(c)

$$\begin{aligned} g_{m1} &= 2 \times 10(-0.3+1)(1+0.1 \times 5) \\ &= 21 \text{ mA/V} \\ r_{o1} &= \frac{1}{0.1 \times 10(-0.3+1)^2} = 2 \text{ k}\Omega \\ r_{o2} &= \frac{1}{0.1 \times 5(0+1)^2} = 2 \text{ k}\Omega \end{aligned}$$

(d)

$$\begin{aligned} A_v &= -g_{m1}(r_{o1} \,//\, r_{o2}) \\ &= -21 \times (2 \,//\, 2) = -21 \text{ V/V} \end{aligned}$$

EXERCISE

5.49 For a MESFET with the gate shorted to the source and having $W = 10\ \mu$m, find the minimum voltage between drain and source to operate in saturation. For $V_{DS} = 5$ V, find the current I_D. What is the output resistance of this current source?

Ans. 1 V; 1.5 mA; 10 kΩ

As already mentioned, the main reason for using GaAs devices and circuits is their high frequency and high speed of operation. A remark is therefore in order on the internal capacitances and f_T of GaAs transistors. For a particular GaAs technology with $L = 1\ \mu$m, C_{gs} (at $V_{GS} = 0$ V) is 1.6 fF/μm-width, and C_{gd} (at $V_{DS} = 2$ V) is 0.16 fF/μm-width. Thus for a MESFET with $W = 100\ \mu$m, $C_{gs} = 0.16$ pF and $C_{gd} = 0.016$ pF. f_T typically ranges from 5 to 15 GHz.

6.8 GaAs AMPLIFIERS[3]

Gallium arsenide (GaAs) technology makes possible the design of amplifiers having very wide bandwidths, in the hundreds of megahertz or even gigahertz range. In this section we shall study some of the circuit design techniques that have been developed over the last few years for the design of GaAs amplifiers. As will be seen, these techniques aim to circumvent the major problem of the MESFET, namely, its low output resistance in saturation. Before proceeding with this section the reader is advised to review the material on GaAs devices presented in Section 5.12.

Current Sources

Current sources play a fundamental role in the design of integrated-circuit amplifiers, being employed both for biasing and as active loads. In GaAs technology, the simplest way to implement a current source is to connect the gate of a depletion-type MESFET to its source,

[3] This section can be omitted with no loss in continuity.

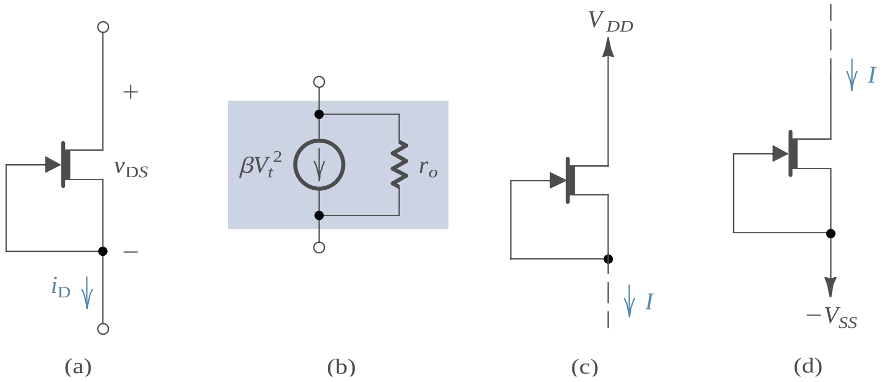

FIGURE 6.39 **(a)** The basic MESFET current source; **(b)** equivalent circuit of the current source; **(c)** the current source connected to a positive power supply to source currents to loads at voltages $\leq V_{DD} - |V_t|$; **(d)** the current source connected to a negative power supply to sink currents from loads at voltages $\geq -V_{SS} + |V_t|$.

as shown in Fig. 6.39(a). Provided that v_{DS} is maintained greater than $|V_t|$, the MESFET will operate in saturation and the current i_D will be

$$i_D = \beta V_t^2(1 + \lambda v_{DS}) \tag{6.126}$$

Thus the current source will have the equivalent circuit shown in Fig. 6.39(b), where the output resistance is the MESFET r_o,

$$r_o = 1/\lambda\beta V_t^2 \tag{6.127}$$

In JFET terminology, $\beta V_t^2 = I_{DSS}$ and $\lambda = 1/|V_A|$; thus

$$r_o = |V_A|/I_{DSS} \tag{6.128}$$

Since for the MESFET, λ is relatively high (0.1 to 0.3 V^{-1}) the output resistance of the current source of Fig. 6.39(a) is usually low, rendering this current-source realization inadequate for most applications. Before considering means for increasing the effective output resistance of the current source, we show in Fig. 6.39(c) how the basic current source can be connected to *source* currents to a load whose voltage can be as high as $V_{DD} - |V_t|$. Alternatively, the same device can be connected as shown in Fig. 6.39(d) to *sink* currents from a load whose voltage can be as low as $-V_{SS} + |V_t|$.

EXERCISE

6.23 Using the device data given in Table 5.2 (page 456), find the current provided by a 10-μm-wide MESFET connected in the current-source configuration. Let the source be connected to a −5-V supply and find the current when the drain voltage is −4V. What is the output resistance of the current source? What change in current occurs if the drain voltage is raised by +4V?

Ans. 1.1 mA; 10 kΩ; 0.4 mA

A Cascode Current Source

The output resistance of the current source can be increased by utilizing the cascode configuration as shown in Fig. 6.40. The output resistance R_o of the cascode current source can be

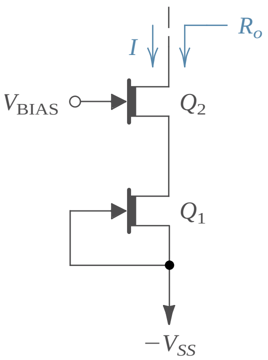

FIGURE 6.40 Adding the cascode transistor Q_2 increases the output resistance of the current source by the factor $g_{m2}r_{o2}$; that is, $R_o = g_{m2}r_{o2}r_{o1}$.

found by using Eq. (6.116),

$$R_o \simeq g_{m2}r_{o2}r_{o1} \tag{6.129}$$

Thus, adding the cascode transistor Q_2 raises the output resistance of the current source by the factor $g_{m2}r_{o2}$, which is the intrinsic voltage gain of Q_2. For GaAs MESFETs, $g_{m2}r_{o2}$ is typically 10 to 40. To allow a wide range of voltages at the output of the cascode current source, V_{BIAS} should be the lowest value that results in Q_1 operating in saturation.

EXERCISE

D6.24 For the cascode current source of Fig. 6.40 let $V_{SS} = 5$ V, $W_1 = 10$ μm, and $W_2 = 20$ μm, and assume that the devices have the typical parameter values given in Table 5.2. (a) Find the value of V_{BIAS} that will result in Q_1 operating at the edge of the saturation region (i.e., $V_{DS1} = |V_t|$) when the voltage at the output is –3 V. (b) What is the lowest allowable voltage at the current-source output? (c) What value of output current is obtained for $V_O = -3$ V? (d) What is the output resistance of the current source? (e) What change in output current results when the output voltage is raised from –3 V to +1 V?

Ans. (a) –4.3 V; (b) –3.3 V; (c) 1.1 mA; (d) 310 kΩ; (e) 0.013 mA

Increasing the Output Resistance by Bootstrapping

Another technique frequently employed to increase the effective output resistance of a MESFET, including the current-source-connected MESFET, is known as **bootstrapping.** The bootstrapping idea is illustrated in Fig. 6.41(a). Here the circuit inside the box senses the voltage at the bottom node of the current source, v_A, and causes a voltage v_B to appear at the top node of a value

$$v_B = V_S + \alpha v_A \tag{6.130}$$

where V_S is the dc voltage required to operate the current-source transistor in saturation $(V_S \geq |V_t|)$ and α is a constant ≤1. The incremental output resistance of the bootstrapped current source can be found by causing the voltage v_A to increase by an increment v_a. From Eq. (6.130) we find that the resulting increment in v_B is $v_b = \alpha v_a$. The incremental current through the current source is therefore $(v_a - v_b)/r_o$ or $(1 - \alpha)v_a/r_o$. Thus the output resistance R_o is

$$R_o = \frac{v_a}{(1-\alpha)v_a/r_o} = \frac{r_o}{1-\alpha} \tag{6.131}$$

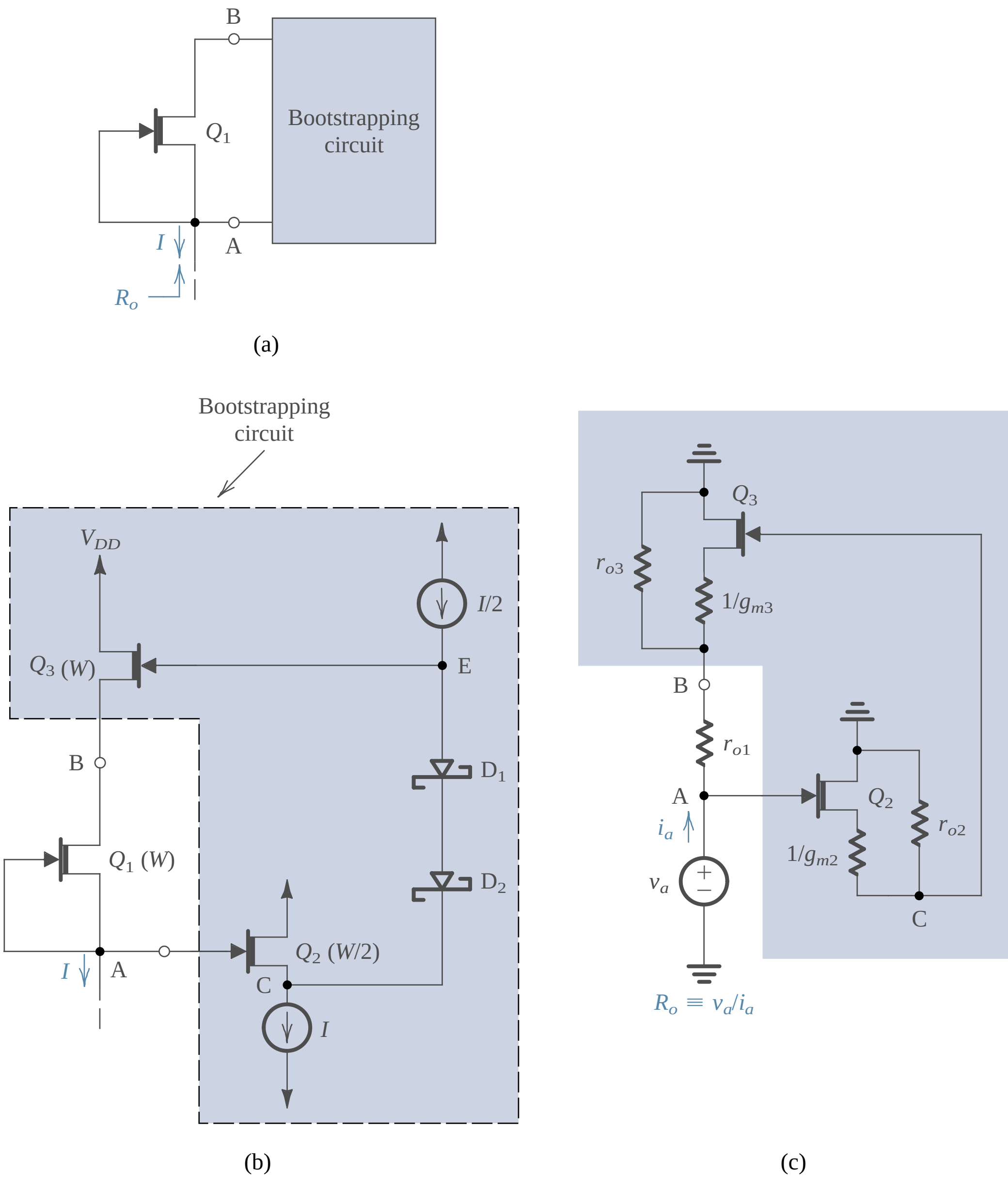

FIGURE 6.41 Bootstrapping of a MESFET current source Q_1: **(a)** basic arrangement; **(b)** an implementation; **(c)** small-signal equivalent circuit model of the circuit in (b), for the purpose of determining the output resistance R_o.

Thus, bootstrapping increases the output resistance by the factor $1/(1-\alpha)$, which increases as α approaches unity. Perfect bootstrapping is achieved with $\alpha = 1$, resulting in $R_o = \infty$.

From the above we observe that the bootstrapping circuit senses whatever change occurs in the voltage at one terminal of the current source and causes an almost equal change to occur at the other terminal, thus maintaining an almost constant voltage across the current source and minimizing the change in current through the current-source transistor. The action of the bootstrapping circuit can be likened to that of a person who attempts to lift himself off the ground by pulling on the straps of his boots (!), the origin of the name of this circuit technique, which, incidentally, predates GaAs technology. Bootstrapping is a form of positive feedback; the signal v_b that is fed back by the bootstrapping circuit is in phase with (has the same polarity as) the signal that is being sensed, v_a. Feedback will be studied formally in Chapter 8.

An implementation of the bootstrapped current source is shown in Fig. 6.41(b). Here transistor Q_2 is a source follower used to buffer node A, whose voltage is being sensed. The width of Q_2 is half that of Q_1 and is operating at half the bias current. (Transistors Q_1 and Q_2 are said to operate at the same **current density.**) Thus V_{GS} of Q_2 will be equal to that of Q_1—namely, zero—and hence $V_C = V_A$. The two Schottky diodes behave as a battery of approximately 1.4 V, resulting in the dc voltage at node E being 1.4 V higher than V_C. Note that the signal voltage at node C appears intact at node E; only the dc level is shifted. The diodes are said to perform **level shifting,** a common application of Schottky diodes in GaAs MESFET technology.

Transistor Q_3 is a source follower that is operating at the same current density as Q_1, and thus its V_{GS} must be zero, resulting in $V_B = V_E$. The end result is that the bootstrapping circuit causes a dc voltage of 1.4 V to appear across the current-source transistor Q_1. Provided that $|V_t|$ of Q_1 is less than 1.4 V, Q_1 will be operating in saturation as required.

To determine the output resistance of the bootstrapped current source, apply an incremental voltage v_a to node A, as shown in Fig. 6.41(c). Note that this small-signal equivalent circuit is obtained by implicitly using the T model (including r_o) for each FET and assuming that the Schottky diodes act as a perfect level shifter (that is, as an ideal dc voltage of 1.4 V with zero internal resistance). Analysis of this circuit is straightforward and yields

$$\alpha \equiv \frac{v_b}{v_a} = \frac{g_{m3}r_{o3}\dfrac{g_{m2}r_{o2}}{g_{m2}r_{o2}+1} + \dfrac{r_{o3}}{r_{o1}}}{g_{m3}r_{o3} + \dfrac{r_{o3}}{r_{o1}} + 1} \tag{6.132}$$

which is smaller than, but close to, unity, as required. The output resistance R_o is then obtained as

$$\begin{aligned} R_o \equiv \frac{v_a}{i_a} &= \frac{r_{o1}}{1-\alpha} \\ &= r_{o1}\frac{g_{m3}r_{o3} + (r_{o3}/r_{o1}) + 1}{g_{m3}r_{o3}/(g_{m2}r_{o2}+1) + 1} \end{aligned} \tag{6.133}$$

For $r_{o3} = r_{o1}$, assuming that $g_{m3}r_{o3}$ and $g_{m2}r_{o2}$ are $\gg 1$, and using the relationships for g_m and r_o for Q_2 and Q_3, one can show that

$$R_o \simeq r_{o1}(g_{m3}r_{o3}/2) \tag{6.134}$$

which represents an increase of about an order of magnitude in output resistance. Unfortunately, however, the circuit is rather complex.

A Simple Cascode Configuration—The Composite Transistor

The rather low output resistance of the MESFET places a severe limitation on the performance of MESFET current sources and various MESFET amplifiers. This problem can be alleviated by using the composite MESFET configuration shown in Fig. 6.42(a) in place of a

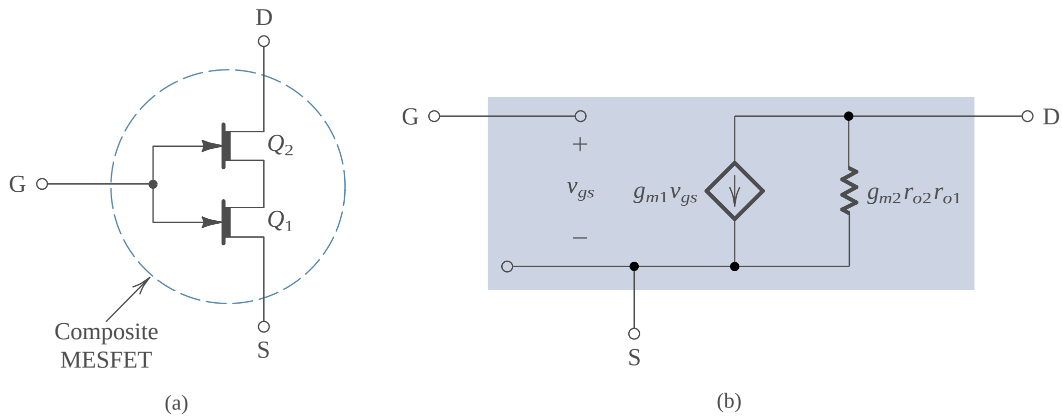

FIGURE 6.42 (**a**) The composite MESFET and (**b**) its small-signal model.

single MESFET. This circuit is unique to GaAs MESFETs and works only because of the early-saturation phenomenon observed in these devices. Recall from the discussion in Section 5.12 that **early saturation** refers to the fact that in a GaAs MESFET the drain current saturates at a voltage v_{DSsat} that is lower than $v_{GS} - V_t$.

In the composite MESFET of Fig. 6.42(a), Q_2 is made much wider than Q_1. It follows that since the two devices are conducting the same current, Q_2 will have a gate-to-source voltage v_{GS2} whose magnitude is much closer to $|V_t|$ than $|v_{GS1}|$ is (thus, $|v_{GS2}| \gg |v_{GS1}|$). For instance, if we use the devices whose typical parameters are given in Table 5.2 and ignore for the moment channel-length modulation ($\lambda = 0$), we find that for $W_1 = 10\ \mu$m and $W_2 = 90\ \mu$m, at a current of 1 mA, $v_{GS1} = 0$ and $v_{GS2} = -\frac{2}{3}$ V. Now, since the drain-to-source voltage of Q_1 is $v_{DS1} = -v_{GS2} + v_{GS1}$, we see that v_{DS1} will be positive and close to but lower than $v_{GS1} - V_t$ ($\frac{2}{3}$ V in our example compared to 1 V). Thus in the absence of early saturation, Q_1 would be operating in the triode region. With early saturation, however, it has been found that saturation-mode operation is achieved for Q_1 by making Q_2 5 to 10 times wider.

The composite MESFET of Fig. 6.42(a) can be thought of as a cascode configuration, in which Q_2 is the cascode transistor, but without a separate bias line to feed the gate of the cascode transistor (as in Fig. 6.40). By replacing each of Q_1 and Q_2 with their small-signal models one can show that the composite device can be represented with the equivalent circuit model of Fig. 6.42(b). Thus while g_m of the composite device is equal to that of Q_1, the output resistance is increased by the intrinsic gain of Q_2, $g_{m2}r_{o2}$, which is typically in the range 10 to 40. This is a substantial increase and is the reason for the attractiveness of the composite MESFET.

The composite MESFET can be employed in any of the applications that can benefit from its increased output resistance. Some examples are shown in Fig. 6.43. The circuit in Fig. 6.43(a) is that of a current source with increased output resistance. Another view of the operation of this circuit can be obtained by considering Q_2 as a source follower that causes the drain of Q_1 to follow the voltage changes at the current-source terminal (node A), thereby bootstrapping Q_1 and increasing the effective output resistance of the current source. This alternative interpretation of circuit operation has resulted in its alternative name: the **self-bootstrapped** current source.

The application of the composite MESFET as a source follower is depicted in Fig. 6.43(b). Assuming the bias-current source I to be ideal, we can write for the gain of

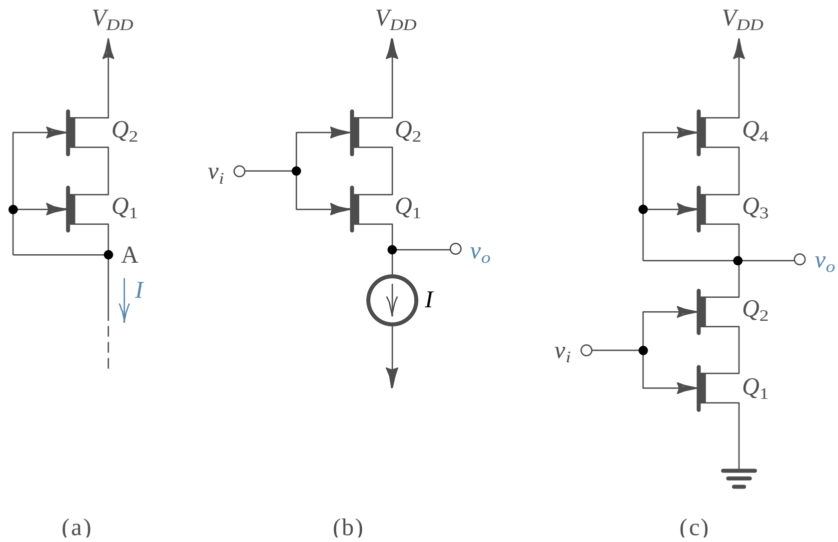

FIGURE 6.43 Applications of the composite MESFET: **(a)** as a current source; **(b)** as a source follower; and **(c)** as a gain stage.

this follower

$$\frac{v_o}{v_i} = \frac{r_{o,\text{eff}}}{r_{o,\text{eff}} + (1/g_{m1})}$$

$$= \frac{g_{m2} r_{o2} r_{o1}}{g_{m2} r_{o2} r_{o1} + (1/g_{m1})} \tag{6.135}$$

which is much closer to the ideal value of unity than is the gain of a single MESFET source follower.

EXERCISE

6.25 Using the device data given in Table 5.2, contrast the voltage gain of a source follower formed using a single MESFET having $W = 10\ \mu$m with a composite MESFET follower with $W_1 = 10\ \mu$m and $W_2 = 90\ \mu$m. In both cases assume biasing at 1 mA and neglect λ while calculating g_m (for simplicity).

Ans. Single: 0.952 V/V; composite: 0.999 V/V

A final example of the application of the composite MESFET is shown in Fig. 6.43(c). The circuit is a gain stage utilizing a composite MESFET (Q_1, Q_2) as a driver and another composite MESFET (Q_3, Q_4) as a current-source load. The small-signal gain is given by

$$\frac{v_o}{v_i} = -g_{m1} R_o \tag{6.136}$$

where R_o is the output resistance,

$$R_o = r_{o,\text{eff}}\,(Q_1, Q_2) // r_{o,\text{eff}}\,(Q_3, Q_4)$$

$$= g_{m2} r_{o2} r_{o1} // g_{m4} r_{o4} r_{o3} \tag{6.137}$$

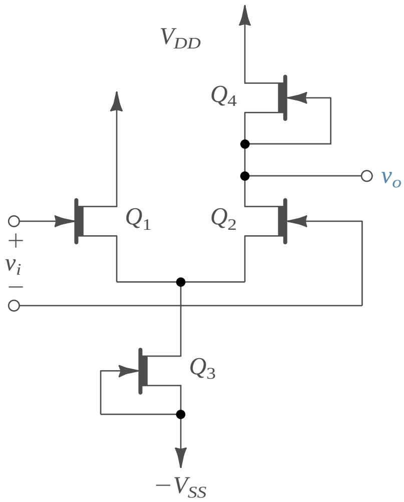

FIGURE 6.44 A simple MESFET differential amplifier.

Differential Amplifiers

The simplest possible implementation of a differential amplifier in GaAs MESFET technology is shown in Fig. 6.44. Here Q_1 and Q_2 form the differential pair, Q_3 forms the bias current source, and Q_4 forms the active (current-source) load. The performance of the circuit is impaired by the low output resistances of Q_3 and Q_4. The voltage gain is given by

$$\frac{v_o}{v_i} = -g_{m2}(r_{o2} // r_{o4}) \tag{6.138}$$

The gain can be increased by using one of the improved current-source implementations discussed above. Also, a rather ingenious technique has been developed for enhancing the gain of the MESFET differential pair. The circuit is shown in Fig. 6.45(a). While the drain

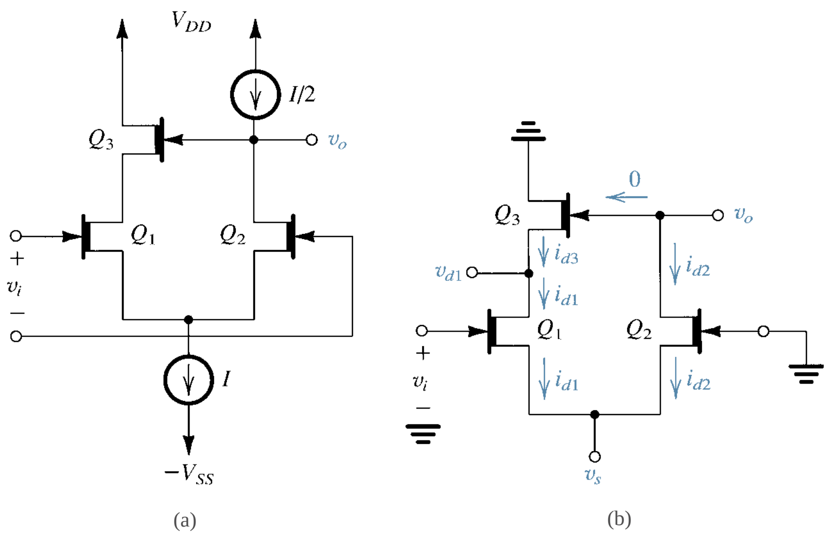

FIGURE 6.45 **(a)** A MESFET differential amplifier whose gain is enhanced by the application of positive feedback through the source follower Q_3; **(b)** small-signal analysis of the circuit in (a).