5.12 GALLIUM ARSENIDE (GaAs) DEVICES—THE MESFET[10]

The devices discussed thus far, and indeed the devices used in most of the circuits studied in this book, are made of silicon. This reflects the situation that has existed in the microelectronics industry for at least three decades. Furthermore, owing to the advances that are continually being made in silicon device and circuit technologies, the dominance of silicon as the most useful semiconductor material is expected to continue for many years to come. Nevertheless, another semiconductor material has been making inroads into digital applications that require extremely high speeds of operation and analog applications that require very high operating frequencies. We refer to gallium arsenide (GaAs), a compound semiconductor formed of gallium, which is in the third column of the periodic table of elements, and arsenic, which is in the fifth column; thus GaAs is known as a III-V semiconductor.

The major advantage that GaAs offers over silicon is that electrons travel much faster in n-type GaAs than in silicon. This is a result of the fact that the electron drift mobility μ_n (which is the constant that relates the electron drift velocity to the electric field; velocity = $\mu_n E$) is five to ten times higher in GaAs than in silicon. Thus for the same input voltages, GaAs devices have higher output currents, and thus higher g_m, than the corresponding silicon devices. The larger output currents enable faster charging and discharging of load and parasitic capacitances and thus result in increased speeds of operation.

Gallium arsenide devices have been used for some years in the design of discrete-component amplifiers for microwave applications (in the 10^9 Hz or GHz frequency range). More recently, GaAs has begun to be employed in the design of very-high-speed digital integrated circuits and in analog ICs, such as op amps, that operate in the hundreds of MHz frequency range. Although the technology is still relatively immature, suffering from yield and reliability problems and generally limited to low levels of integration, it offers great potential. Therefore, this book includes a brief study of GaAs devices and circuits. Specifically, the basic GaAs devices are studied in this section; their basic amplifier circuit configurations are discussed in Section 6.8; and GaAs digital circuits are studied in Section 14.8.

The Basic GaAs Devices

Although there are a number of GaAs technologies currently in various stages of development, we shall study the most mature of these technologies. The active device available in this technology is an n-channel field effect transistor known as the **metal semiconductor FET** or **MESFET.** The technology also provides a type of diode known as the **Schottky-barrier diode (SBD).** (Recall that the SBD was briefly introduced in Section 3.9.) The structure of these two basic devices is illustrated by their cross sections, depicted in Fig. 5.71. The GaAs circuit is formed on an undoped GaAs substrate. Since the conductivity of undoped GaAs is very low, the substrate is said to be semi-insulating. This turns out to be an advantage for GaAs technology as it simplifies the process of isolating the devices on the chip from one another, as well as resulting in smaller parasitic capacitances between the devices and the circuit ground.

As indicated in Fig. 5.71, a Schottky-barrier diode consists of a metal–semiconductor junction. The metal, referred to as the Schottky-barrier metal to distinguish it from the different kind of metal used to make a contact (see Long and Butner (1990) for a detailed explanation of the difference), forms the anode of the diode. The n-type GaAs forms the

[10] The material in this section is required only for the study of the GaAs circuits in Sections 6.8 and 14.8. Otherwise, this section can be skipped without loss of continuity.

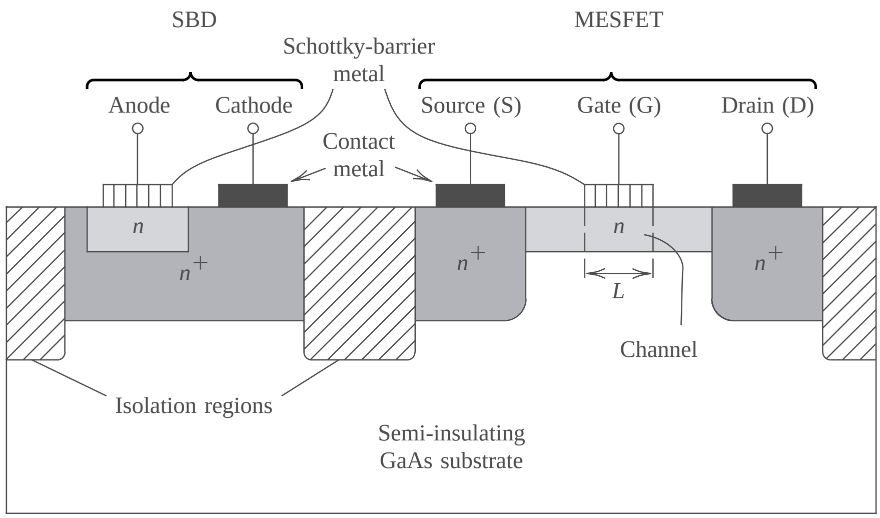

FIGURE 5.71 Cross-section of a GaAs Schottky-barrier diode (SBD) and a MESFET.

cathode. Note that heavily doped *n*-type GaAs (indicated by n^+) is used between the *n* region and the cathode metal contact in order to keep the parasitic series resistance low.

The gate of the MESFET is formed by Schottky-barrier metal in direct contact with the *n*-type GaAs that forms the channel region. The channel length L is defined by the length of the gate electrode, and similarly for the width W (in the direction perpendicular to the page). To reduce the parasitic resistances between the drain and source contacts and the channel, the two contacts are surrounded with heavily doped (n^+) GaAs.

Since the main reason for using GaAs circuits is to achieve high speed/frequency of operation, the channel length is made as small as possible. Typically $L = 0.2$–$2\ \mu$m. Also, usually all the transistors on the IC chip are made to have the same length, leaving only the width W of each device to be specified by the circuit designer.

Only *n*-channel MESFETs are available in GaAs technology. This is because holes have a relatively low drift mobility in GaAs, making *p*-channel MESFETs unattractive. The lack of complementary transistors is a definite disadvantage of GaAs technology. Correspondingly, it makes the task of the circuit designer even more challenging than usual.

Device Operation

The MESFET operates in a very similar manner to the JFET, with the Schottky metal playing the role of the *p*-type gate of the JFET (refer to Fig. 5.69). Basically, a depletion region forms in the channel below the gate surface, and the thickness of the depletion region is controlled by the gate voltage v_{GS}. This in turn effects control over the channel dimensions and thus on the current that flows from drain to source in response to an applied v_{DS}. The latter voltage causes the channel to have a tapered shape, with pinch-off eventually occurring at the drain end of the channel.

The most common GaAs MESFETs available are of the depletion type with a threshold voltage V_t (or, equivalently, pinch-off voltage V_P) in the range of -0.5 to -2.5 V. These devices can be operated with v_{GS} values ranging from the negative V_t to positive values as high as a few tenths of a volt. However, as v_{GS} reaches 0.7 V or so, the Schottky-barrier diode between gate and channel conducts heavily and the gate voltage no longer effectively controls the drain-to-source current. Gate conduction, which is not possible in MOSFETs, is another definite disadvantage of the MESFET.

Although less common, enhancement-mode MESFETs are available in certain technologies. These normally-off devices are obtained by arranging that the depletion region existing at $v_{GS} = 0$ extends through the entire channel depth, thus blocking the channel and causing $i_D = 0$. To cause current to flow from drain to source the channel must be opened by applying to the gate a positive voltage of sufficient magnitude to reduce the thickness of the depletion region below that of the channel region. Typically, the threshold voltage V_t is between 0.1 and 0.3 V.

The above description of MESFET operation suggests that the i_D–v_{DS} characteristics should saturate at $v_{DS} = v_{GS} - V_t$, as is the case in a silicon JFET. It has been observed, however, that the i_D–v_{DS} characteristics of GaAs MESFETs saturate at lower values of v_{DS} and, furthermore, that the saturation voltages $v_{DS\text{sat}}$ do not depend strongly on the value of v_{GS}. This "early saturation" phenomenon comes about because the velocity of the electrons in the channel does not remain proportional to the electric field (which in turn is determined by v_{DS} and L; $E = v_{DS}/L$) as is the case in silicon; rather, the electron velocity reaches a high peak value and then saturates (that is, becomes constant independent of v_{DS}). The velocity-saturation effect is even more pronounced in short-channel devices ($L \le 1$ μm), occurring at values of v_{DS} lower than $(v_{GS} - V_t)$.

Finally, a few words about the operation of the Schottky-barrier diode. Forward current is conducted by the majority carriers (electrons) flowing into the Schottky-barrier metal (the anode). Unlike the *pn*-junction diode, minority carriers play no role in the operation of the SBD. As a result, the SBD does not exhibit minority-carrier storage effects, which give rise to the diffusion capacitance of the *pn*-junction diode. Thus, the SBD has only one capacitive effect, that associated with the depletion-layer capacitance C_j.

Device Characteristics and Models

A first-order model for the MESFET, suitable for hand calculations, is obtained by neglecting the velocity-saturation effect, and thus the resulting model is almost identical to that of the JFET though expressed somewhat differently in order to correspond to the literature:

$$
\begin{aligned}
i_D &= 0 \qquad \text{for } v_{GS} < V_t \\
i_D &= \beta[2(v_{GS} - V_t)v_{DS} - v_{DS}^2](1 + \lambda v_{DS}) \qquad \text{for } v_{GS} \ge V_t,\ v_{DS} < v_{GS} - V_t \\
i_D &= \beta(v_{GS} - V_t)^2(1 + \lambda v_{DS}) \qquad \text{for } v_{GS} \ge V_t,\ v_{DS} \ge v_{GS} - V_t
\end{aligned}
\tag{5.120}
$$

The only differences between these equations and those for the JFETs are (1) the channel-length modulation factor, $1 + \lambda v_{DS}$, is included also in the equation describing the triode region (also called the ohmic region) simply because λ of the MESFET is rather large and including this factor results in a better fit to measured characteristics; and (2) a transconductance parameter β is used so as to correspond with the MESFET literature. Obviously, β is related to I_{DSS} of the JFET and $k'(W/L)$ of the MOSFET. (Note, however, that this β has absolutely nothing to do with β of the BJT!)

A modification of this model to account for the early saturation effects is given in Hodges and Jackson (1988).

Figure 5.72(a) shows the circuit symbol for the depletion-type *n*-channel GaAs MESFET. Since only one type of transistor (*n* channel) is available, all devices will be drawn the

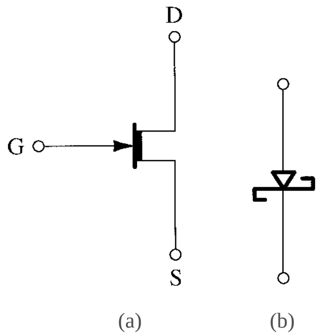

FIGURE 5.72 Circuit symbols for **(a)** an *n*-channel depletion-type GaAs MESFET, and **(b)** a Schottky-barrier diode (SBD).

same way, and there should be no confusion as to which terminal is the drain and which is the source.

The circuit symbol of the Schottky-barrier diode is depicted in Fig. 5.72(b). In spite of the fact that the physical operation of the SBD differs from that of the *pn*-junction diode, their i–v characteristics are identical. Thus the i–v characteristic of the SBD is given by the same exponential relationship studied in Chapter 3. For the GaAs SBD, the constant n is typically in the range of 1 to 1.2.

The small-signal model of the MESFET is identical to that of other FET types. The parameter values are given by

$$g_m = 2\beta(V_{GS} - V_t)(1 + \lambda V_{DS}) \tag{5.121}$$

$$r_o \equiv \left[\frac{\partial i_D}{\partial v_{DS}}\right]^{-1}$$

$$= 1/\lambda\beta(V_{GS} - V_t)^2 \tag{5.122}$$

The MESFET, however, has a rather high value for λ (0.1 to 0.3 V^{-1}) which results in a small output resistance r_o. This turns out to be a serious drawback of GaAs MESFET technology, resulting in low voltage-gain obtainable from each stage. Furthermore, it has been found that r_o decreases at high frequencies. Circuit design techniques for coping with the low r_o will be presented in Section 6.8.

For easy reference, Table 5.2 gives typical values for device parameters in a GaAs MESFET technology. The devices in this technology have a channel length $L = 1\ \mu$m. The values given are for a device with a width $W = 1\ \mu$m. The parameter values for actual devices can be obtained by appropriately scaling by the width W. This process is illustrated in the following example. Unless otherwise specified, the values of Table 5.2 are to be used for the exercises and the end-of-chapter problems.

TABLE 5.2 Typical Parameter Values for GaAs MESFETS and Schottky Diodes in $L = 1\ \mu$m Technology, Normalized for $W = 1\ \mu$m

$$V_t = -1.0\ \text{V}$$
$$\beta = 10^{-4}\ \text{A/V}^2$$
$$\lambda = 0.1\ \text{V}^{-1}$$
$$I_S = 10^{-15}\ \text{A}$$
$$n = 1.1$$

EXAMPLE 5.11

Figure 5.73 shows a simple GaAs MESFET amplifier, with the W values of the transistors indicated. Assume that the dc component of v_I, that is V_{GS1}, biases Q_1 at the current provided by the current source Q_2 so that both devices operate in saturation and that the dc output is at half of the supply voltage. Find:

(a) the β values for Q_1 and Q_2;

(b) V_{GS1};

(c) g_{m1}, r_{o1}, and r_{o2}; and

(d) the small-signal voltage gain.

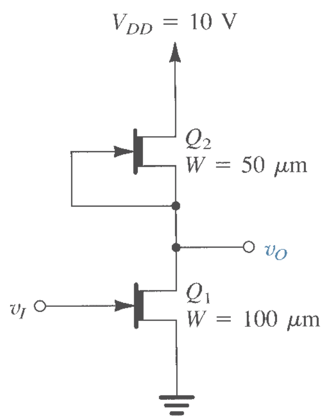

FIGURE 5.73 Circuit for Example 5.11: a simple MESFET amplifier.

Solution

(a) The values of β can be obtained by scaling the value given in Table 5.2 using the specified values of W,

$$\beta_1 = 100 \times 10^{-4} = 10^{-2} \text{ A/V}^2 = 10 \text{ mA/V}^2$$

$$\beta_2 = 50 \times 10^{-4} = 5 \times 10^{-3} \text{ A/V}^2 = 5 \text{ mA/V}^2$$

(b)

$$\begin{aligned} I_{D2} &= \beta_2 (V_{GS2} - V_t)^2 (1 + \lambda V_{DS2}) \\ &= 5(0+1)^2(1 + 0.1 \times 5) \\ &= 7.5 \text{ mA} \end{aligned}$$

$$I_{D1} = I_{D2} = 7.5 \text{ mA}$$

$$\begin{aligned} 7.5 &= \beta_1 (V_{GS1} - V_t)^2 (1 + \lambda V_{DS1}) \\ &= 10(V_{GS1} + 1)^2 (1 + 0.1 \times 5) \end{aligned}$$

Thus,

$$V_{GS1} = -0.3 \text{ V}$$