III. Metal–Semiconductor Field-Effect Transistors (MESFETs)

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GaAs metal–semiconductor field-effect transistors (MESFETs) are the most commonly used and important active devices in microwave circuits. In fact, until the late 1980s, almost all microwave integrated circuits used GaAs MESFETs. Although more complicated devices with better performance for some applications have been introduced, the MESFET is still the dominant active device for power amplifiers and switching circuits in the microwave spectrum.

The basic MESFET is shown schematically in Figure 3-12. The base material on which the transistor is fabricated is a semi-insulating GaAs substrate. A buffer layer is epitaxially grown over the semi-insulating substrate to isolate defects in the substrate from the transistor. The channel or the conducting layer is a thin, lightly doped (n) conducting layer of semiconducting material epitaxially grown over the buffer layer. Since the electron mobility is approximately 20 times greater than the hole mobility for GaAs, the conducting channel is always n type for microwave transistors. Finally, a highly doped (n^+) layer is grown on the surface to aid in the fabrication of low-resistance ohmic contacts to the transistor. This layer is etched away in the channel region. Alternatively, ion implantation may be used to create the n channel and the highly doped ohmic contact regions directly in the semi-insulating substrate. Two ohmic contacts, the source and drain, are fabricated on the highly doped layer to provide access to the external circuit. Between the two ohmic contacts, a rectifying or Schottky contact is fabricated. Typically, the ohmic contacts are Au–Ge based and the Schottky contact is Ti–Pt–Au.

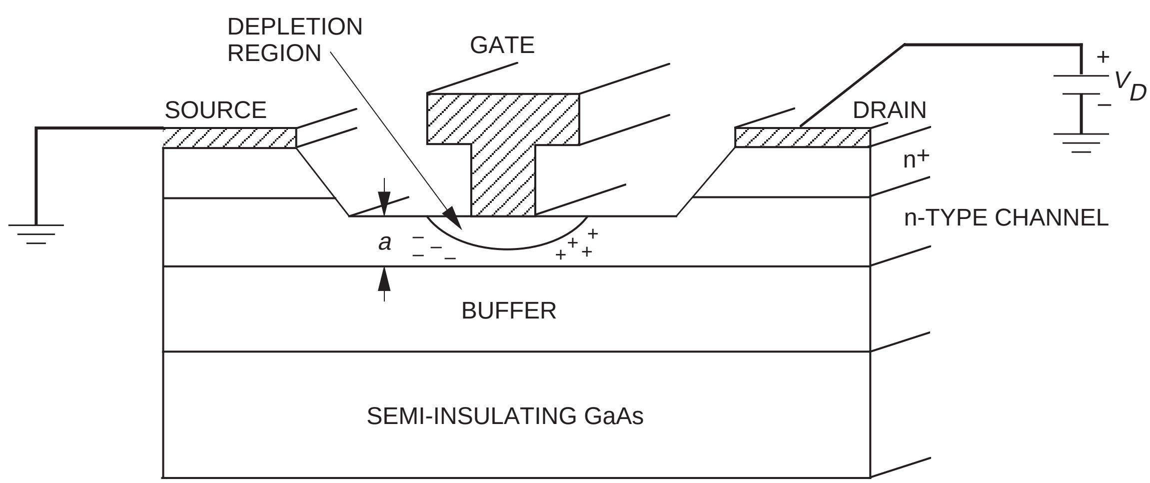

Figure 3-12. Schematic and cross section of a MESFET.

A. Device Physics

The basic operation of the MESFET is easily understood by first considering the I–V characteristics of the device without the gate contact, as shown in Figure 3-13. If a small voltage is applied between the source and drain, a current will flow between the two contacts. As the voltage is increased, the current increases linearly with an associated resistance that is the sum of the two ohmic resistances, R_S and R_D, and the channel resistance, R_{DS}.

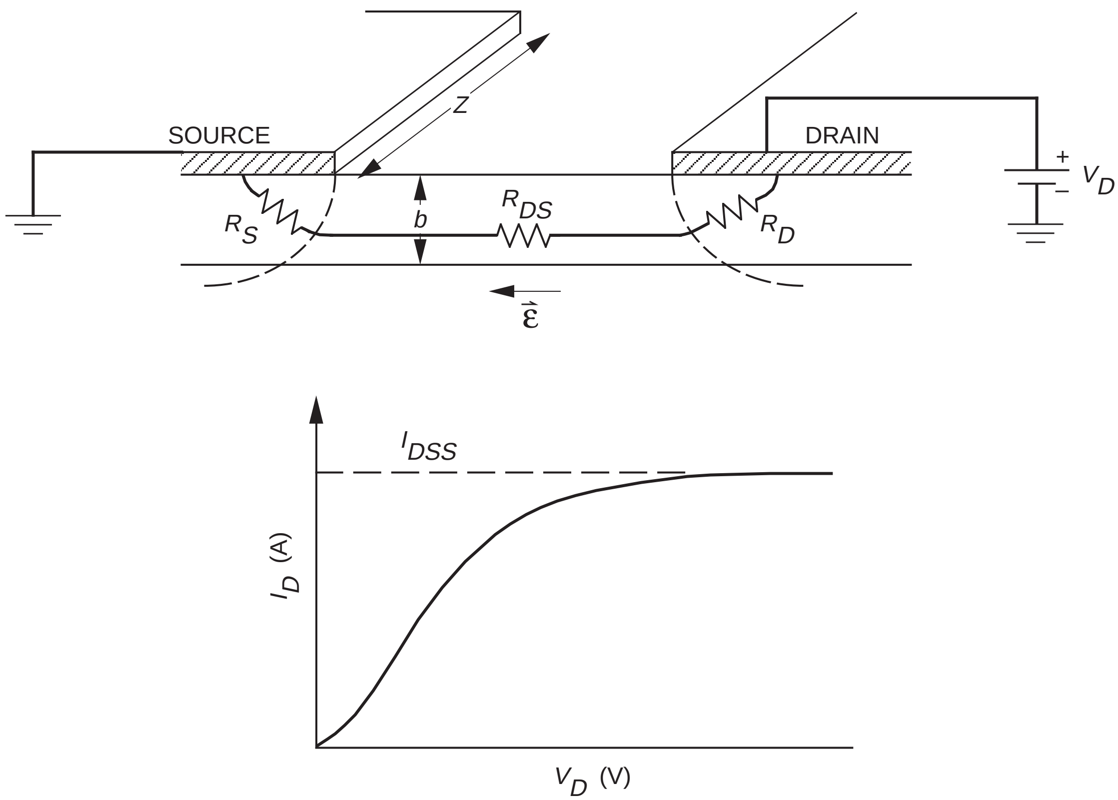

Figure 3-13. Schematic and I–V characteristics for an ungated MESFET.

$$I_D = \frac{V_D}{R_D + R_S + R_{DS}} \tag{3-10}$$

If the voltage is increased further, the applied electric field will become greater than the electric field required for saturation of electron velocity, as shown in Figure 3-4. Under large bias conditions, an alternative expression for I_D is useful; this expression relates the current directly to the channel parameters:

$$I_D = Q(x)v(x) = Zb(x)qn(x)v(x) \tag{3-11}$$

This expression omits the parasitic resistances, R_S and R_D. The parameters in Equation (3-11) are Z, the width of the channel; $b(x)$, the effective channel depth; q, the electron charge; $n(x)$, the electron density; and $v(x)$, the electron velocity, which is related to the electric field across the channel. Note that if $v(x)$ saturates, I_D will also saturate. This saturation current is called I_{DSS}.

Now consider the effect of the gate electrode placed over the channel but without any gate bias, $V_G = 0$. As presented in Section 3-II, a depletion region formed under the gate electrode reduces the effective channel depth, $b(x)$, and therefore increases the resistance to current flow under the gate. The depletion region depth is dependent on the voltage drop across the Schottky junction. Since the current flowing through the channel is equivalent to a current flow through a distributed resistor, there is a larger voltage drop across the drain end of the channel than at the source end. This results in the depletion region depth being greater on the drain side of the channel. The nonuniform channel depth has two effects on the device operation. First, there is an accumulation of electrons on the source side and a depletion of electrons on the drain side of the depletion region. This dipole of charge creates a feedback capacitance between the drain and the channel; this capacitance is typically called C_{DC}. The second effect is that the electric field due to the dipole adds to the applied electric field causing the saturation conditions to occur at a lower V_D. By applying a bias to the gate junction, the depletion depth and therefore the resistance of the current flow between the source and drain and the saturation current can be controlled. If a large enough negative gate bias is applied, the depletion region depth will equal the channel depth, or the channel will be pinched off. This gate bias is called the pinch-off voltage and is given by

$$V_P = \left(\frac{qN_d}{2\varepsilon_0 \varepsilon_r} \right) a^2 \tag{3-12}$$

Under pinch-off conditions, the drain current drops to a very small value. Therefore, the transistor can act as a voltage-controlled resistor or a switch.

The most important feature of MESFETs is that they may be used to increase the power level of a microwave signal, or that they provide gain. Because the drain current can be made to vary greatly by introducing small variations in the gate potential, the MESFET can be modeled as a voltage-controlled current source. The transconductance of the MESFET is defined as

$$g_m = \left. \frac{-\partial I_D}{\partial V_{GS}} \right|_{-V_{DS-constant}} \tag{3-13}$$

Using short-channel approximations, it can be shown that the transconductance may be written as

$$g_m = \frac{I_S}{2V_P} \left(\frac{I_S}{I_S - I_D} \right) \tag{3-14}$$

where I_S is the maximum current that can flow if the channel were fully undepleted under saturated velocity conditions. This is the same as the saturation current discussed for the device without the gate electrode shown in Figure 3-13. Since I_S is proportional to the channel depth, a, and V_P is proportional to the square of the channel depth, g_m is inversely proportional to the channel depth. In addition, from Equation (3-10), we note that for large I_S and g_m, the parasitic resistances R_S and R_D must be minimized.

The most commonly used figures of merit for microwave transistors are the gain bandwidth product, the maximum frequency of oscillation, f_{max}, and the frequency where the unilateral power gain of the device is equal to one, f_t. Consider first the parameter f_t. If short gate length approximations are made, f_t can be related to the transit time of the electrons through the channel, t, by the expression

$$f_t = \frac{1}{2\pi\tau} = \frac{v_{sat}}{2\pi L} \tag{3-15}$$

Since v_{sat} is approximately 6×10^{10} µm/s for GaAs with doping levels typically used in the channel, the gate length must be less than 1 µm for f_t to be greater than

10 GHz. The parameter f_{max} may be approximated by

$$f_{\max} = \frac{f_t}{2}\sqrt{\frac{R_{DS}}{R_G}} \qquad (3\text{-}16)$$

where R_G is the gate resistance. From the above two expressions for f_t and $f_{max,}$ it is apparent that the gate length should be made as small as possible. Both the limits of fabrication and the need to keep the electric field under the channel less than the critical field strength required for avalanche breakdown set the lower limit on L at approximately 0.1 µm. For the gate to have effective control of the channel current, the gate length L must be larger than the channel depth, a, or $L/a > 1$. This requires a channel depth on the order of 0.05 to 0.3 µm for most GaAs MESFETs. The small channel depth requires that the carrier concentration in the channel be as high as possible to maintain a high current.

B. Reliability

The small feature sizes described above may create reliability problems in microwave GaAs MESFETs. The small cross section of the gate electrode results in a high current density, especially for power transistors, which leads to electromigration failures. To reduce the gate resistance, gold is typically used over the gate refractory metal. Since gold creates deep-level traps in GaAs, which effectively reduce the carrier concentration and therefore the current of the device, barrier metals such as platinum must be used. In addition, because the channel depth is so small, any diffusion of gate metals into the GaAs creates large changes in the current that flows through the channel and decreases the pinch-off voltage. The small distance between the gate and drain electrodes also creates high electric fields, which may create an avalanche generation of electrons. These "hot electrons" may then become trapped in the surface states of the GaAs or in the passivation material that is commonly deposited over the device. The reliability problems that occur greatly depend on the device technology, as well as its application. In small-signal applications, the degradation of the ohmic contacts or interdiffusion of the gate metals with the GaAs in the channel leads to shifts in I_D, g_m, and V_P.

Although power MESFETs also suffer from parametric degradation, catastrophic failures are more common. However, advances in device technology and operation within safe limits have decreased the incidence of burnout. For power amplifiers, the MESFET must be designed for maximum power output. This is equivalent to requiring a large drain-to-source voltage and a large drain current. Unfortunately, both of these parameters may not be maximized simultaneously. To maximize I_D, a large carrier concentration or a large gate width is required; note that the channel depth may not be increased since that would degrade the frequency range of the device. The carrier concentration may not be increased without degrading the gate-to-drain breakdown voltage, which must be maximized to maximize V_{DS}. Therefore, the only alternative is to increase the gate width, Z. Unfortunately, in microwave circuit design, long line lengths do not appear as lumped elements with a uniform potential along the length, but rather as distributed transmission lines with potential nulls occurring every half wavelength. The general rule of thumb is that a line should be less than one tenth of a wavelength long to be considered a lumped element. For GaAs, this is equivalent to

$$Z \leq \frac{11.3}{f}\ \text{mm} \qquad (3\text{-}17)$$

where f is the frequency in GHz. Therefore, at X-band, 8 to 12 GHz, the maximum gate width that may be used is approximately 1 mm. If greater current is required, multiple gate fingers may be used in a parallel connection. This parallel connection of gate fingers in a tightly packed region increases the localized temperature of the circuit. Since GaAs is a poor thermal conductor, power transistors will typically operate at least 10 deg above the carrier temperature. This increased device temperature, with the higher fields and currents used in power MESFETs, often leads to catastrophic failures.

Additional Reading

Bahl, I., and P. Bhartia, *Microwave Solid State Circuit Design*, John Wiley & Sons, New York, 1988.

Sze, S. M., *Physics of Semiconductor Devices*, John Wiley & Sons, New York, 1981.