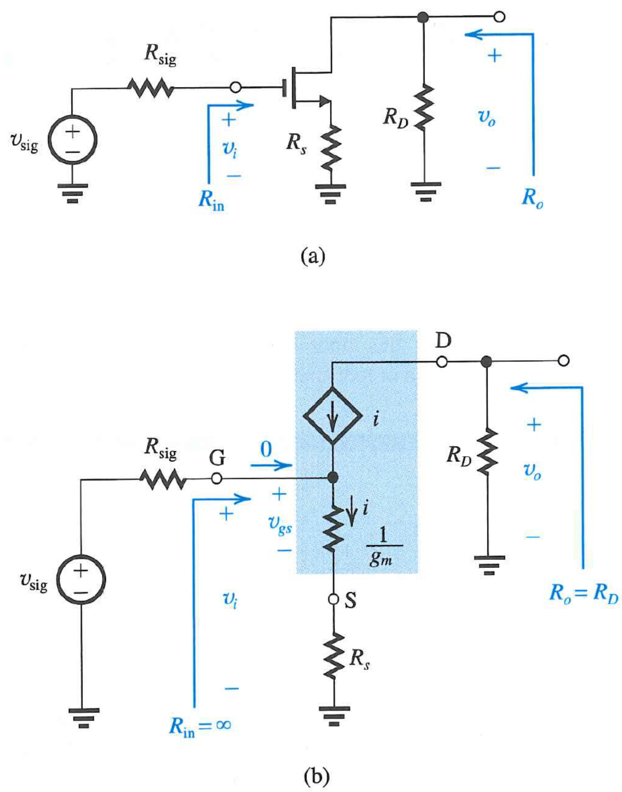

Figure 2: A CS amplifier with a source resistance: (top) detail circuit, (bottom) equivalent circuit T model (Courtesy of Sedra and Smith).

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

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

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

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)

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

Because the input resistance is infinite, hence $v_i = v_{\text{sig}}$ 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.

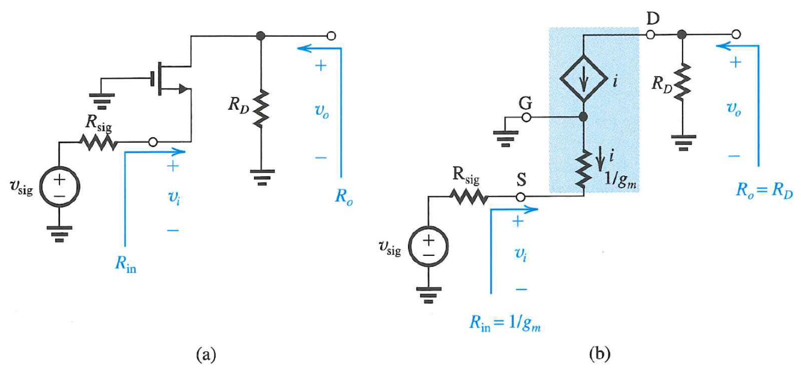

Figure 3: (a) Small-signal model for a common-gate amplifier. (b) The T model equivalent circuit for the common-gate amplifier. Note that the gate current is always zero in the T model (Courtesy of Sedra and Smith).

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

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

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

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.

4 The Source Follower

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.

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,

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

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, the value of $v_i = 0$, and thus

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

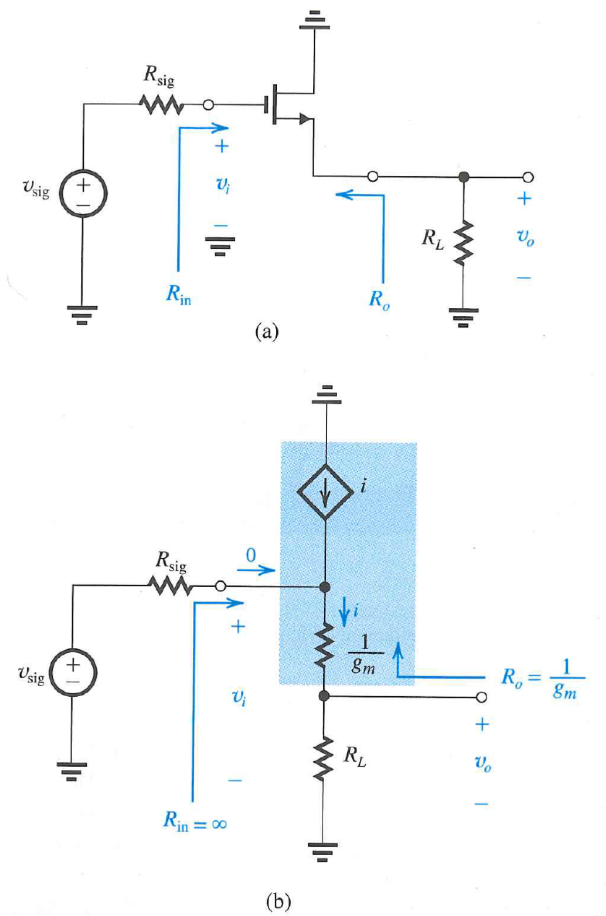

Figure 4: (a) Common-drain MOSFET amplifier or source follower for small signals. (b) The T model equivalent circuit for the common-drain or source follower amplifier. Note that the gate current is always zero in this model (Courtesy of Sedra and Smith).

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*.

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 improves the linearity of the circuit and better high frequency performance.

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

6 Discrete-Circuit Amplifiers

Due to history and tradition, most discrete-circuit amplifiers are BJT's. Also, capacitive coupling is often used in discrete amplifier design. They make the design simpler as capacitors are DC blockers, and can be approximated as a short circuit for AC signals.

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)	∞	$-\frac{g_m R_D}{1+g_m R_s}$	R_D	$\frac{-g_m(R_D \parallel R_L)}{1+g_m R_s}$ $-\frac{R_D \parallel R_L}{1/g_m + R_s}$	$-\frac{g_m(R_D \parallel R_L)}{1+g_m R_s}$ $-\frac{R_D \parallel R_L}{1/g_m + R_s}$
Common gate (Fig. 7.39)	$\frac{1}{g_m}$	$g_m R_D$	R_D	$g_m(R_D \parallel R_L)$	$\frac{R_D \parallel R_L}{R_{sig} + 1/g_m}$
Source follower (Fig. 7.42)	∞	1	$\frac{1}{g_m}$	$\frac{R_L}{R_L + 1/g_m}$	$\frac{R_L}{R_L + 1/g_m}$

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

6.1 A Common-Source (CS) Amplifier

The circuit to be analyzed here is shown in Figiure 5(a). The bias point which is a DC operating point, is determined by Figure 5(b) where all capacitors are open circuited. The small signal model, which is for AC signal, is shown in Figure 5(c) where all capacitors are short circuited.

It is noted that the MOSFET source (S) terminal is grounded for the AC signal because of the large coupling capacitor C_S, and hence, it is also called the **signal ground** or **AC ground**. Hence, C_S is also called the **bypass capacitor** as its impedance is much smaller than that of R_S. The presence of R_S is to stabilize the biasing point. Looking at Figure 5(b), if R_S is not there, since V_{GS} is small, and hence, V_G has to be small. Thus, all of the fluctuation of V_G will appear across V_{GS}. However, with R_S present, any fluctuation in V_G will be shared by V_{GS} and the voltage drop across R_S.

Then C_{C1} is another **coupling capacitor**, which will be acting approximately like a short circuit to AC signals, but is a DC blocker. The second coupling capacitor C_{C2} is also acting like a short circuit to the AC signal, or the small signal. These give the rational for the small signal model in Figure 5(c).

Using the small signal model for AC signals, and the hybrid-π model for MOSFET as shown in Figure 5(c), it is seen that

$$R_{in} = R_{G1} \parallel R_{G2} \tag{6.1}$$

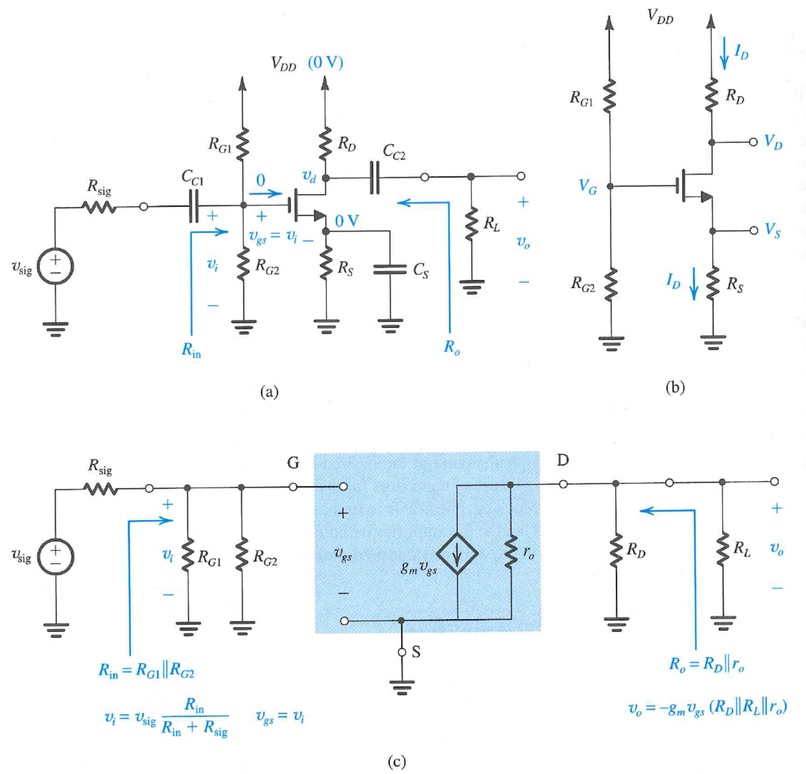

Figure 5: (a) Common-source MOSFET amplifier with the biasing circuit in place. (b) The biasing circuit at DC, where the capacitors are open circuited. (c) Small signal equivalent circuit model for AC signals where the capacitors are assumed to be short circuited (Courtesy of Sedra and Smith).

Here, R_{in} can be kept high by making R_{G1} and R_{G2} high, usually in the megaohm range. It is seen that the voltage gain proper (terminal voltage gain) is

$$A_v = -g_m(R_D \parallel R_L \parallel r_o) \tag{6.2}$$

and the overall voltage gain

$$G_v = -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m(R_D \parallel R_L \parallel r_o) \tag{6.3}$$

6.2 A Common-Emitter Amplifier

This is the most commonly used configuration of the BJT amplifiers, as shown in Figure 6(a) with the coupling capacitors C_{C1} and C_{C2}, and the bypass capacitor

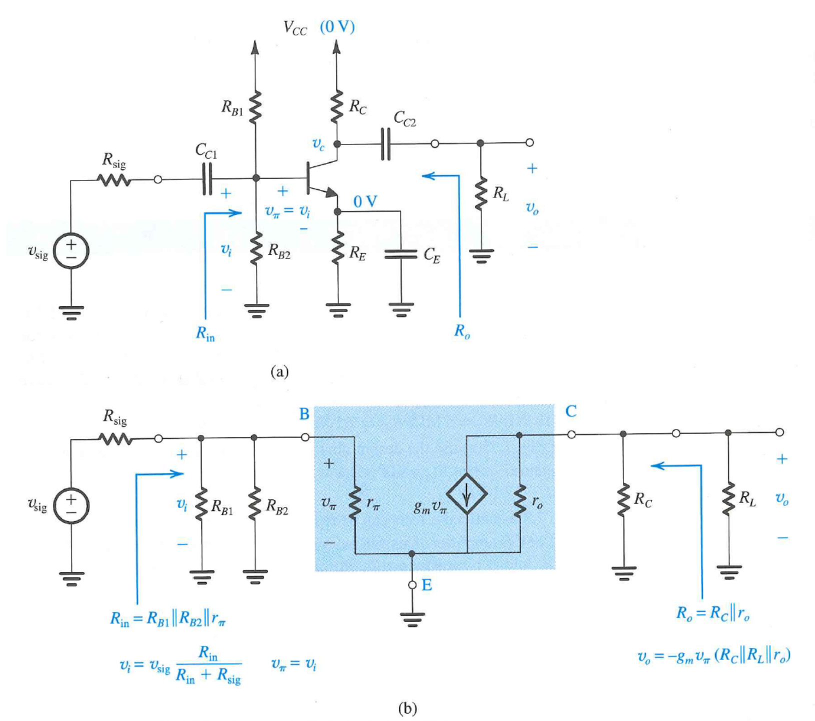

Figure 6: (a) Common-emitter BJT amplifier with the biasing circuit in place. (b) The biasing circuit at DC, where the capacitors are open circuited. (c) Small signal equivalent circuit model for AC signals where the capacitors are assumed to be short circuited (Courtesy of Sedra and Smith).

C_E in place. These capacitors, to simplify the analysis, are assumed to be open circuited for DC or the bias-point analysis, but are short circuited for the AC small signal analysis. Again, as in the MOSFET case, R_E is there to stabilize the bias point of the base voltage.

The equivalent small signal model is shown in Figure 6(b). From it, it is seen that

$$R_{\text{in}} = R_{B1} \parallel R_{B2} \parallel r_\pi \tag{6.4}$$

In the above R_{B1} and R_{B2} should be kept large, around tens to hundreds of kilo-ohms, to maintain high input impedance.

The overall voltage gain G_v is then given by

$$G_v = -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m (R_C \parallel R_L \parallel r_o) \tag{6.5}$$