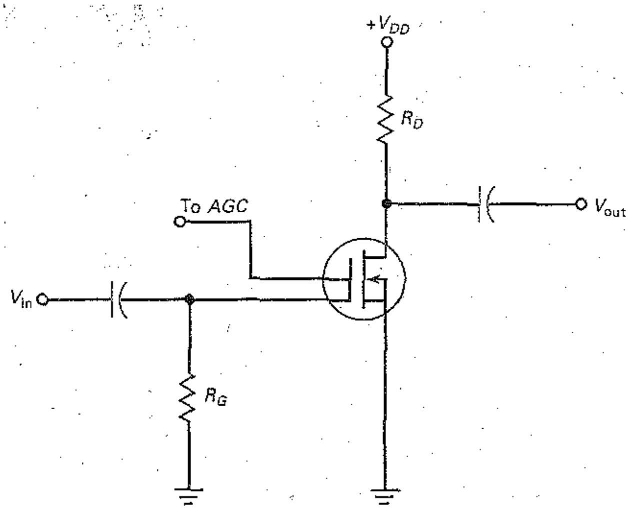
Figure 14-7 Dual-gate MOSFET.



14-4 The Enhancement-Mode MOSFET

The depletion-mode MOSFET was part of the evolution toward the **enhancement-mode MOSFET,** abbreviated *E-MOSFET.* Without the E-MOSFET, the personal computers that are now so widespread would not exist.

The Basic Idea

Figure 14-8*a* shows an E-MOSFET. The *p* substrate now extends all the way to the silicon dioxide. As you can see, there no longer is an *n* channel between the source and the drain. How does an E-MOSFET work? Figure 14-8*b* shows normal biasing polarities. When the gate voltage is zero, the current between source and drain is zero. For this reason, an E-MOSFET is *normally off* when the gate voltage is zero.

The only way to get current is with a positive gate voltage. When the gate is positive, it attracts free electrons into the *p* region. The free electrons recombine with the holes next to the silicon dioxide. When the gate voltage is positive enough, all the holes touching the silicon dioxide are filled and free electrons begin to flow from the source to the drain. The effect is the same as creating a thin layer of *n*-type material next to the silicon dioxide. This thin conducting layer is

Figure 14-8 Enhancement-mode MOSFET: (*a*) Unbiased; (*b*) biased.

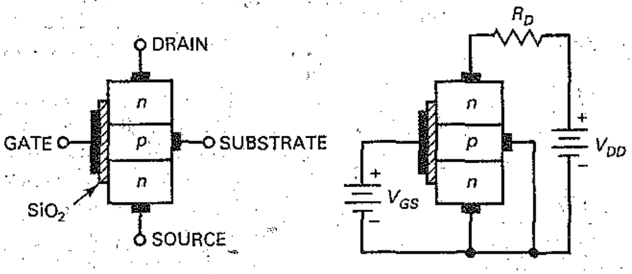
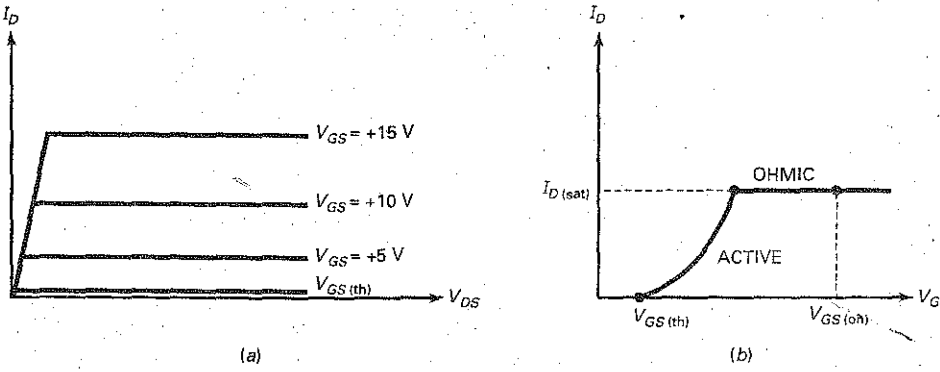


Figure 14-9 EMOS graphs: (*a*) Drain curves; (*b*) transconductance curve.



called the *n-type inversion layer.* When it exists, free electrons can flow easily from the source to the drain.

The minimum V_{GS} that creates the n-type inversion layer is called the **threshold voltage,** symbolized $V_{GS(th)}$. When V_{GS} is less than $V_{GS(th)}$, the drain current is zero. When V_{GS} is greater than $V_{GS(th)}$, an n-type inversion layer connects the source to the drain and the drain current can flow. Typical values of $V_{GS(th)}$ for small-signal devices are from 1 to 3 V.

The JFET is referred to as a *depletion-mode device* because its conductivity depends on the action of depletion layers. The E-MOSFET is classified as an *enhancement-mode device* because a gate voltage greater than the threshold voltage enhances its conductivity. With zero gate voltage, a JFET is *on,* whereas an E-MOSFET is *off.* Therefore, the E-MOSFET is considered to be a normally off device.

Drain Curves

A small-signal E-MOSFET has a power rating of 1 W or less. Figure 14-9*a* shows a set of drain curves for a typical small-signal E-MOSFET. The lowest curve is the $V_{GS(th)}$ curve. When V_{GS} is less than $V_{GS(th)}$, the drain current is approximately zero. When V_{GS} is greater than $V_{GS(th)}$, the device turns on and the drain current is controlled by the gate voltage.

The almost-vertical part of the graph is the ohmic region, and the almost-horizontal parts are the active region. When biased in the ohmic region, the E-MOSFET is equivalent to a resistor. When biased in the active region, it is equivalent to a current source. Although the E-MOSFET can operate in the active region, the main use is the ohmic region.

Figure 14-9*b* shows a typical transconductance curve. There is no drain current until $V_{GS} = V_{GS(th)}$. The drain current then increases rapidly until it reaches the saturation current $I_{D(sat)}$. Beyond this point, the device is biased in the ohmic region. Therefore, I_D cannot increase, even though V_{GS} increases. To ensure hard saturation, a gate voltage of $V_{GS(on)}$ well above $V_{GS(th)}$ is used, as shown in Fig. 14-9*b*.

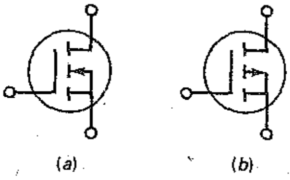
Schematic Symbol

When $V_{GS} = 0$, the E-MOSFET is off because there is no conducting channel between source and drain. The schematic symbol of Fig. 14-10*a* has a broken channel line to indicate this normally off condition. As you know, a gate voltage greater than the threshold voltage creates an n-type inversion layer that connects

GOOD TO KNOW

With the E-MOSFET, V_{GS} has to be greater than $V_{GS(th)}$ to get any drain current at all. Therefore, when E-MOSFETs are biased, self-bias, current-source bias, and zero bias cannot be used because these forms of bias depend on the depletion mode of operation. This leaves gate bias, voltage-divider bias, and source bias as the means for biasing E-MOSFETs.

Figure 14-10 EMOS Schematic symbols: (*a*) *N*-channel device; (*b*) *p*-channel device.



the source to the drain. The arrow points to this inversion layer, which acts like an *n* channel when the device is conducting.

There is also a *p*-channel E-MOSFET. The schematic symbol is similar, except that the arrow points outward, as shown in Fig. 14-10*b*.

GOOD TO KNOW

E-MOSFETs are often used in class AB amplifiers, where the E-MOSFET is biased with a value of V_{GS} slightly exceeding that of $V_{GS(th)}$. This "trickle bias" prevents crossover distortion. D-MOSFETs are not suitable for use in class B or class AB amplifiers because a large drain current flows for $V_{GS} = 0$ V.

Maximum Gate-Source Voltage

MOSFETs have a thin layer of silicon dioxide, an insulator that prevents gate current for positive as well as negative gate voltages. This insulating layer is kept as thin as possible to give the gate more control over the drain current. Because the insulating layer is so thin, it is easily destroyed by excessive gate-source voltage.

For instance, a 2N7000 has a $V_{GS(\max)}$ rating of ±20 V. If the gate-source voltage becomes more positive than +20 V or more negative than −20 V, the thin insulating layer will be destroyed.

Aside from directly applying an excessive V_{GS}, you can destroy the thin insulating layer in more subtle ways. If you remove or insert a MOSFET into a circuit while the power is on, transient voltages caused by inductive kickback may exceed the $V_{GS(\max)}$ rating. Even picking up a MOSFET may deposit enough static charge to exceed the $V_{GS(\max)}$ rating. This is the reason why MOSFETs are often shipped with a wire ring around the leads, or wrapped in tin foil, or inserted into conductive foam.

Some MOSFETs are protected by a built-in zener diode in parallel with the gate and the source. The zener voltage is less than the $V_{GS(\max)}$ rating. Therefore, the zener diode breaks down before any damage to the thin insulating layer occurs. The disadvantage of these internal zener diodes is that they reduce the MOSFET's high input resistance. The trade-off is worth it in some applications because expensive MOSFETs are easily destroyed without zener protection.

In conclusion, MOSFET devices are delicate and can be easily destroyed. You have to handle them carefully. Furthermore, you should never connect or disconnect them while the power is on. Finally, before you pick up a MOSFET device, you should ground your body by touching the chassis of the equipment you are working on.

14-5 The Ohmic Region

Although the E-MOSFET can be biased in the active region, this is seldom done because it is primarily a switching device. The typical input voltage is either low or high. Low voltage is 0 V, and high voltage is $V_{GS(on)}$, a value specified on data sheets.

Drain-Source on Resistance

When an E-MOSFET is biased in the ohmic region, it is equivalent to a resistance of $R_{DS(on)}$. Almost all data sheets will list the value of this resistance at a specific drain current and gate-source voltage.

Figure 14-11 illustrates the idea. There is a Q_{test} point in the ohmic region of the $V_{GS} = V_{GS(on)}$ curve. The manufacturer measures $I_{D(on)}$ and $V_{DS(on)}$ at this Q_{test} point. From this, the manufacturer calculates the value of $R_{DS(on)}$ using this definition:

$$R_{DS(on)} = \frac{V_{DS(on)}}{I_{D(on)}} \tag{14-3}$$