4.7 SINGLE-STAGE MOS AMPLIFIERS

Having studied MOS amplifier biasing (Section 4.5) and the small-signal operation and models of the MOSFET amplifier (Section 4.6), we are now ready to consider the various configurations utilized in the design of MOS amplifiers. In this section we shall do this for the case of discrete MOS amplifiers, leaving the study of integrated-circuit (IC) MOS amplifiers to Chapter 6. Beside being useful in their own right, discrete MOS amplifiers are somewhat easier to understand than their IC counterparts for two main reasons: The separation between dc and signal quantities is more obvious in discrete circuits, and discrete circuits utilize resistors as amplifier loads. In contrast, as we shall see in Chapter 6, IC MOS amplifiers employ constant-current sources as amplifier loads, with these being implemented using additional MOSFETs and resulting in more complicated circuits. Thus the circuits studied in this section should provide us with both an introduction to the subject of MOS amplifier configurations and a solid base on which to build during our study of IC MOS amplifiers in Chapter 6.

Since in discrete circuits the MOSFET source is usually tied to the substrate, the body effect will be absent. Therefore in this section we shall *not* take the body effect into account. Also, in some circuits we will neglect r_o in order to keep the analysis simple and focus our attention at this early stage on the salient features of the amplifier configurations studied.

4.7.1 The Basic Structure

Figure 4.42 shows the basic circuit we shall utilize to implement the various configurations of discrete-circuit MOS amplifiers. Among the various schemes for biasing discrete MOS

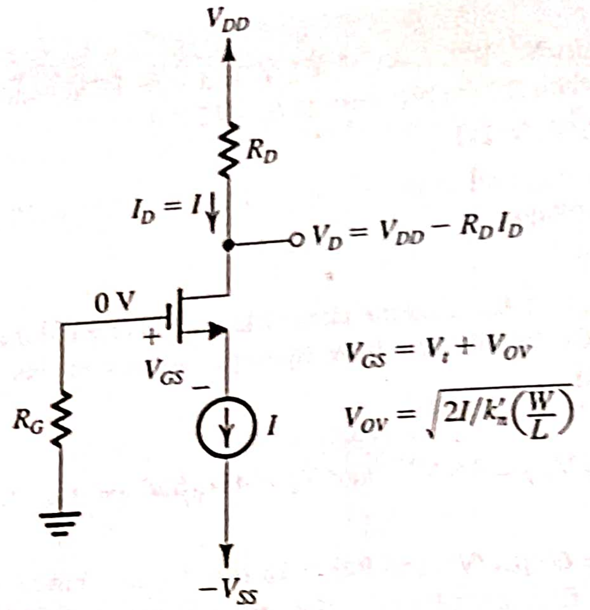


FIGURE 4.42 Basic structure of the circuit to realize single-stage discrete-circuit MOS ampli configurations.

amplifiers (Section 4.5) we have selected, for both its effectiveness and its simplicity, one employing constant-current biasing. Figure 4.42 indicates the dc current and the dc v ages resulting at various nodes.

EXERCISE

4.30 Consider the circuit of Fig. 4.42 for the case $V_{DD} = V_{SS} = 10$ V, $I = 0.5$ mA, $R_G = 4.7$ MΩ, $R_D = 15$ kΩ, $V_t = 1.5$ V, and $k_n'(W/L) = 1$ mA/V^2. Find V_{OV}, V_{GS}, V_G, V_S, and V_D. Also, calculate the values of g_m and r_o, assuming that $V_A = 75$ V. What is the maximum possible signal swing at the drain for which the MOSFET remains in saturation?

Ans. See Fig. E4.30; without taking into account the signal swing at the gate, the drain can swing to −1.5 V, a negative signal swing of 4 V.

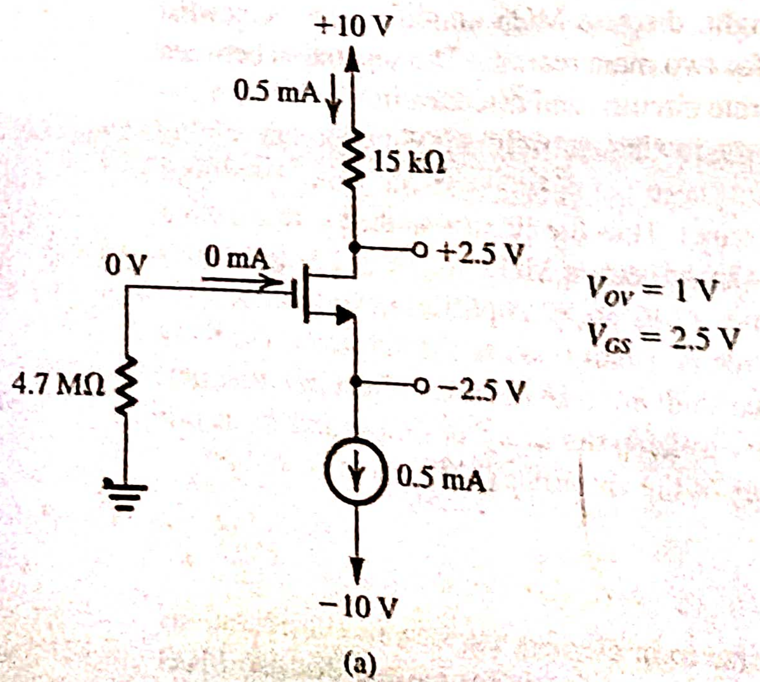


FIGURE E4.30

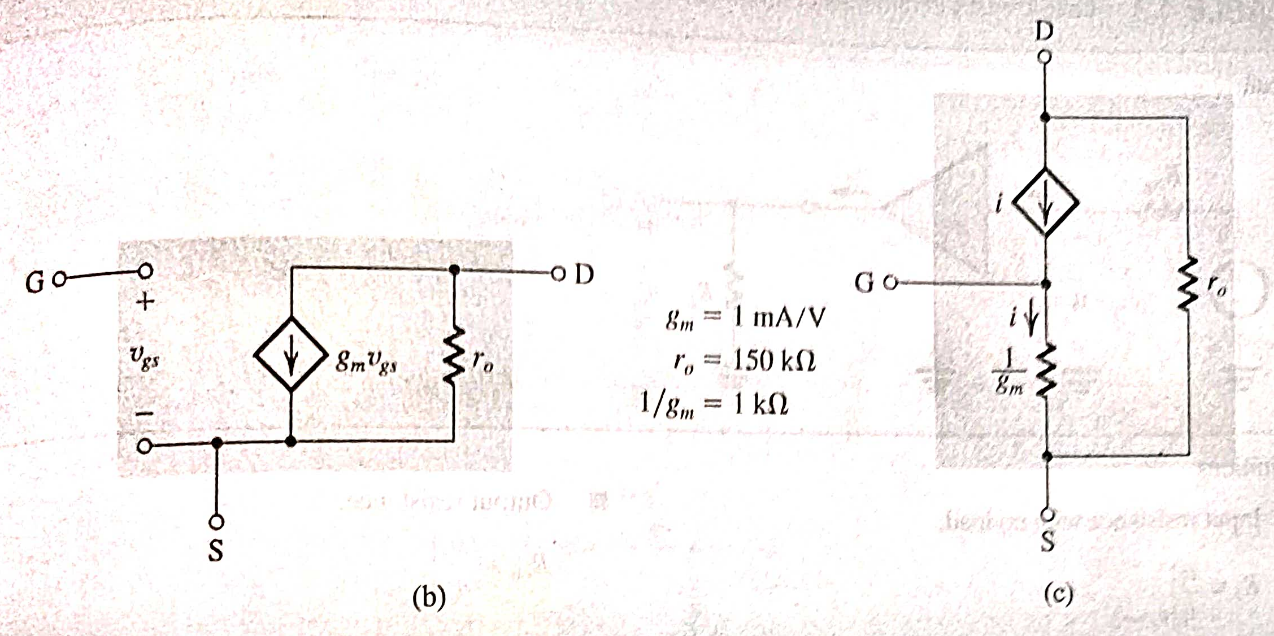


FIGURE E4.30 *(Continued)*

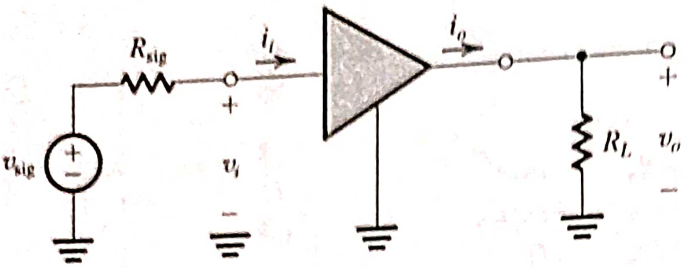
4.7.2 Characterizing Amplifiers

As we begin our study of MOS amplifier circuits, it is important to know how to characterize the performance of amplifiers as circuit building blocks. An introduction to this subject was presented in Section 1.5. However, the material of Section 1.5 was limited to **unilateral amplifiers.** A number of the amplifier circuits we shall study in this book, though none in this chapter, are not unilateral; that is, they have internal feedback that may cause their input resistance to depend on the load resistance. Similarly, internal feedback may cause the output resistance to depend on the value of the resistance of the signal source feeding the amplifier. To accommodate **nonunilateral amplifiers,** we present, in Table 4.3, a general set of parameters and equivalent circuits that we will employ in characterizing and comparing transistor amplifiers. A number of remarks are in order:

1. The amplifier is shown fed with a signal source having an open-circuit voltage v_{sig} and an internal resistance R_{sig}. These can be the parameters of an actual signal source or the Thévenin equivalent of the output circuit of another amplifier stage preceding the one under study in a cascade amplifier. Similarly, R_L can be an actual load resistance or the input resistance of a succeeding amplifier stage in a cascade amplifier.
2. Parameters R_i, R_o, A_{vo}, A_{is}, and G_m pertain to the *amplifier proper;* that is, they do *not* depend on the values of R_{sig} and R_L. By contrast, R_{in}, R_{out}, A_v, A_i, G_{vo}, and G_v may depend on one or both of R_{sig} and R_L. Also, observe the relationships of related pairs of these parameters; for instance, $R_i = R_{in}|_{R_L=\infty}$, and $R_o = R_{out}|_{R_{sig}=0}$.
3. As mentioned above, for nonunilateral amplifiers, R_{in} may depend on R_L, and R_{out} may depend on R_{sig}. Although none of the amplifiers studied in this chapter are of this type, we shall encounter nonunilateral MOSFET amplifiers in Chapter 6 and beyond. No such dependencies exist for unilateral amplifiers, for which $R_{in} = R_i$ and $R_{out} = R_o$.
4. The *loading* of the amplifier on the signal source is determined by the input resistance R_{in}. The value of R_{in} determines the current i_i that the amplifier draws from the signal source. It also determines the proportion of the signal v_{sig} that appears at the input of the amplifier proper (i.e., v_i).

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:

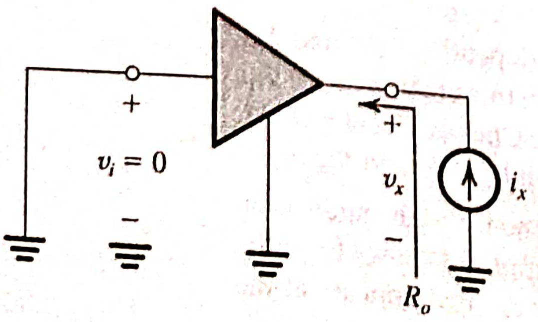
$$A_i \equiv \frac{i_o}{i_i}$$

- Short-circuit transconductance:

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

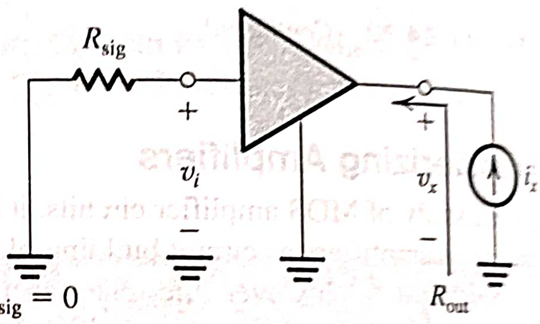
- Output resistance of amplifier proper:

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



- 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:

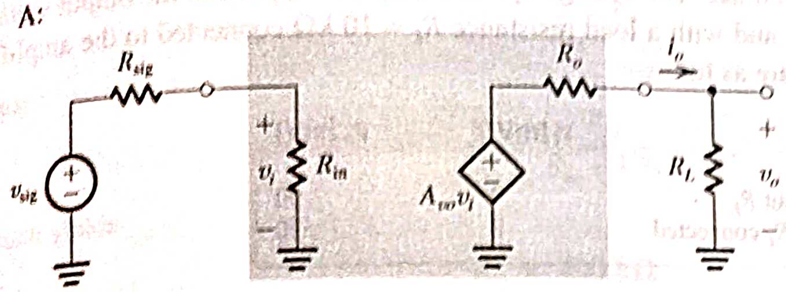
$$G_v \equiv \frac{v_o}{v_{sig}}$$

(Continued)

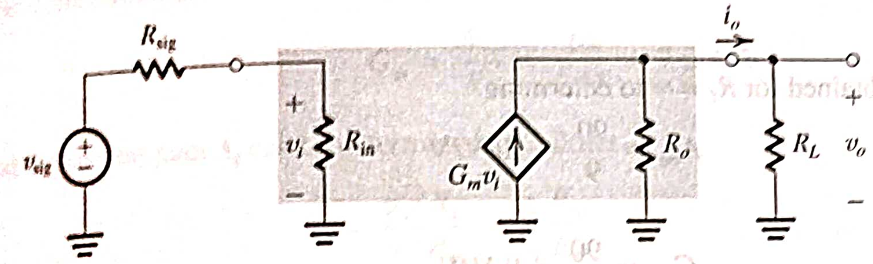
TABLE 4.3 *(Continued)*

Equivalent Circuits

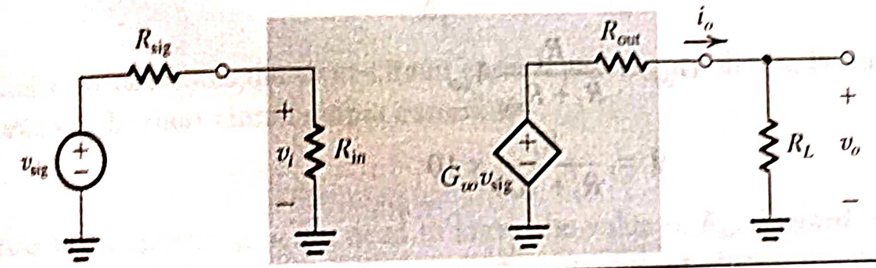
- A:



- B:



- C:



Relationships

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

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.

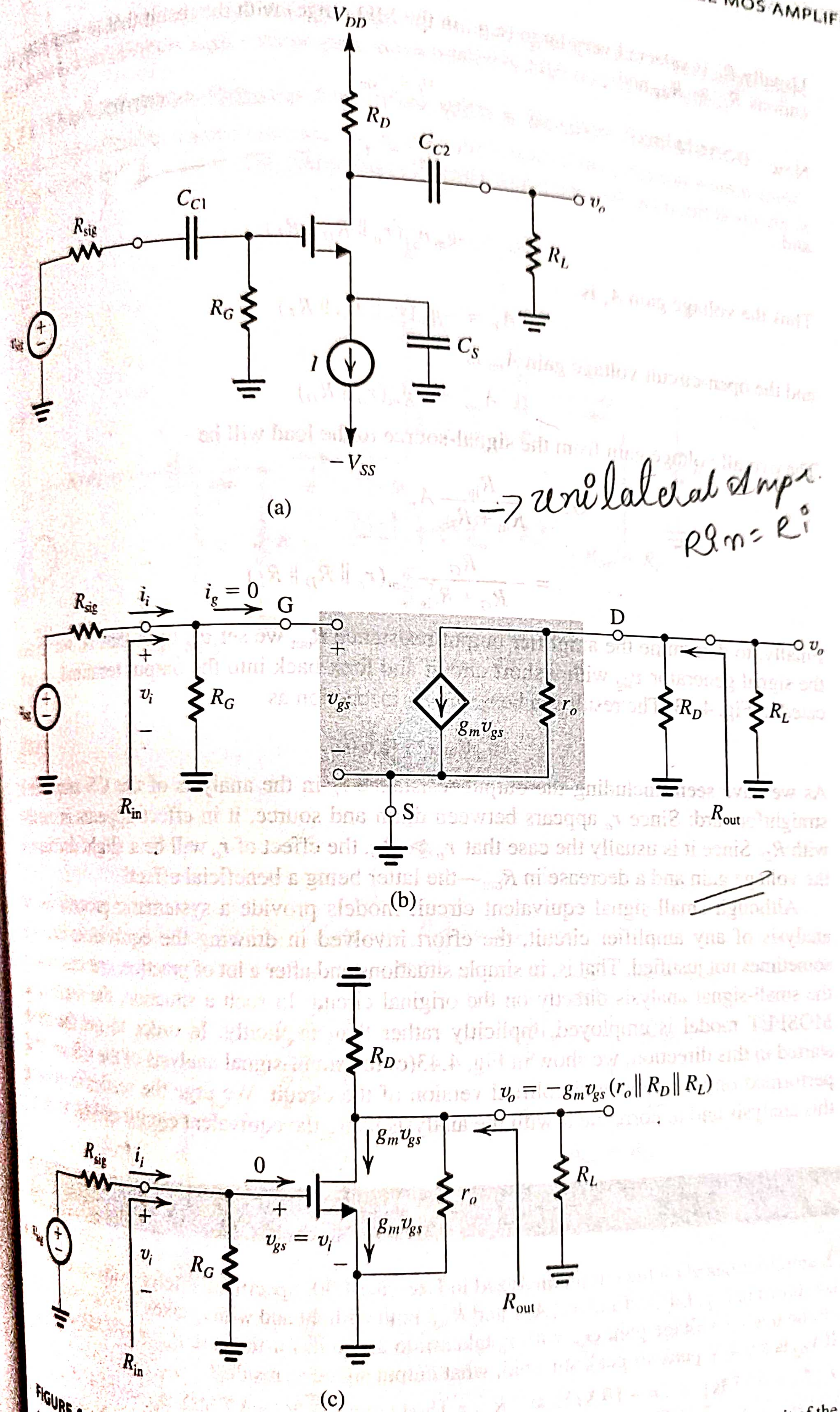
The voltage signal resulting at the drain is coupled to the load resistance R_L via another coupling capacitor C_{C2}. We shall assume that C_{C2} acts as a perfect short circuit at all signal frequencies of interest and thus that the output voltage $v_o = v_d$. Note that R_L can be either an actual 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 8.)

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

$$i_g = 0$$

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

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



→ unilateral Ampl.
Rin = Ri

Rin ≠ RL

Rout ≠ Rsig
Rout = Ro

I/p & o/p
Res
V/g Gain

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.

Usually R_G is selected very large (e.g., in the MΩ range) with the result that in many applications $R_G \gg R_{sig}$ and

$$v_i \cong v_{sig}$$

Now

$$v_{gs} = v_i$$

and

$$v_o = -g_m v_{gs}(r_o \,\|\, R_D \,\|\, R_L)$$

Thus the voltage gain A_v is

$$A_v = -g_m(r_o \,\|\, R_D \,\|\, R_L) \tag{4.80}$$

and the open-circuit voltage gain A_{vo} is

$$A_{vo} = -g_m(r_o \,\|\, R_D) \tag{4.81}$$

The overall voltage gain from the signal-source to the load will be

$$G_v = \frac{R_{in}}{R_{in}+R_{sig}}A_v$$

$$= -\frac{R_G}{R_G+R_{sig}}g_m(r_o \,\|\, R_D \,\|\, R_L) \tag{4.82}$$

Finally, to determine the amplifier output resistance R_{out} we set v_{sig} to 0; that is, we replace the signal generator v_{sig} with a short circuit and look back into the output terminal, as indicated in Fig. 4.43. The result can be found by inspection as

$$R_{out} = r_o \,\|\, R_D \tag{4.83}$$

As we have seen, including the output resistance r_o in the analysis of the CS amplifier is straightforward: Since r_o appears between drain and source, it in effect appears in parallel with R_D. Since it is usually the case that $r_o \gg R_D$, the effect of r_o will be a slight decrease in the voltage gain and a decrease in R_{out}—the latter being a beneficial effect!

Although small-signal equivalent circuit models provide a systematic process for the analysis of any amplifier circuit, the effort involved in drawing the equivalent circuit is sometimes not justified. That is, in simple situations and after a lot of practice, one can perform the small-signal analysis directly on the original circuit. In such a situation, the small-signal MOSFET model is employed implicitly rather than explicitly. In order to get the reader started in this direction, we show in Fig. 4.43(c) the small-signal analysis of the CS amplifier performed on a somewhat simplified version of the circuit. We urge the reader to examine this analysis and to correlate it with the analysis using the equivalent circuit of Fig. 4.43(b).

EXERCISE

4.32 Consider a CS amplifier based on the circuit analyzed in Exercise 4.30. Specifically, refer to the results of that exercise shown in Fig. E4.30. Find R_{in}, A_{vo}, and R_{out}, both without and with r_o taken into account. Then calculate the overall voltage gain G_v, with r_o taken into account, for the case $R_{sig} = 100$ kΩ and $R_L = 15$ kΩ. If v_{sig} is a 0.4-V peak-to-peak sinusoid, what output signal v_o results?

Ans. Without r_o: $R_{in} = 4.7$ MΩ, $A_{vo} = -15$ V/V, and $R_{out} = 15$ kΩ; with r_o: $R_{in} = 4.7$ MΩ, $A_{vo} = -13.6$ V/V, and $R_{out} = 13.6$ kΩ; $G_v = -7$ V/V; v_o is a 2.8-V peak-to-peak sinusoid superimposed on a dc drain voltage of +2.5 V.

We conclude our study of the CS amplifier by noting that it has a very high input resistance, a moderately high voltage gain, and a relatively high output resistance.

4.7.4 The Common-Source Amplifier with a Source Resistance

It is often beneficial to insert a resistance R_S in the source lead of the common-source amplifier, as shown in Fig. 4.44(a). The corresponding small-signal equivalent circuit is shown in

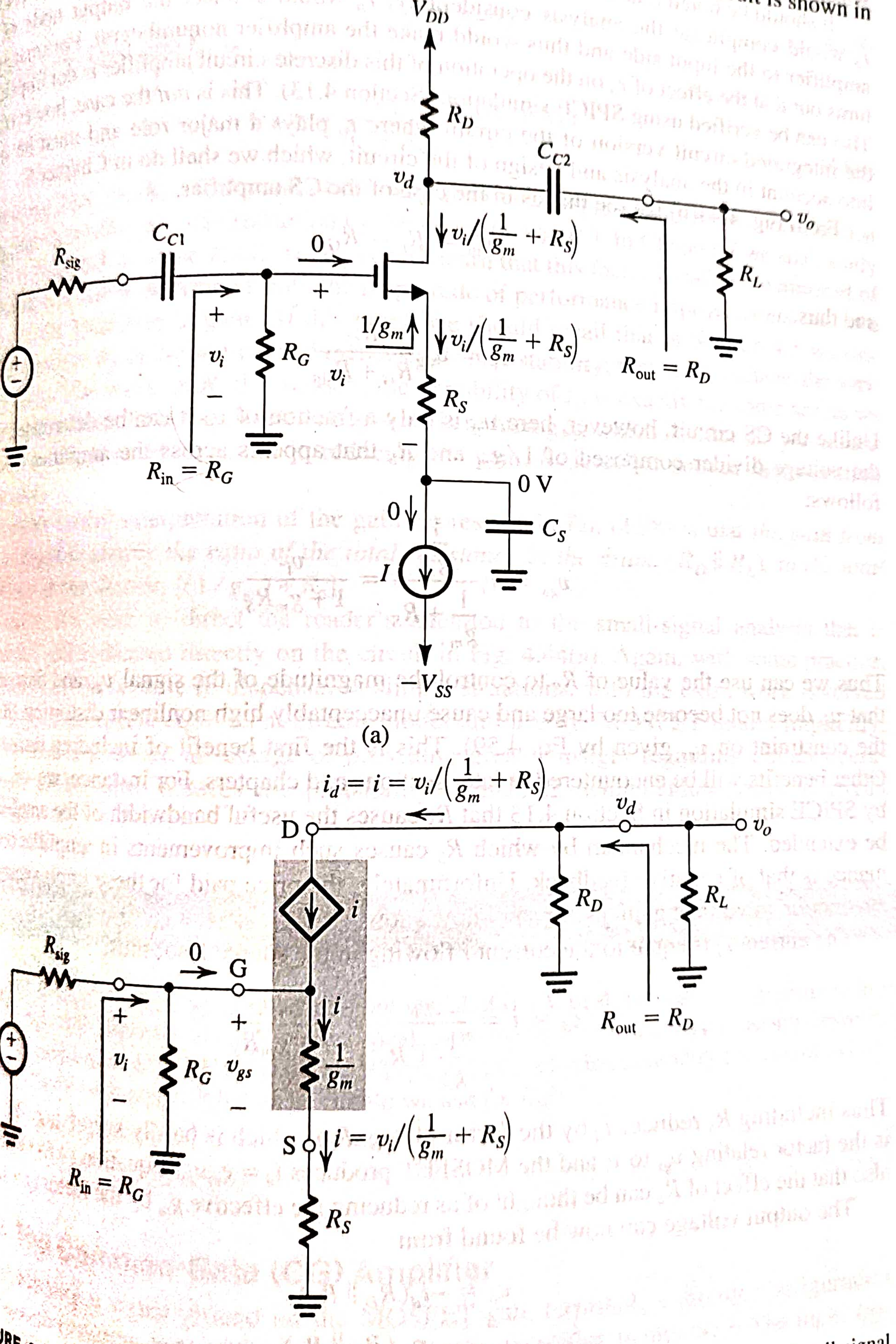


FIGURE 4.44 (a) Common-source amplifier with a resistance R_S in the source lead. (b) Small-signal equivalent circuit with r_o neglected.

Fig. 4.44(b) where we note that the transistor has been replaced by its T equivalent-circuit model. The T model is used in preference to the π model because it makes the analysis in this case somewhat simpler. In general, whenever a resistance is connected in the source lead, as for instance in the source-follower circuit we shall consider shortly, the T model is preferred: The source resistance then simply appears in series with the resistance $1/g_m$, which represents the resistance between source and gate, looking into the source.

It should be noted that we have not included r_o in the equivalent-circuit model. Including r_o would complicate the analysis considerably; r_o would connect the output node of the amplifier to the input side and thus would make the amplifier nonunilateral. Fortunately, it turns out that the effect of r_o on the operation of this discrete-circuit amplifier is not important. This can be verified using SPICE simulation (Section 4.13). This is *not* the case, however, for the integrated-circuit version of the circuit where r_o plays a major role and must be taken into account in the analysis and design of the circuit, which we shall do in Chapter 6.

From Fig. 4.44(b) we see that as in the case of the CS amplifier,

$$R_{in} = R_i = R_G \tag{4.84}$$

and thus,

$$v_i = v_{sig}\frac{R_G}{R_G + R_{sig}} \tag{4.85}$$

Unlike the CS circuit, however, here v_{gs} is only a fraction of v_i. It can be determined from the voltage divider composed of $1/g_m$ and R_S that appears across the amplifier input as follows:

$$v_{gs} = v_i \frac{\frac{1}{g_m}}{\frac{1}{g_m} + R_S} = \frac{v_i}{1 + g_m R_S} \tag{4.86}$$

Thus we can use the value of R_S to control the magnitude of the signal v_{gs} and thus ensure that v_{gs} does not become too large and cause unacceptably high nonlinear distortion. (Recall the constraint on v_{gs} given by Eq. 4.59). This is the first benefit of including resistor R_S. Other benefits will be encountered in later sections and chapters. For instance, we will show by SPICE simulation in Section 4.13 that R_S causes the useful bandwidth of the amplifier to be extended. The mechanism by which R_S causes such improvements in amplifier performance is that of negative feedback. Unfortunately, the price paid for these improvements is a reduction in voltage gain, as we shall now show.

The current i_d is equal to the current i flowing in the source lead; thus,

$$i_d = i = \frac{v_i}{\frac{1}{g_m} + R_S} = \frac{g_m v_i}{1 + g_m R_S} \tag{4.87}$$

Thus including R_S reduces i_d by the factor $(1 + g_m R_S)$, which is hardly surprising since this is the factor relating v_{gs} to v_i and the MOSFET produces $i_d = g_m v_{gs}$. Equation (4.87) indicates also that the effect of R_S can be thought of as reducing the effective g_m by the factor $(1 + g_m R_S)$.

The output voltage can now be found from

$$v_o = -i_d(R_D \parallel R_L)$$
$$= -\frac{g_m(R_D \parallel R_L)}{1 + g_m R_S} v_i$$

Thus the voltage gain is

$$A_v = -\frac{g_m(R_D \| R_L)}{1 + g_m R_S} \tag{4.88}$$

and setting $R_L = \infty$ gives

$$A_{vo} = -\frac{g_m R_D}{1 + g_m R_S} \tag{4.89}$$

The overall voltage gain G_v is

$$G_v = -\frac{R_G}{R_G + R_{sig}} \frac{g_m(R_D \| R_L)}{1 + g_m R_S} \tag{4.90}$$

Comparing Eqs. (4.88), (4.89), and (4.90) with their counterparts without R_S indicates that including R_S results in a gain reduction by the factor $(1 + g_m R_S)$. In Chapter 7 we shall study negative feedback in some detail. There we will learn that this factor is called the **amount of feedback** and that it determines both the magnitude of performance improvements and, as a trade-off, the reduction in gain. At this point, we should recall that in Section 4.5 we saw that a resistance R_S in the source lead increases dc bias stability; that is, R_S reduces the variability in I_D. The action of R_S that reduces the variability of I_D is exactly the same action we are observing here: R_S in the circuit of Fig. 4.44 is reducing i_d, which is, after all, just a variation in I_D. Because of its action in reducing the gain, R_S is called **source degeneration resistance.**

Another useful interpretation of the gain expression in Eq. (4.88) is that *the gain from gate to drain is simply the ratio of the total resistance in the drain,* $(R_D \| R_L)$*, to the total resistance in the source,* $[(1/g_m) + R_S]$.

Finally, we wish to direct the reader's attention to the small-signal analysis that is performed and indicated directly on the circuit in Fig. 4.44(a). Again, with some practice, the reader should be able to dispense, in simple situations, with the extra work involved in drawing a complete equivalent circuit model and use the MOSFET model implicitly. This also has the added advantage of providing greater insight regarding circuit operation and, furthermore, reduces the probability of making manipulation errors in circuit analysis.

EXERCISE

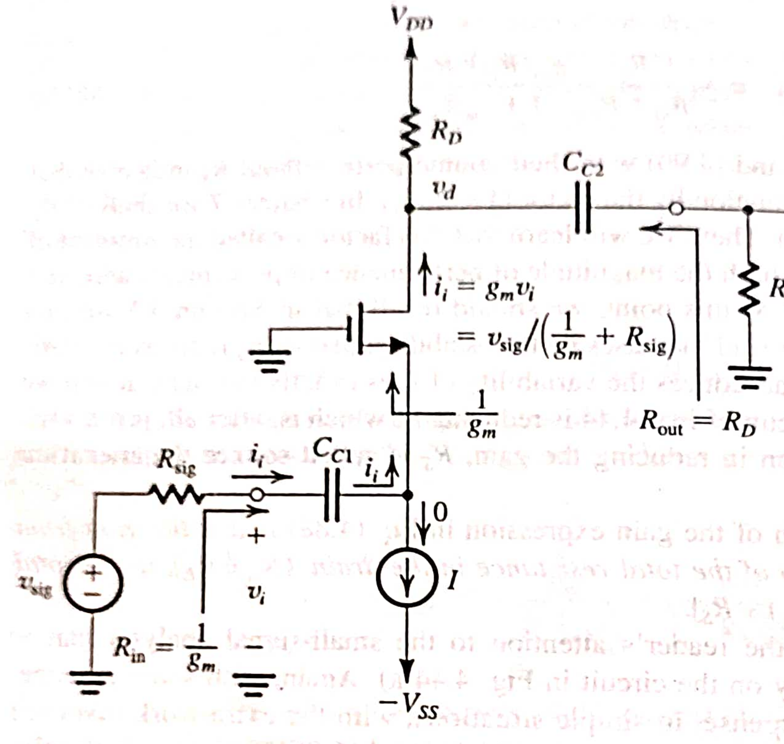
4.33 In Exercise 4.32 we applied an input signal of 0.4 V peak-to-peak, which resulted in an output signal of the CS amplifier of 2.8 V peak-to-peak. Assume that for some reason we now have an input signal three times as large as before (i.e., 1.2 V p-p) and that we wish to modify the circuit to keep the output signal level unchanged. What value should we use for R_S?

Ans. 2.15 kΩ

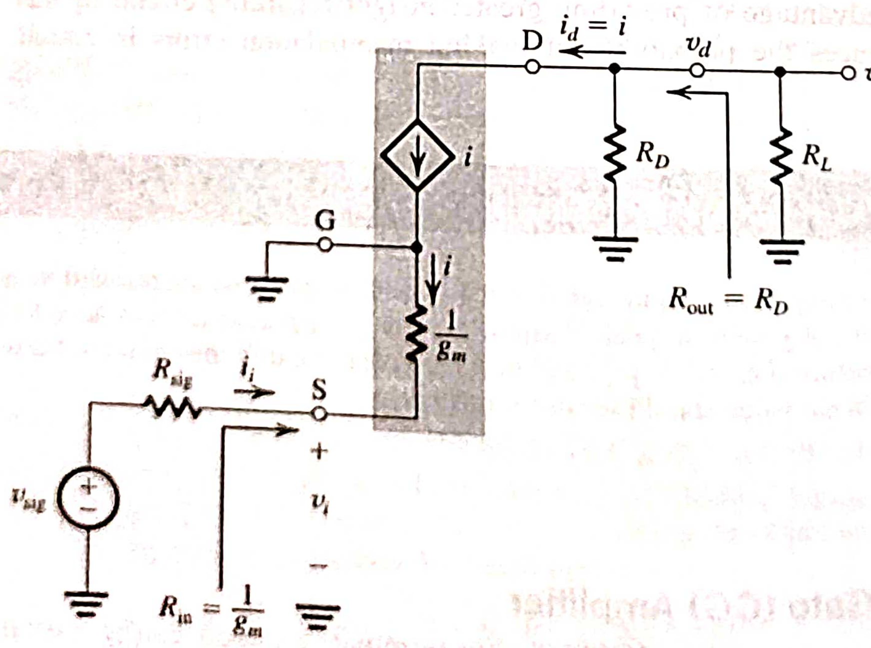
4.7.5 The Common-Gate (CG) Amplifier

By establishing a signal ground on the MOSFET gate terminal, a circuit configuration aptly named **common-gate (CG)** or **grounded-gate amplifier** is obtained. The input signal is applied to the source, and the output is taken at the drain, with the gate forming a common terminal between the input and output ports. Figure 4.45(a) shows a CG amplifier obtained from the circuit of Fig. 4.42. Observe that since both the dc and ac voltages at the gate are to be zero, we have connected the gate directly to ground, thus eliminating resistor R_G altogether. Coupling capacitors C_{C1} and C_{C2} perform similar functions to those in the CS circuit.

The small-signal equivalent circuit model of the CG amplifier is shown in Fig. 4.45(b). Since resistor R_{sig} appears directly in series with the MOSFET source lead we have selected the T model for the transistor. Either model, of course, can be used and yields identical



(a)



(b)

FIGURE 4.45 (a) A common-gate amplifier based on the circuit of Fig. 4.42. (b) A small-signal equivalent circuit of the amplifier in (a).

EXERCISE

4.33 In Exercise 4.32 we applied an input signal of 0.4 V peak-to-peak, which resulted in an output signal of the CS amplifier of 2.8 V peak-to-peak. Assume that for some reason we now have an input signal three times as large as before (i.e., 1.2 V p-p) and that we wish to modify the circuit to keep the output signal level unchanged. What value should we use for R_S?

Ans. 2.15 kΩ

4.7.5 The Common-Gate (CG) Amplifier

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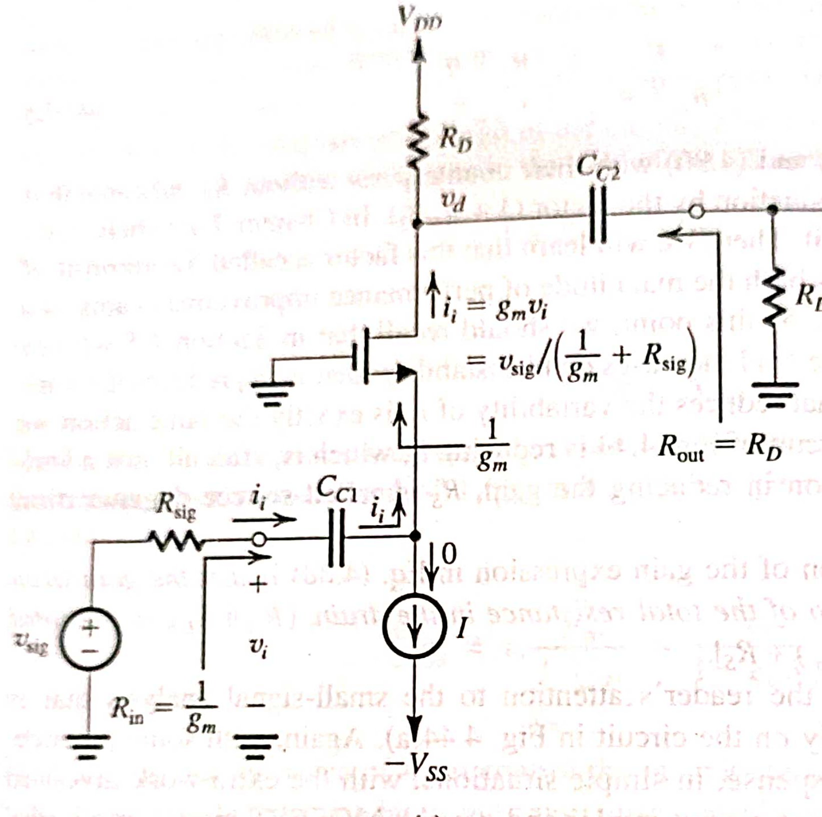
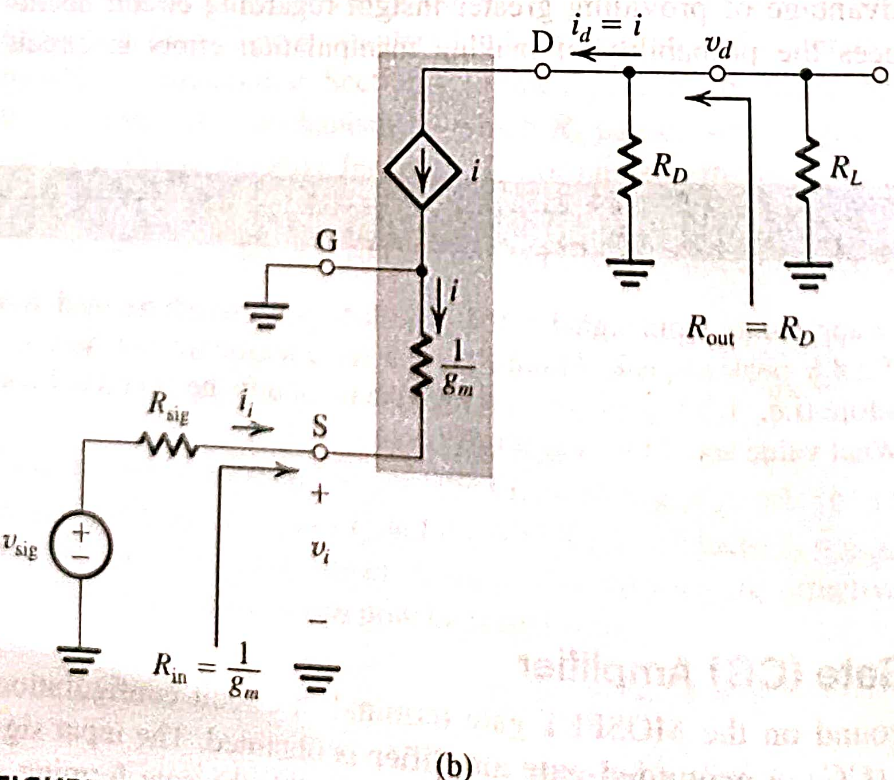
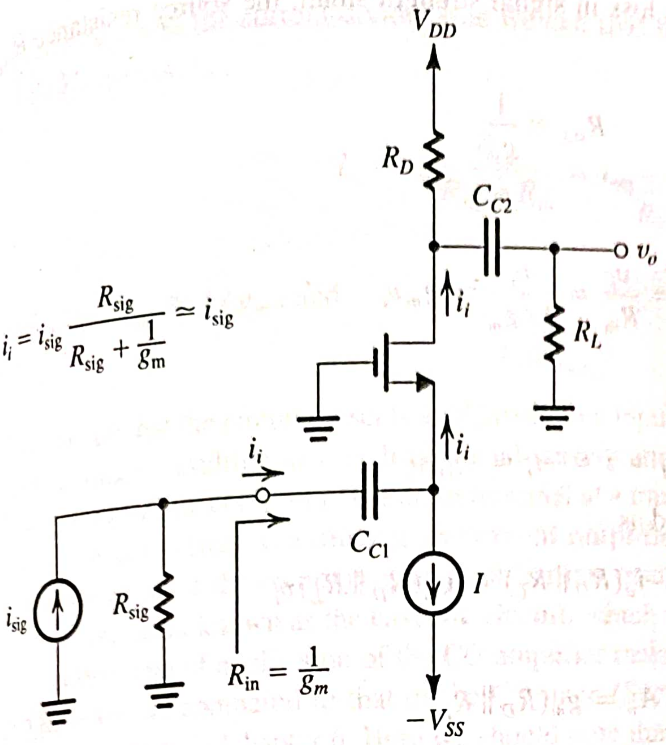


(a)



(b)

FIGURE 4.45 (a) A common-gate amplifier based on the circuit of Fig. 4.42. (b) A small-signal equivalent circuit of the amplifier in (a).



(c)

FIGURE 4.45 *(Continued)* (c) The common-gate amplifier fed with a current-signal input.

results; however, the T model is more convenient in this case. Observe also that we have not included r_o. Including r_o here would complicate the analysis considerably, for it would appear between the output and input of the amplifier. We will consider the effect of r_o when we study the IC form of the CG amplifier in Chapter 6.

From inspection of the equivalent-circuit model in Fig. 4.45(b) we see that the input resistance is

$$R_{in} = \frac{1}{g_m} \tag{4.91}$$

This should have been expected since we are looking into the source terminal of the MOSFET and the gate is grounded.[7] Furthermore, since the circuit is unilateral, R_{in} is independent of R_L, and $R_{in} = R_i$. Since g_m is of the order of 1 mA/V, the input resistance of the CG amplifier can be relatively low (of the order of 1 kΩ) and certainly much lower than in the case of the CS amplifier. It follows that significant loss of signal strength can occur in coupling the signal to the input of the CG amplifier, since

$$v_i = v_{sig} \frac{R_{in}}{R_{in} + R_{sig}} \tag{4.92}$$

Thus,

$$v_i = v_{sig} \frac{\dfrac{1}{g_m}}{\dfrac{1}{g_m} + R_{sig}} = v_{sig} \frac{1}{1 + g_m R_{sig}} \tag{4.93}$$

[7] As we will see in Chapter 6, when r_o is taken into account, R_{in} depends on R_D and R_L and can be quite different from $1/g_m$.

from which we see that to keep the loss in signal strength small, the source resistance R_{sig} should be small,

$$R_{sig} \ll \frac{1}{g_m}$$

The current i_i is given by

$$i_i = \frac{v_i}{R_{in}} = \frac{v_i}{1/g_m} = g_m v_i$$

and the drain current i_d is

$$i_d = i = -i_i = -g_m v_i$$

Thus the output voltage can be found as

$$v_o = v_d = -i_d(R_D \| R_L) = g_m(R_D \| R_L)v_i$$

resulting in the voltage gain

$$A_v = g_m(R_D \| R_L) \tag{4.94}$$

from which the open-circuit voltage gain can be found as

$$A_{vo} = g_m R_D \tag{4.95}$$

The overall voltage gain can be obtained as follows:

$$G_v = \frac{R_{in}}{R_{in}+R_{sig}} A_v = \frac{\dfrac{1}{g_m}}{\dfrac{1}{g_m}+R_{sig}} A_v = \frac{A_v}{1+g_m R_{sig}} \tag{4.96a}$$

resulting in

$$G_v = \frac{g_m(R_D \| R_L)}{1+g_m R_{sig}} \tag{4.96b}$$

Finally, the output resistance is found by inspection to be

$$R_{out} = R_o = R_D \tag{4.97}$$

Comparing these expressions with those for the common-source amplifier we make the following observations:

1. Unlike the CS amplifier, which is inverting, the CG amplifier is noninverting. This, however, is seldom a significant consideration.
2. While the CS amplifier has a very high input resistance, the input resistance of the CG amplifier is low.
3. While the A_v values of both CS and CG amplifiers are nearly identical, the overall voltage gain of the CG amplifier is smaller by the factor $1 + g_m R_{sig}$ (Eq. 4.96b), which is due to the low input resistance of the CG circuit.

The observations above do not show any particular advantage for the CG circuit; to explore this circuit further we take a closer look at its operation. Figure 4.45(c) shows the CG amplifier fed with a signal current-source i_{sig} having an internal resistance R_{sig}. This can, of course, be the Norton equivalent of the signal source used in Fig. 4.45(a). Now, using

$R_{in} = 1/g_m$ and the current-divider rule we can find the fraction of i_{sig} that flows into the MOSFET source, i_i,

$$i_i = i_{sig}\frac{R_{sig}}{R_{sig}+R_{in}} = i_{sig}\frac{R_{sig}}{R_{sig}+\dfrac{1}{g_m}} \tag{4.98}$$

Normally, $R_{sig} \gg 1/g_m$, and

$$i_i \cong i_{sig} \tag{4.98a}$$

Thus we see that the circuit presents a relatively low input resistance $1/g_m$ to the input signal-current source, resulting in very little signal-current attenuation at the input. The MOSFET then reproduces this current in the drain terminal at a much higher output resistance. The circuit thus acts in effect as a **unity-gain current amplifier** or a **current follower.** This view of the operation of the common-gate amplifier has resulted in its most popular application, in a configuration known as the **cascode circuit,** which we shall study in Chapter 6.

Another area of application of the CG amplifier makes use of its superior high-frequency performance, as compared to that of the CS stage (Section 4.9). We shall study wideband amplifier circuits in Chapter 6. Here we should note that the low input-resistance of the CG amplifier can be an advantage in some very-high-frequency applications where the input signal connection can be thought of as a *transmission line* and the $1/g_m$ input resistance of the CG amplifier can be made to function as the *termination resistance* of the transmission line (see Problem 4.86).

EXERCISE

4.34 Consider a CG amplifier designed using the circuit of Fig. 4.42, which is analyzed in Exercise 4.30 with the analysis results displayed in Fig. E4.30. Note that $g_m = 1$ mA/V and $R_D = 15$ kΩ. Find R_{in}, R_{out}, A_{vo}, A_v, and G_v for $R_L = 15$ kΩ and $R_{sig} = 50$ Ω. What will the overall voltage gain become for $R_{sig} =$ 1 kΩ? 10 kΩ? 100 kΩ?

Ans. 1 kΩ, 15 kΩ, +15 V/V, +7.5 V/V, +6.85 V/V; +3.75 V/V; 0.68 V/V ; 0.07 V/V

4.7.6 The Common-Drain or Source-Follower Amplifier

The last single-stage MOSFET amplifier configuration we shall study is that obtained by establishing a signal ground at the drain and using it as a terminal common to the input port, between gate and drain, and the output port, between source and drain. By analogy to the CS and CG amplifier configurations, this circuit is called **common-drain** or **grounded-drain amplifier.** However, it is known more popularly as the source follower, for a reason that will become apparent shortly.

Figure 4.46(a) shows a common-drain amplifier based on the circuit of Fig. 4.42. Since the drain is to function as a signal ground, there is no need for resistor R_D, and it has therefore been eliminated. The input signal is coupled via capacitor C_{C1} to the MOSFET gate, and the output signal at the MOSFET source is coupled via capacitor C_{C2} to a load resistor R_L.

Since R_L is in effect connected in series with the source terminal of the transistor (current source I acts as an open circuit as far as signals are concerned), it is more convenient to use the MOSFET's T model. The resulting small-signal equivalent circuit of the common-drain

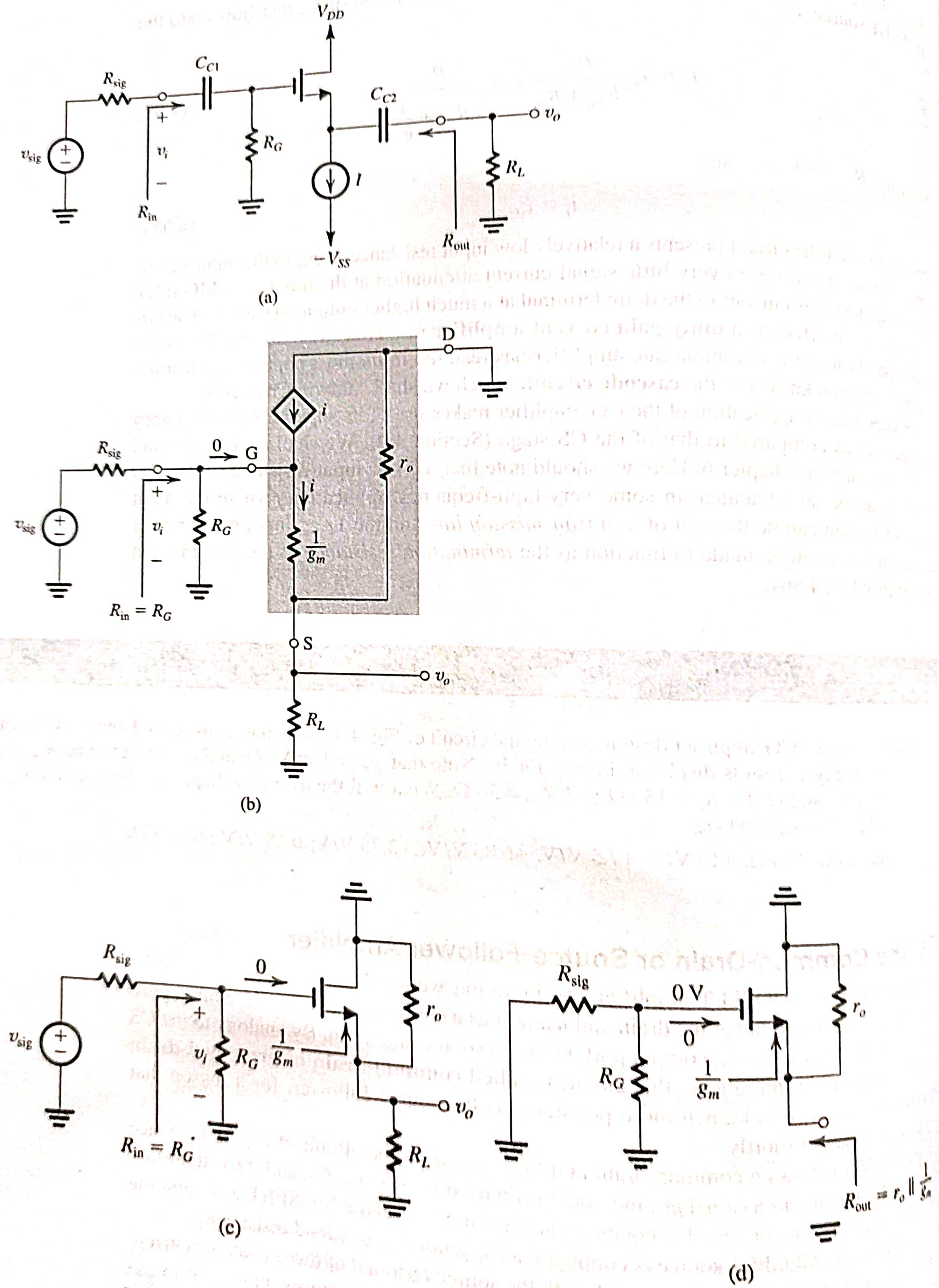


FIGURE 4.46 (a) A common-drain or source-follower amplifier. (b) Small-signal equivalent-circuit model. (c) Small-signal analysis performed directly on the circuit. (d) Circuit for determining the output resistance R_{out} of the source follower.

amplifier is shown in Fig. 4.46(b). Analysis of this circuit is straightforward and proceeds as follows: The input resistance R_{in} is given by

$$R_{in} = R_G \tag{4.99}$$

Thus,

$$v_i = v_{sig}\frac{R_{in}}{R_{in}+R_{sig}} = v_{sig}\frac{R_G}{R_G+R_{sig}} \tag{4.100}$$

Usually R_G is selected to be much larger than R_{sig} with the result that

$$v_i \cong v_{sig}$$

To proceed with the analysis, it is important to note that r_o appears in effect in parallel with R_L, with the result that between the gate and ground we have a resistance $(1/g_m)$ in series with $(R_L \| r_o)$. The signal v_i appears across this total resistance. Thus we may use the voltage-divider rule to determine v_o as

$$v_o = v_i\frac{R_L \| r_o}{(R_L \| r_o)+\dfrac{1}{g_m}} \tag{4.101}$$

from which the voltage gain A_v is obtained as

$$A_v = \frac{R_L \| r_o}{(R_L \| r_o)+\dfrac{1}{g_m}} \tag{4.102}$$

and the open-circuit voltage gain A_{vo} as

$$A_{vo} = \frac{r_o}{r_o+\dfrac{1}{g_m}} \tag{4.103}$$

Normally $r_o \gg 1/g_m$, causing the open-circuit voltage gain from gate to source, A_{vo} in Eq. (4.103), to become nearly unity. Thus the voltage at the source follows that at the gate, giving the circuit its popular name of **source follower.** Also, in many discrete-circuit applications, $r_o \gg R_L$, which enables Eq. (4.102) to be approximated by

$$A_v \cong \frac{R_L}{R_L+\dfrac{1}{g_m}} \tag{4.102a}$$

The overall voltage gain G_v can be found by combining Eqs. (4.100) and (4.102), with the result that

$$G_v = \frac{R_G}{R_G+R_{sig}}\,\frac{R_L \| r_o}{(R_L \| r_o)+\dfrac{1}{g_m}} \tag{4.104}$$

which approaches unity for $R_G \gg R_{sig}$, $r_o \gg 1/g_m$, and $r_o \gg R_L$.

To emphasize the fact that it is usually faster to perform the small-signal analysis directly on the circuit diagram with the MOSFET small-signal model utilized only implicitly, we show such as analysis in Fig. 4.46(c). Once again, observe that to separate the intrinsic action of the MOSFET from the Early effect, we have extracted the output resistance r_o and shown it separately.

The circuit for determining the output resistance R_{out} is shown in Fig. 4.46(d). Because the gate voltage is now zero, looking back into the source we see between the source and ground a resistance $1/g_m$ in parallel with r_o; thus,

$$R_{out} = \frac{1}{g_m} \parallel r_o \tag{4.105}$$

Normally, $r_o \gg 1/g_m$, reducing R_{out} to

$$R_{out} \simeq \frac{1}{g_m} \tag{4.106}$$

which indicates that R_{out} will be moderately low.

We observe that although the source-follower circuit has a large amount of internal feedback (as we will find out in Chapter 7), its R_{in} is independent of R_L (and thus $R_i = R_{in}$) and its R_{out} is independent of R_{sig} (and thus $R_o = R_{out}$). The reason for this, however, is the zero gate current.

In conclusion, the source follower features a very high input resistance, a relatively low output resistance, and a voltage gain that is less than but close to unity. It finds application in situations in which we need to connect a voltage-signal source that is providing a signal of reasonable magnitude but has a very high internal resistance to a much smaller load resistance—that is, as a unity-gain voltage buffer amplifier. The need for such amplifiers was discussed in Section 1.5. The source follower is also used as the output stage in a multistage amplifier, where its function is to equip the overall amplifier with a low output resistance, thus enabling it to supply relatively large load currents without loss of gain (i.e., with little reduction of output signal level.) The design of output stages is studied in Chapter 12.

EXERCISE

4.35 Consider a source follower such as that in Fig. 4.46(a) designed on the basis of the circuit of Fig. 4.42, the results of whose analysis are displayed in Fig. E4.30. Specifically, note that $g_m = 1$ mA/V and $r_o = 150$ kΩ. Let $R_{sig} = 1$ MΩ and $R_L = 15$ kΩ. (a) Find R_{in}, A_{vo}, A_v, and R_{out} without and with r_o taken into account. (b) Find the overall small-signal voltage gain G_v with r_o taken into account.

Ans. (a) $R_{in} = 4.7$ MΩ; $A_{vo} = 1$ V/V (without r_o), 0.993 V/V (with r_o); $A_v = 0.938$ (without r_o), 0.932 V/V (with r_o); $R_{out} = 1$ kΩ (without r_o), 0.993 kΩ (with r_o); (b) 0.768 V/V

4.7.7 Summary and Comparisons

For easy reference we present in Table 4.4 a summary of the characteristics of the various configurations of discrete single-stage MOSFET amplifiers. In addition to the remarks already made throughout this section on the relative merits of the various configurations, the results displayed in Table 4.4 enable us to make the following concluding points:

1. The CS configuration is the best suited for obtaining the bulk of the gain required in an amplifier. Depending on the magnitude of the gain required, either a single CS stage or a cascade of two or three CS stages can be used.
2. Including a resistor R_S in the source lead of the CS stage provides a number of improvements in its performance, as will be seen in later chapters, at the expense of reduced gain.