THE MOSFET

The MOSFET (metal oxide semiconductor field-effect transistor) is another category of field-effect transistor. The n-channel MOSFET (Figure 12) has only a single p region (called the substrate), one side of which acts as a conducting channel. A metallic gate is separated from the conducting channel by an insulating metal oxide (usually SiO_2). The p-channel MOSFET, formed by interchanging p and n semiconductor materials, is described by complementary voltages and currents. The MOSFET, different from the JFET, has no pn junction structure. The two basic types of MOSFETs are enhancement and depletion. Because of the insulated gate, MOSFETs are sometimes called IGFETs.

Enhancement MOSFET (E-MOSFET)

The E-MOSFET operates only in the enhancement mode and has no depletion mode. It differs in construction from the D-MOSFET, in that it has no structural channel, and the substrate extends completely to the SiO_2 layer as shown in Figure 12(a). For an n-channel device, A channel is induced by applying a V_{GS} greater than the threshold value, $V_{GS(th)}$, by creating a thin layer of negative charges in the substrate region adjacent to the SiO_2 layer, as shown in Figure 12(b). The positive gate voltage attracts electron from the substrate to the region along the insulating layer. If the gate is made sufficiently positive, enough electrons will be pulled up from the substrate, an n-channel starts to form. The channel does not form uniformly but rather begins to form on the drain side. As the gate voltage increases, the channel length also increases. Finally, the gate voltage increases to the point ($V_{GS(th)}$) where the channel reaches the source, and conduction begins. The conductivity of the channel is enhanced by increasing the V_{GS}

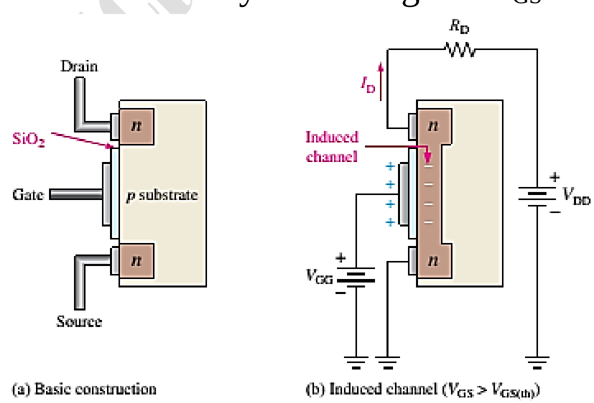

Figure 12: The basic E-MOSFET construction and operation (n-channel).

E-MOSFET Transfer Characteristic

The transfer curve for a MOSFET is has the same parabolic shape as the JFET but the position is shifted along the *x*-axis. The transfer curve for p-channel and *n*-channel E-MOSFET is entirely in the first quadrant as shown. The curve is on the enhancement region, I_D = 0A when V_{GS} = 0V and I_D = 0A until V_{GS} reaches the threshold value.

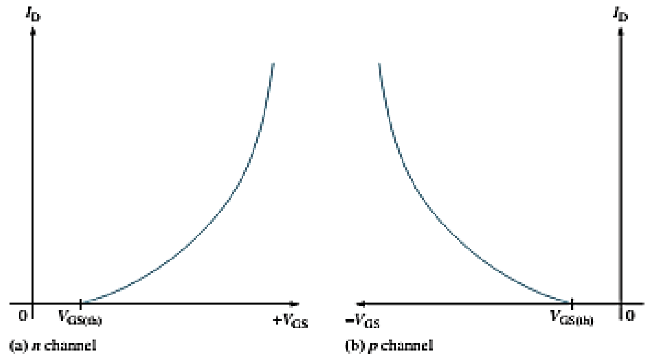

Figure 13: E-MOSFET general transfer characteristic curves.

The curve starts at $V_{GS(th)}$, which is a nonzero voltage that is required to have channel conduction. The equation for the drain current is

$$\mathbf{I_D = K(V_{GS} - V_{GS(th)})^2} \quad \text{where K is constant is given by:} \quad \mathbf{K = \frac{I_{D(on)}}{(V_{GS} - V_{GS(th)})^2}}$$

Depletion MOSFET (D-MOSFET)

The D-MOSFET has a channel that can is controlled by the gate voltage. For an n-channel type, a negative voltage depletes the channel; and a positive voltage enhances the channel. The D-MOSFET can be operated in either of two modes—the depletion mode or the enhancement mode, depending on the gate voltage, and is sometimes called a depletion/enhancement MOSFET. The n-channel MOSFET operates in the **depletion** mode when a negative gate-to-source voltage (V_{GS}) is applied and in the **enhancement** mode when a positive gate-to-source voltage (V_{GS}) is applied. D-MOSFET are generally operated in the depletion mode.

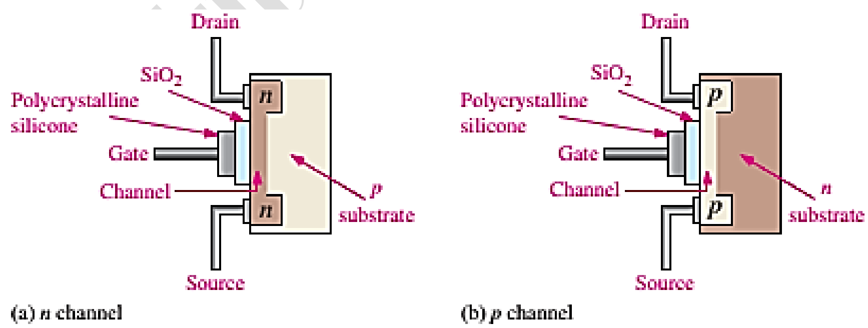

Figure 14: The basic structure of D-MOSFETs.

Depletion Mode: with a negative V_{GS}, the electric field produces in the channel drives electrons away from a portion of the channel near the SiO_2 layer. This portion is depleted of carriers and the channel width is effectively narrowed. The channel conductivity is decreased. Further increasing the negative voltage at the gate pushes even more electrons away, narrowing the channel and decreasing the current (Figure 15)

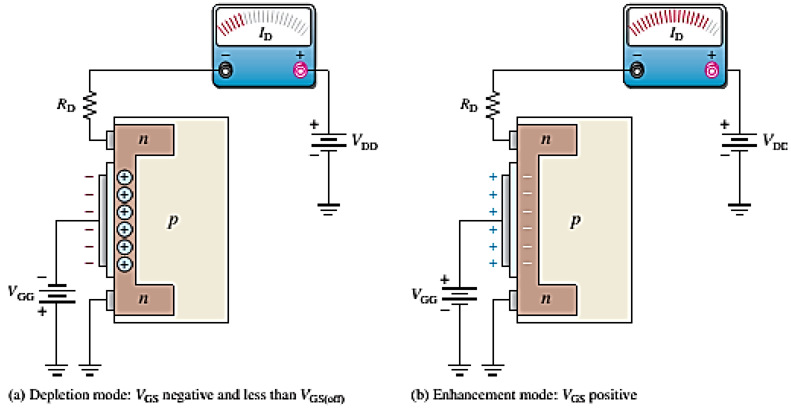

Figure 15: Operation of n-channel D-MOSFET.

Enhancement Mode: V_{GS} can be made positive without any concern for the consequences of forward biasing a junction. With a positive V_{GG}, more conduction electrons are attracted into the channel. The channel conductivity is enhanced (increased), as shown in Figure 15 (b).

D-MOSFET Transfer Characteristic

Recall that the D-MOSFET can be operated in either mode. This is indicated on the general transfer characteristic curves in Figure 16 for both n-channel and p-channel MOSFETs. For the region $V_{GS} < 0V$ operation is in depletion mode, in the region $V_{GS} > 0V$ operation in enhancement mode. As with the JFET, The point on the curves where $V_{GS}=0$ corresponds to I_{DSS}. The equation for drain current is

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

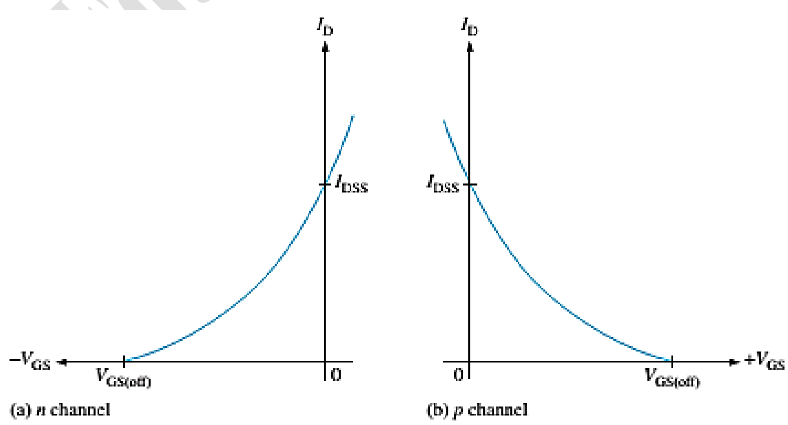

Figure 16: D-MOSFET general transfer characteristic curves.

MOSFET Symbols

The symbols for the n-channel and p-channel MOSFETs are shown in Figure 17. Notice the broken line representing the E-MOSFET that has an induced channel. An **inward-**

pointing substrate arrow is for n-channel, and an **outward**-pointing arrow is for p-channel.

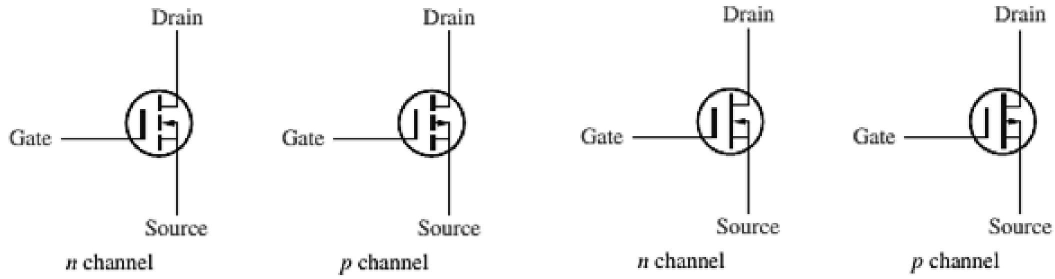

Figure 17: (a) E-MOSFET schematic symbols (b) D-MOSFET schematic symbols.

MOSFET Biasing

E-MOSFETs can be biased using bias methods like the BJT methods studied earlier. Voltage-divider bias and drain-feedback bias are illustrated for *n*-channel devices.

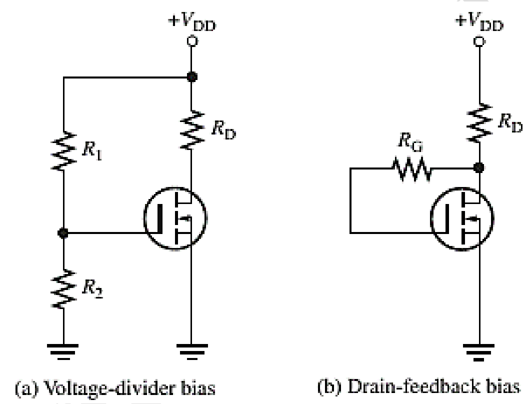

Figure 18: Common E-MOSFET biasing arrangements.

The simplest way to bias a **D-MOSFET** is with zero bias. This works because the device can operate in either depletion or enhancement mode, so the gate can go above or below 0 V.

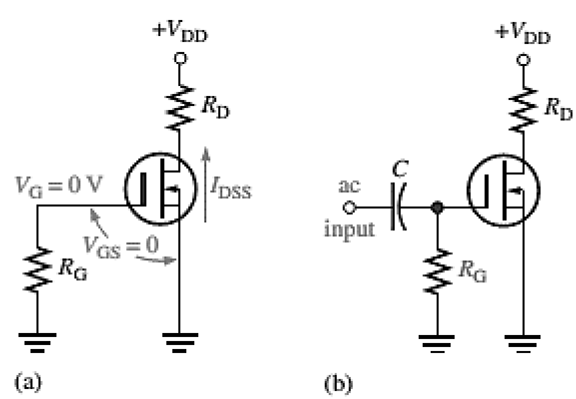

Figure 19: A zero-biased D-MOSFET.

The drain-to-source voltage is expressed as follows:

$$V_{DS} = V_{DD} - I_{DSS}R_D$$

The purpose of R_G is to accommodate an ac signal input by isolating it from ground, as shown in Figure 19(b). Since there is no dc gate current, R_G does not affect the zero gate-to-source bias.

Example: The datasheet for a 2N7002 E-MOSFET gives $I_{D(on)}$=500 mA (minimum) at V_{GS}=10 V and $V_{GS(th)}$=1 V. Determine the drain current for V_{GS} = 5V.

Solution: First, solve for K

$$K = \frac{I_{D(on)}}{(V_{GS} - V_{GS(th)})^2} = \frac{500mA}{(10V - 1V)^2} = 6.17mA/V^2$$

Next, using the value of K, calculate I_D for V_{GS}=5 V.

$$I_D = K(V_{GS}-V_{GS(th)})^2=(6.17mA/V^2)(5V-1V)^2=\mathbf{98.7mA}$$

Example: For a certain D-MOSFET, I_{DSS}=10 mA and $V_{GS(off)}$ = -8V.

(a) Is this an n-channel or a p-channel?
(b) Calculate I_D at V_{GS} = -3 V.
(c) Calculate I_D at V_{GS} =+3 V.

Solution:

(a) The device has a negative $V_{GS(off)}$; therefore, it is an **n-channel** MOSFET**.**

(b) $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2 = 10\text{ mA}\left(1 - \frac{-3V}{-8V}\right)^2 = \mathbf{3.91mA}$

(c) $I_D = 10\text{ mA}\left(1 - \frac{+3V}{-8V}\right)^2 = \mathbf{18.9mA}$

JFET vs MOSFET

JFET	MOSFET
1. The gate and channel in a JFET are separated by a pn junction	**1.** The gate of a MOSFET is insulated from the channel by a SiO_2 layer
2. The channel width is controlled by the size of the depletion region of a pn junction	**2.** The channel width is controlled by the action of the electric field
3. Operates in depletion mode	**3.** Operates in depletion and enhancement modes

JFET	BJT
source S	emitter E
drain D	collector C
gate G	base B
drain supply V_{DD}	collector supply V_{CC}
gate supply V_{GG}	base supply V_{BB}
drain current i_D	collector current i_C