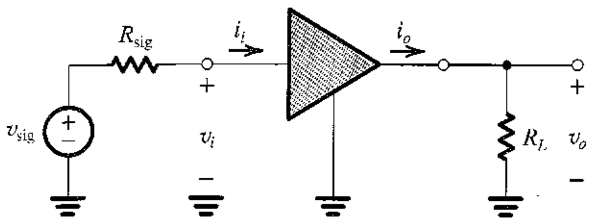
TABLE 4.3 Characteristic Parameters of Amplifiers

Circuit



Definitions

- Input resistance with no load:

$$R_i \equiv \left.\frac{v_i}{i_i}\right|_{R_L=\infty}$$

- Input resistance:

$$R_{in} \equiv \frac{v_i}{i_i}$$

- Open-circuit voltage gain:

$$A_{vo} \equiv \left.\frac{v_o}{v_i}\right|_{R_L=\infty}$$

- Voltage gain:

$$A_v \equiv \frac{v_o}{v_i}$$

- Short-circuit current gain:

$$A_{is} \equiv \left.\frac{i_o}{i_i}\right|_{R_L=0}$$

- Current gain:

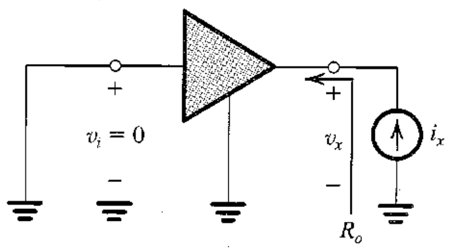
$$A_i \equiv \frac{i_o}{i_i}$$

- Short-circuit transconductance:

$$G_m \equiv \left.\frac{i_o}{v_i}\right|_{R_L=0}$$

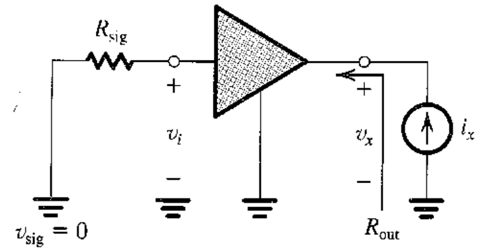
- Output resistance of amplifier proper:

$$R_o \equiv \left.\frac{v_x}{i_x}\right|_{v_i=0}$$



- Output resistance:

$$R_{out} \equiv \left.\frac{v_x}{i_x}\right|_{v_{sig}=0}$$



- Open-circuit overall voltage gain:

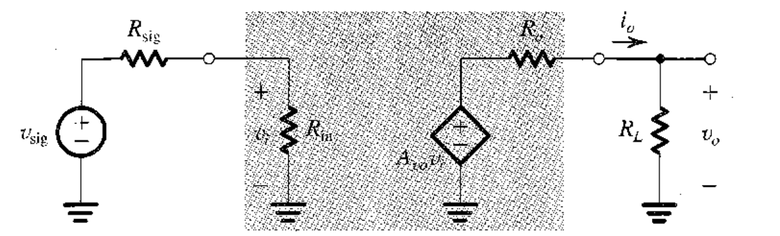
$$G_{vo} \equiv \left.\frac{v_o}{v_{sig}}\right|_{R_L=\infty}$$

- Overall voltage gain:

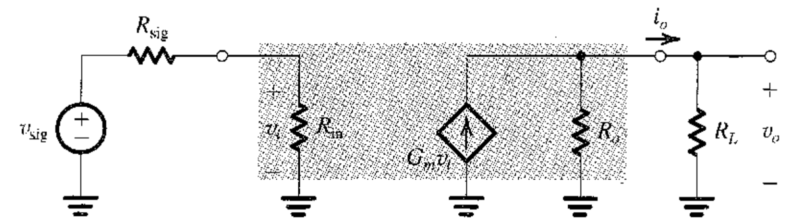
$$G_v \equiv \frac{v_o}{v_{sig}}$$

Equivalent Circuits

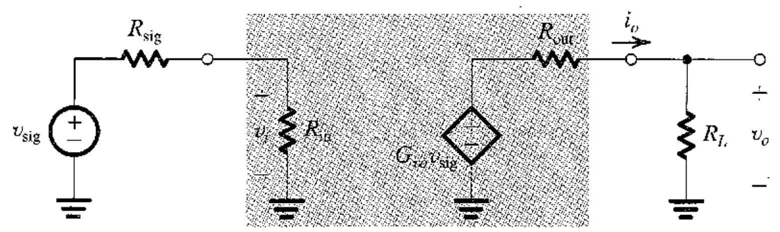
- A:



- B:



- C:



Relationships

- $\frac{v_i}{v_{sig}} = \frac{R_{in}}{R_{in}+R_{sig}}$
- $A_v = A_{vo}\frac{R_L}{R_L+R_o}$
- $A_{vo} = G_m R_o$
- $G_v = \frac{R_{in}}{R_{in}+R_{sig}} A_{vo} \frac{R_L}{R_L+R_o}$
- $G_{vo} = \frac{R_i}{R_i+R_{sig}} A_{vo}$
- $G_v = G_{vo}\frac{R_L}{R_L+R_{out}}$

5. When evaluating the gain A_v from the open-circuit value A_{vo}, R_o is the output resistance to use. This is because A_v is based on feeding the amplifier with an ideal voltage signal v_i. This should be evident from Equivalent Circuit A in Table 4.3. On the other hand, if we are evaluating the overall voltage gain G_v from its open-circuit value G_{vo}, the output resistance to use is R_{out}. This is because G_v is based on feeding the amplifier with v_{sig}, which has an internal resistance R_{sig}. This should be evident from Equivalent Circuit C in Table 4.3.
6. We urge the reader to carefully examine and reflect on the definitions and the six relationships presented in Table 4.3. Example 4.11 should help in this regard.

EXAMPLE 4.11

A transistor amplifier is fed with a signal source having an open-circuit voltage v_{sig} of 10 mV and an internal resistance R_{sig} of 100 kΩ. The voltage v_i at the amplifier input and the output voltage v_o are measured both without and with a load resistance $R_L = 10$ kΩ connected to the amplifier output. The measured results are as follows:

	v_i (mV)	v_o (mV)
Without R_L	9	90
With R_L connected	8	70

Find all the amplifier parameters.

Solution

First, we use the data obtained for $R_L = \infty$ to determine

$$A_{vo} = \frac{90}{9} = 10 \text{ V/V}$$

and

$$G_{vo} = \frac{90}{10} = 9 \text{ V/V}$$

Now, since

$$G_{vo} = \frac{R_i}{R_i + R_{sig}} A_{vo}$$

$$9 = \frac{R_i}{R_i + 100} \times 10$$

which gives

$$R_i = 900 \text{ k}\Omega$$

Next, we use the data obtained when $R_L = 10$ kΩ is connected to the amplifier output to determine

$$A_v = \frac{70}{8} = 8.75 \text{ V/V}$$

and

$$G_v = \frac{70}{10} = 7 \text{ V/V}$$

The values of A_v and A_{vo} can be used to determine R_o as follows:

$$A_v = A_{vo}\frac{R_L}{R_L + R_o}$$

$$8.75 = 10\frac{10}{10 + R_o}$$

which gives

$$R_o = 1.43 \text{ k}\Omega$$

Similarly, we use the values of G_v and G_{vo} to determine R_{out} from

$$G_v = G_{vo}\frac{R_L}{R_L + R_{out}}$$

$$7 = 9\frac{10}{10 + R_{out}}$$

resulting in

$$R_{out} = 2.86 \text{ k}\Omega$$

The value of R_{in} can be determined from

$$\frac{v_i}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}}$$

Thus,

$$\frac{8}{10} = \frac{R_{in}}{R_{in} + 100}$$

which yields

$$R_{in} = 400 \text{ k}\Omega$$

The short-circuit transconductance G_m can be found as follows:

$$G_m = \frac{A_{vo}}{R_o} = \frac{10}{1.43} = 7 \text{ mA/V}$$

and the current gain A_i can be determined as follows:

$$A_i = \frac{v_o/R_L}{v_i/R_{in}} = \frac{v_o}{v_i}\frac{R_{in}}{R_L}$$

$$= A_v\frac{R_{in}}{R_L} = 8.75 \times \frac{400}{10} = 350 \text{ A/A}$$

Finally, we determine the short-circuit current gain A_{is} as follows. From Equivalent Circuit A in Table 4.3, the short-circuit output current is

$$i_{osc} = A_{vo}v_i/R_o$$

However, to determine v_i we need to know the value of R_{in} obtained with $R_L = 0$. Toward that end, note that from Equivalent Circuit C, the output short-circuit current can be found as

$$i_{osc} = G_{vo}v_{sig}/R_{out}$$

Now, equating the two expressions for i_{osc} and substituting for G_{vo} by

$$G_{vo} = \frac{R_i}{R_i + R_{sig}} A_{vo}$$

and for v_i from

$$v_i = v_{sig}\frac{R_{in}|_{R_L=0}}{R_{in}|_{R_L=0} + R_{sig}}$$

results in

$$R_{in}|_{R_L=0} = R_{sig}\Big/\left[\left(1 + \frac{R_{sig}}{R_i}\right)\left(\frac{R_{out}}{R_o}\right) - 1\right]$$

$$= 81.8 \text{ k}\Omega$$

We now can use

$$i_{osc} = A_{vo}i_i R_{in}|_{R_L=0}/R_o$$

to obtain

$$A_{is} \equiv \frac{i_{osc}}{i_i} = 10 \times 81.8/1.43 = 572 \text{ A/A}$$

EXERCISE

4.31 (a) If in the amplifier of Example 4.11, R_{sig} is doubled, find the values for R_{in}, G_v, and R_{out}. (b) Repeat for R_L doubled (but R_{sig} unchanged; i.e., 100 kΩ). (c) Repeat for both R_{sig} and R_L doubled.
Ans. (a) 400 kΩ, 5.83 V/V, 4.03 kΩ; (b) 538 kΩ, 7.87 V/V, 2.86 kΩ; (c) 538 kΩ, 6.8 V/V, 4.03 kΩ

4.7.3 The Common-Source (CS) Amplifier

The common-source (CS) or grounded-source configuration is the most widely used of all MOSFET amplifier circuits. A common-source amplifier realized using the circuit of Fig. 4.42 is shown in Fig. 4.43(a). Observe that to establish a **signal ground,** or an **ac ground** as it is sometimes called, at the source, we have connected a large capacitor, C_S, between the source and ground. This capacitor, usually in the μF range, is required to provide a very small impedance (ideally, zero impedance; i.e., in effect, a short circuit) at all signal frequencies of interest. In this way, the signal current passes through C_S to ground and thus *bypasses* the output resistance of current source I (and any other circuit component that might be connected to the MOSFET source); hence, C_S is called a **bypass capacitor.** Obviously, the lower the signal frequency, the less effective the bypass capacitor becomes. This issue will be studied in Section 4.9. For our purposes here we shall assume that C_S is acting as a perfect short circuit and thus is establishing a zero signal voltage at the MOSFET source.

In order not to disturb the dc bias current and voltages, the signal to be amplified, shown as voltage source v_{sig} with an internal resistance R_{sig}, is connected to the gate through a large capacitor C_{C1}. Capacitor C_{C1}, known as a **coupling capacitor,** is required to act as a perfect short circuit at all signal frequencies of interest while blocking dc. Here again, we note that as the signal frequency is lowered, the impedance of C_{C1} (i.e., $1/j\omega C_{C1}$) will increase and its effectiveness as a coupling capacitor will be correspondingly reduced. This problem too will be considered in Section 4.9 when the dependence of the amplifier operation on frequency is studied. For our purposes here we shall assume C_{C1} is acting as a perfect short circuit as far as the signal is concerned. Before leaving C_{C1}, we should point out that in situations where the signal source can provide an appropriate dc path to ground, the gate can be connected directly to the signal source and both R_G and C_{C1} can be dispensed with.

The voltage signal resulting at the drain is coupled to the load resistance R_L via another coupling capacitor C_{C2}. We shall assume that C_{C2} acts as a perfect short circuit at all signal frequencies of interest and thus that the output voltage $v_o = v_d$. Note that R_L can be either an actual load resistor, to which the amplifier is required to provide its output voltage signal, or it can be the input resistance of another amplifier stage in cases where more than one stage of amplification is needed. (We will study multistage amplifiers in Chapter 7.)

To determine the terminal characteristics of the CS amplifier—that is, its input resistance, voltage gain, and output resistance—we replace the MOSFET with its small-signal model. The resulting circuit is shown in Fig. 4.43(b). At the outset we observe that this amplifier is unilateral. Therefore R_{in} does not depend on R_L, and thus $R_{in} = R_i$. Also, R_{out} will not depend on R_{sig}, and thus $R_{out} = R_o$. Analysis of this circuit is straightforward and proceeds in a step-by-step manner, from the signal source to the amplifier load. At the input

$$i_g = 0$$

$$R_{in} = R_G \tag{4.78}$$

$$v_i = v_{sig}\frac{R_{in}}{R_{in}+R_{sig}} = v_{sig}\frac{R_G}{R_G+R_{sig}} \tag{4.79}$$

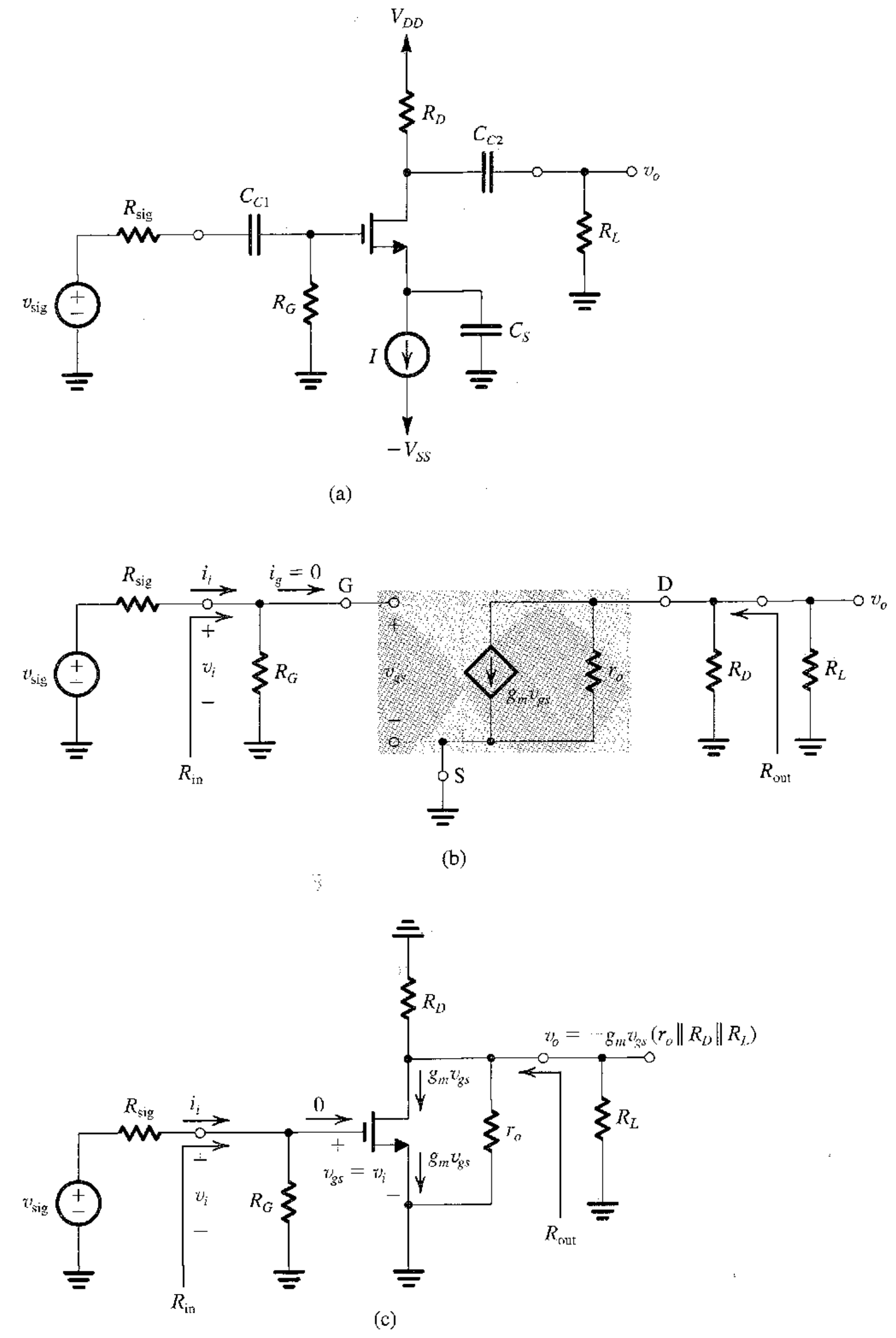


FIGURE 4.43 (a) Common-source amplifier based on the circuit of Fig. 4.42. (b) Equivalent circuit of the amplifier for small-signal analysis. (c) Small-signal analysis performed directly on the amplifier circuit with the MOSFET model implicitly utilized.