# TRANSFER CHARACTERISTICS Derivation

For the BJT transistor the output current $I_C$ and the input controlling current $I_B$ are related by beta, which was considered constant for the analysis to be performed. In equation form,

control variable

$$I_C = f(I_B) = \beta I_B \tag{6.2}$$

constant

In Eq. (6.2) a linear relationship exists between $I_C$ and $I_B$. Double the level of $I_B$ and $I_C$ will increase by a factor of two also.

Unfortunately, this linear relationship does not exist between the output and input quantities of a JFET. The relationship between $I_D$ and $V_{GS}$ is defined by *Shockley's equation* (see Fig. 6.16):

control variable

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 \tag{6.3}$$

constants

The transfer curve can be obtained using Shockley's equation or from the output characteristics of Fig. 6.11. In Fig. 6.17 two graphs are provided, with the vertical scaling in milliamperes for each graph. One is a plot of $I_D$ versus $V_{DS}$, whereas the other is $I_D$ versus $V_{GS}$. Using the drain characteristics on the right of the "y" axis, we can draw a horizontal line from the saturation region of the curve denoted $V_{GS} = 0$ V to the $I_D$ axis. The resulting current level for both graphs is $I_{DSS}$. The point of intersection on the $I_D$ versus $V_{GS}$ curve will be as shown since the vertical axis is defined as $V_{GS} = 0$ V.

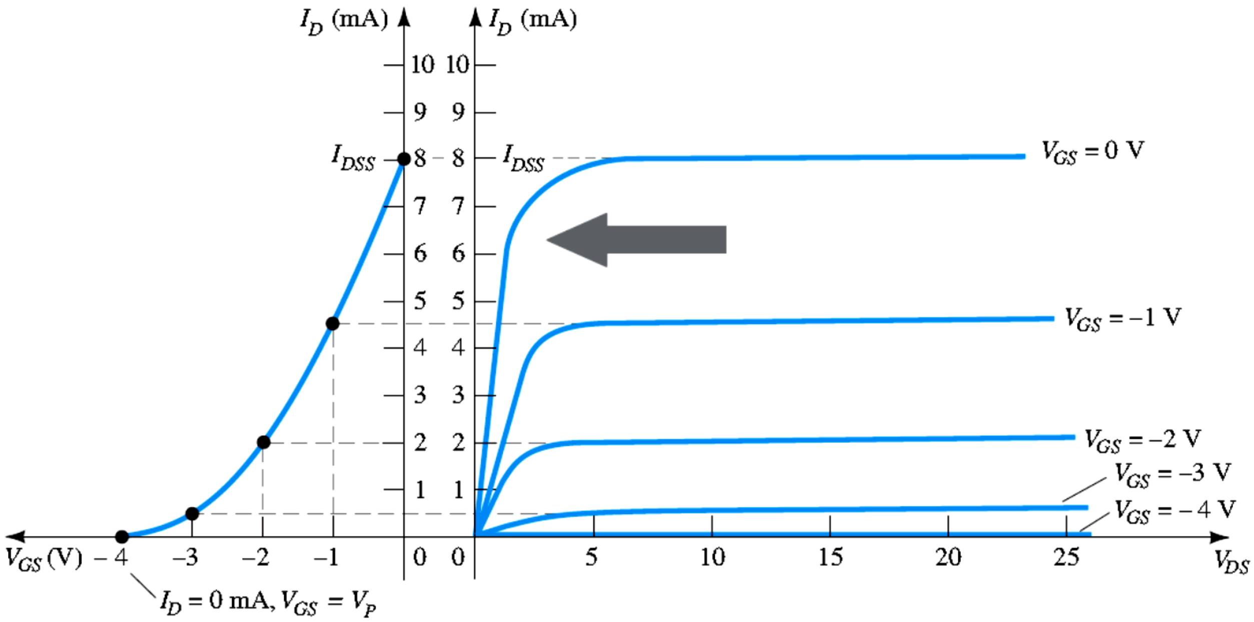



**FIG. 6.17**
*Obtaining the transfer curve from the drain characteristics.*

In review:

$$\boxed{\text{When } V_{GS} = 0\text{ V}, \quad I_D = I_{DSS}} \qquad \textbf{(6.4)}$$

When $V_{GS} = V_P = -4$ V, the drain current is 0 mA, defining another point on the transfer curve. That is:

$$\boxed{\text{When } V_{GS} = V_P, \quad I_D = 0\text{ mA}} \qquad \textbf{(6.5)}$$

## Applying Shockley's Equation

The transfer curve of Fig. 6.17 can also be obtained directly from Shockley's equation (6.3) given simply the values of $I_{DSS}$ and $V_P$. The levels of $I_{DSS}$ and $V_P$ define the limits of the curve on both axes and leave only the necessity of finding a few intermediate plot points. The validity of Eq. (6.3) as a source of the transfer curve of Fig. 6.17 is best demonstrated by examining a few specific levels of one variable and finding the resulting level of the other as follows:

Substituting $V_{GS} = 0$ V gives

$$\text{Eq. (6.3):} \quad I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$= I_{DSS}\left(1 - \frac{0}{V_P}\right)^2 = I_{DSS}(1 - 0)^2$$

and

$$\boxed{I_D = I_{DSS}\big|_{V_{GS}=0\text{ V}}} \qquad \textbf{(6.6)}$$

Substituting $V_{GS} = V_P$ yields

$$I_D = I_{DSS}\left(1 - \frac{V_P}{V_P}\right)^2$$
$$= I_{DSS}(1 - 1)^2 = I_{DSS}(0)$$

$$I_D = 0\ \text{A}\big|_{V_{GS}=V_P} \qquad \textbf{(6.7)}$$

For the drain characteristics of Fig. 6.17, if we substitute $V_{GS} = -1$ V,

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$
$$= 8\text{ mA}\left(1 - \frac{-1\text{ V}}{-4\text{ V}}\right)^2 = 8\text{ mA}\left(1 - \frac{1}{4}\right)^2 = 8\text{ mA}\,(0.75)^2$$
$$= 8\text{ mA}\,(0.5625)$$
$$= \mathbf{4.5\ mA}$$

## Shorthand Method

Since the transfer curve must be plotted so frequently, it would be quite advantageous to have a shorthand method for plotting the curve in the quickest, most efficient manner while maintaining an acceptable degree of accuracy. The format of Eq. (6.3) is such that specific levels of $V_{GS}$ will result in levels of $I_D$ that can be memorized to provide the plot points needed to sketch the transfer curve. If we specify $V_{GS}$ to be one-half the pinch-off value $V_P$, the resulting level of $I_D$ will be the following, as determined by Shockley's equation:

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$
$$= I_{DSS}\left(\frac{1 - V_P/2}{V_P}\right)^2 = I_{DSS}\left(1 - \frac{1}{2}\right)^2 = I_{DSS}(0.5)^2$$
$$= I_{DSS}(0.25)$$

and

$$I_D = \frac{I_{DSS}}{4}\Big|_{V_{GS}=V_P/2} \qquad \textbf{(6.9)}$$

Now it is important to realize that Eq. (6.9) is not for a particular level of $V_P$. It is a general equation for any level of $V_P$ as long as $V_{GS} = V_P/2$. The result specifies that the drain current will always be one-fourth the saturation level $I_{DSS}$ as long as the gate-to-source voltage is one-half the pinch-off value. Note the level of $I_D$ for $V_{GS} = V_P/2 = -4\text{ V}/2 = -2\text{ V}$ in Fig. 6.17.

If we choose $I_D = I_{DSS}/2$ and substitute into Eq. (6.8), we find that

$$V_{GS} = V_P\left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right)$$

$$= V_P\left(1 - \sqrt{\frac{I_{DSS}/2}{I_{DSS}}}\right) = V_P(1 - \sqrt{0.5}) = V_P(0.293)$$

and

$$V_{GS} \cong 0.3V_P\big|_{I_D=I_{DSS}/2} \qquad \textbf{(6.10)}$$

Additional points can be determined, but the transfer curve can be sketched to a satisfactory level of accuracy simply using the four plot points defined above and reviewed in Table 6.1. In fact, in the analysis of Chapter 7, a maximum of four plot points are used to sketch the transfer curves. On most occasions using just the plot point defined by $V_{GS} = V_P/2$ and the axis intersections at $I_{DSS}$ and $V_P$ will provide a curve accurate enough for most calculations.

**TABLE 6.1**
*$V_{GS}$ versus $I_D$ Using Shockley's Equation*

| $V_{GS}$ | $I_D$ |
|---|---|
| 0 | $I_{DSS}$ |
| $0.3V_P$ | $I_{DSS}/2$ |
| $0.5V_P$ | $I_{DSS}/4$ |
| $V_P$ | 0 mA |

**EXAMPLE 6.1** Sketch the transfer curve defined by $I_{DSS} = 12\text{ mA}$ and $V_P = -6\text{ V}$.

***Solution:*** Two plot points are defined by

$$I_{DSS} = \mathbf{12\,mA} \quad \text{and} \quad V_{GS} = \mathbf{0\,V}$$

and

$$I_D = \mathbf{0\,mA} \quad \text{and} \quad V_{GS} = \boldsymbol{V_P}$$

At $V_{GS} = V_P/2 = -6\text{ V}/2 = \mathbf{-3\,V}$ the drain current is determined by $I_D = I_{DSS}/4 = 12\text{ mA}/4 = \mathbf{3\,mA}$. At $I_D = I_{DSS}/2 = 12\text{ mA}/2 = \mathbf{6\,mA}$ the gate-to-source voltage is determined by $V_{GS} \cong 0.3V_P = 0.3(-6\text{ V}) = \mathbf{-1.8\,V}$. All four plot points are well defined on Fig. 6.18 with the complete transfer curve.

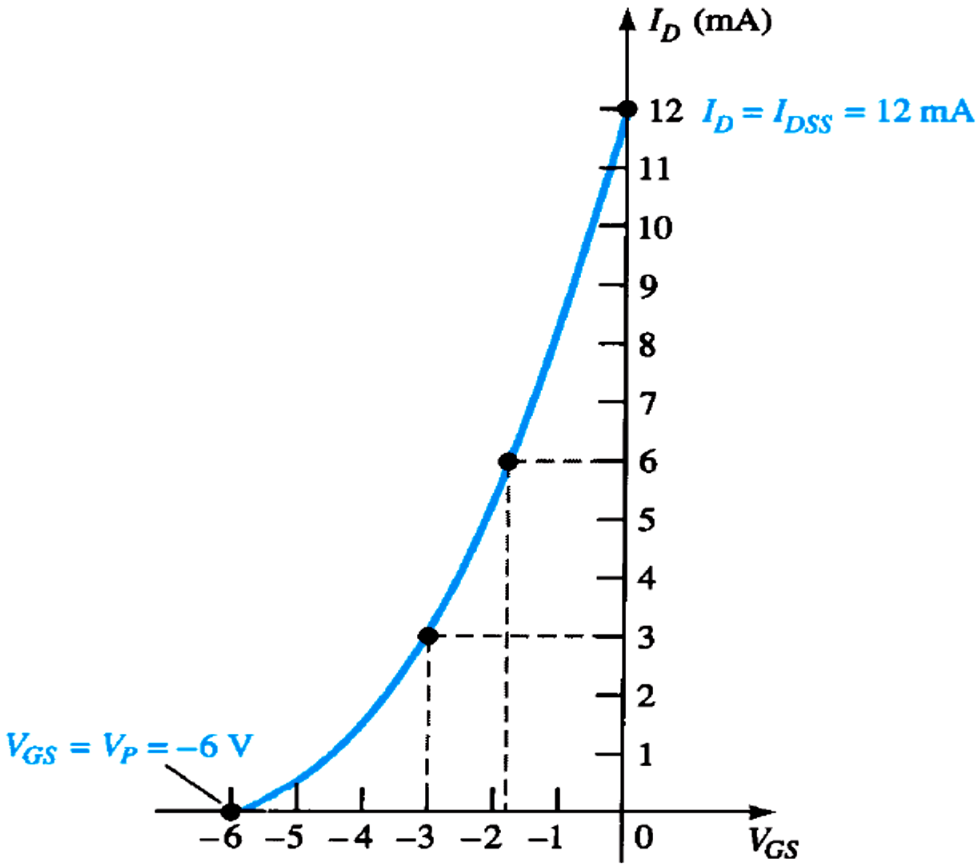



**FIG. 6.18**
*Transfer curve for Example 6.1.*

**EXAMPLE 6.2** Sketch the transfer curve for a *p*-channel device with $I_{DSS} = 4$ mA and $V_P = 3$ V.

***Solution:*** At $V_{GS} = V_P/2 = 3\text{ V}/2 = \mathbf{1.5\ V}, I_D = I_{DSS}/4 = 4\text{ mA}/4 = \mathbf{1\ mA}$. At $I_D = I_{DSS}/2 = 4\text{ mA}/2 = \mathbf{2\ mA}$, $V_{GS} = 0.3V_P = 0.3(3\text{ V}) = \mathbf{0.9\ V}$. Both plot points appear in Fig. 6.19 along with the points defined by $I_{DSS}$ and $V_P$.

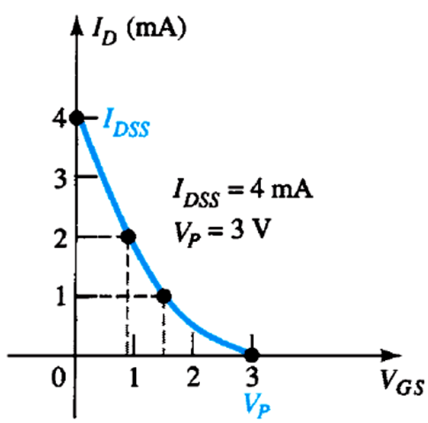



**FIG. 6.19**
*Transfer curve for the p-channel device of Example 6.2.*

# IMPORTANT RELATIONSHIPS

**TABLE 6.2**

| JFET | | BJT |
|---|---|---|
| $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$ | $\Leftrightarrow$ | $I_C = \beta I_B$ |
| $I_D = I_S$ | $\Leftrightarrow$ | $I_C \cong I_E$ |
| $I_G \cong 0\text{ A}$ | $\Leftrightarrow$ | $V_{BE} \cong 0.7\text{ V}$ |

**(6.12)**

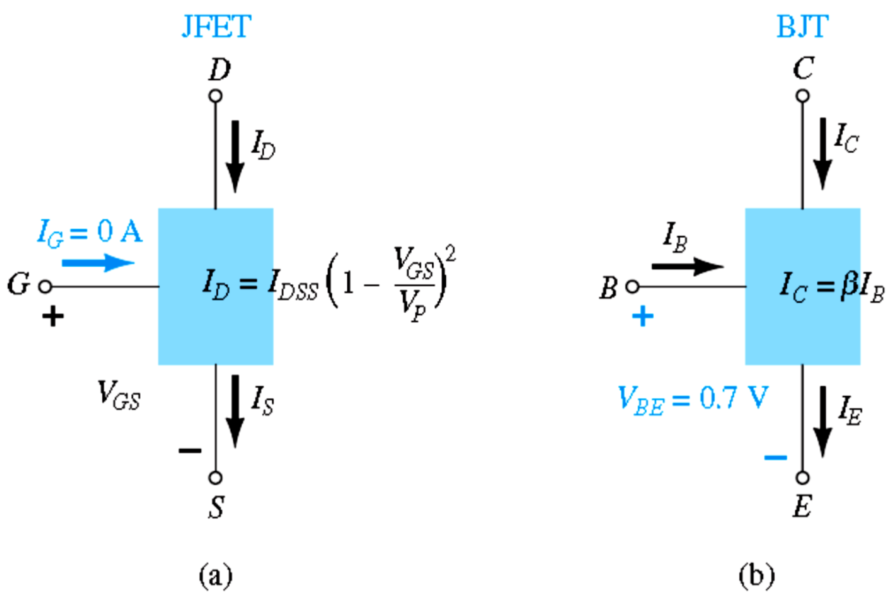



**FIG. 6.23**
*(a) JFET versus (b) BJT.*

# DEPLETION-TYPE MOSFET

## Basic Operation and Characteristics

In Fig. 6.25 the gate-to-source voltage is set to 0 V by the direct connection from one terminal to the other, and a voltage $V_{DD}$ is applied across the drain-to-source terminals. The result is an attraction of the free electrons of the *n*-channel for the positive voltage at the drain. The result is a current similar to that flowing in the channel of the JFET. In fact, the resulting current with $V_{GS} = 0$ V continues to be labeled $I_{DSS}$, as shown in Fig. 6.26.

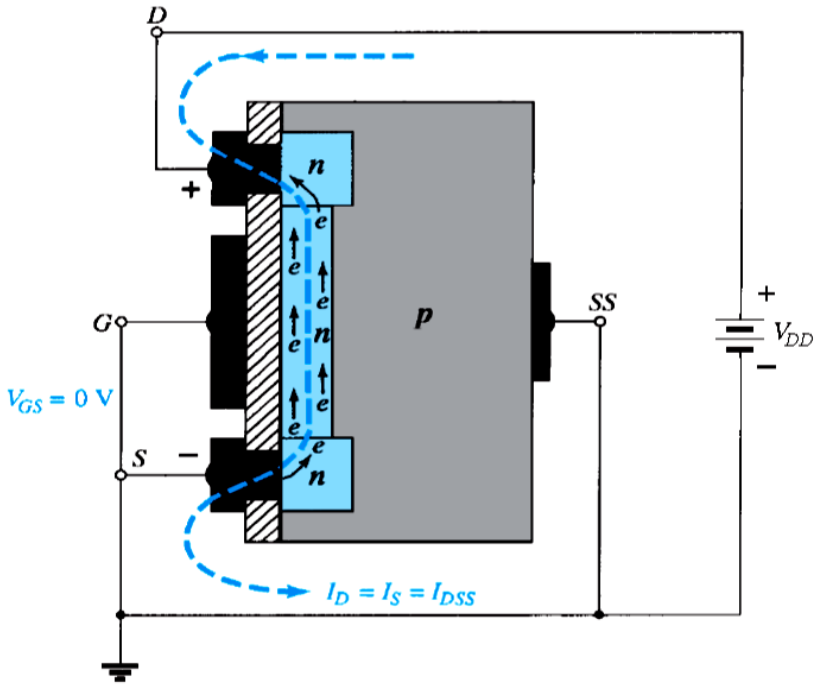



**FIG. 6.25**
*n-Channel depletion-type MOSFET with $V_{GS} = 0$ V and applied voltage $V_{DD}$.*

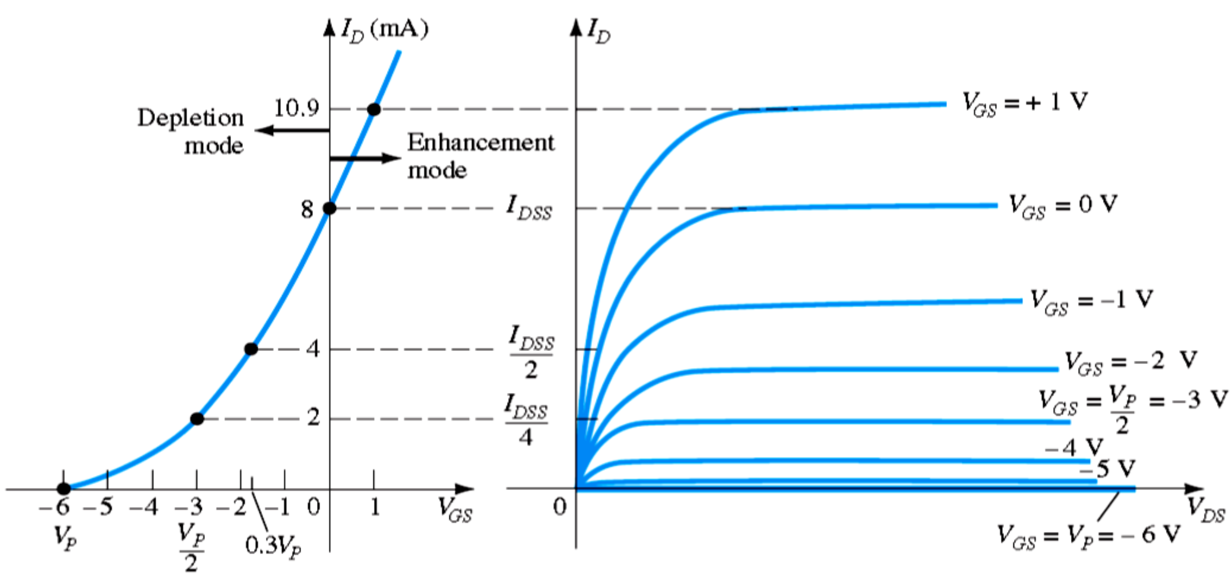



**FIG. 6.26**
*Drain and transfer characteristics for an n-channel depletion-type MOSFET.*

**EXAMPLE 6.3** Sketch the transfer characteristics for an $n$-channel depletion-type MOSFET with $I_{DSS} = 10$ mA and $V_P = -4$ V.

**Solution:**

$$\text{At } V_{GS} = 0\text{ V}, \qquad I_D = I_{DSS} = 10\text{ mA}$$

$$V_{GS} = V_P = -4\text{ V}, \qquad I_D = 0\text{ mA}$$

$$V_{GS} = \frac{V_P}{2} = \frac{-4\text{ V}}{2} = -2\text{ V}, \qquad I_D = \frac{I_{DSS}}{4} = \frac{10\text{ mA}}{4} = 2.5\text{ mA}$$

and at $I_D = \dfrac{I_{DSS}}{2}$,

$$V_{GS} = 0.3V_P = 0.3(-4\text{ V}) = -1.2\text{ V}$$

all of which appear in Fig. 6.28.

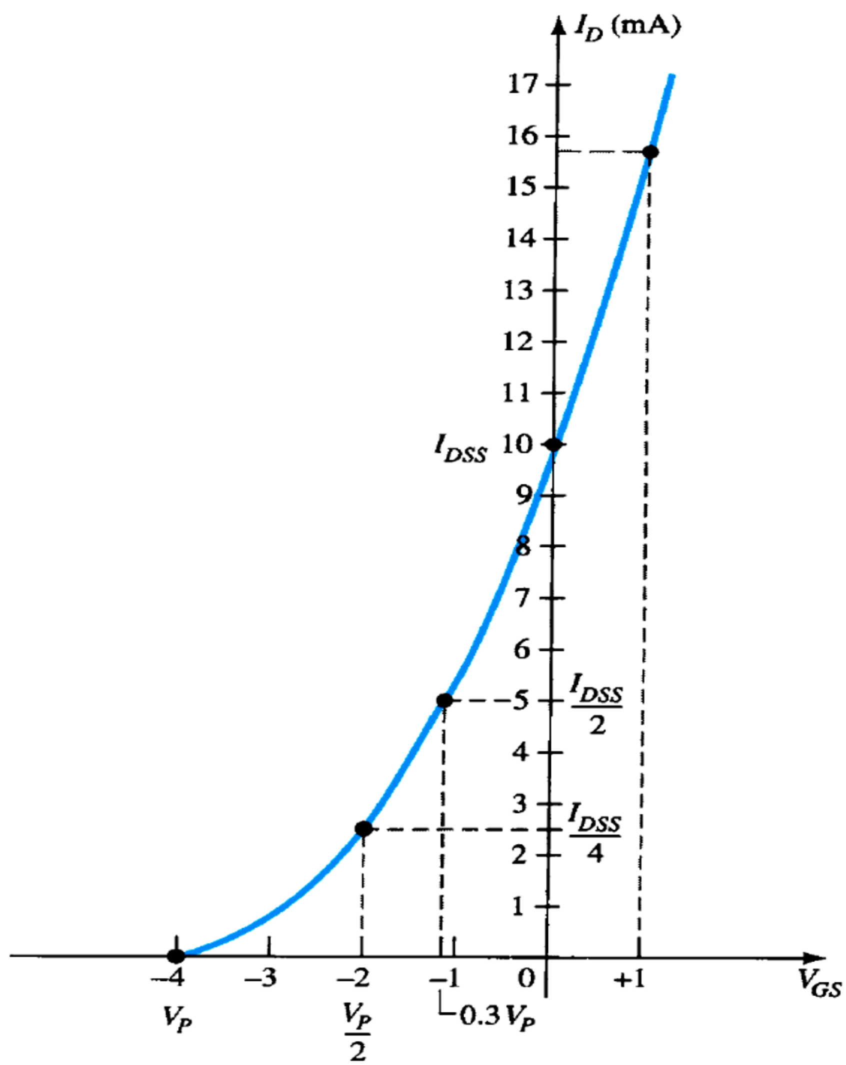



**FIG. 6.28**

*Transfer characteristics for an n-channel depletion-type MOSFET with $I_{DSS} = 10$ mA and $V_P = -4$ V.*

Before plotting the positive region of $V_{GS}$, keep in mind that $I_D$ increases very rapidly with increasing positive values of $V_{GS}$. In other words, be conservative with the choice of values to be substituted into Shockley's equation. In this case, we try +1 V as follows:

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

$$= (10\text{ mA})\left(1 - \frac{+1\text{ V}}{-4\text{ V}}\right)^2 = (10\text{ mA})\,(1 + 0.25)^2 = (10\text{ mA})\,(1.5625)$$

$$\cong 15.63\text{ mA}$$

which is sufficiently high to finish the plot.

## *p*-Channel Depletion-Type MOSFET

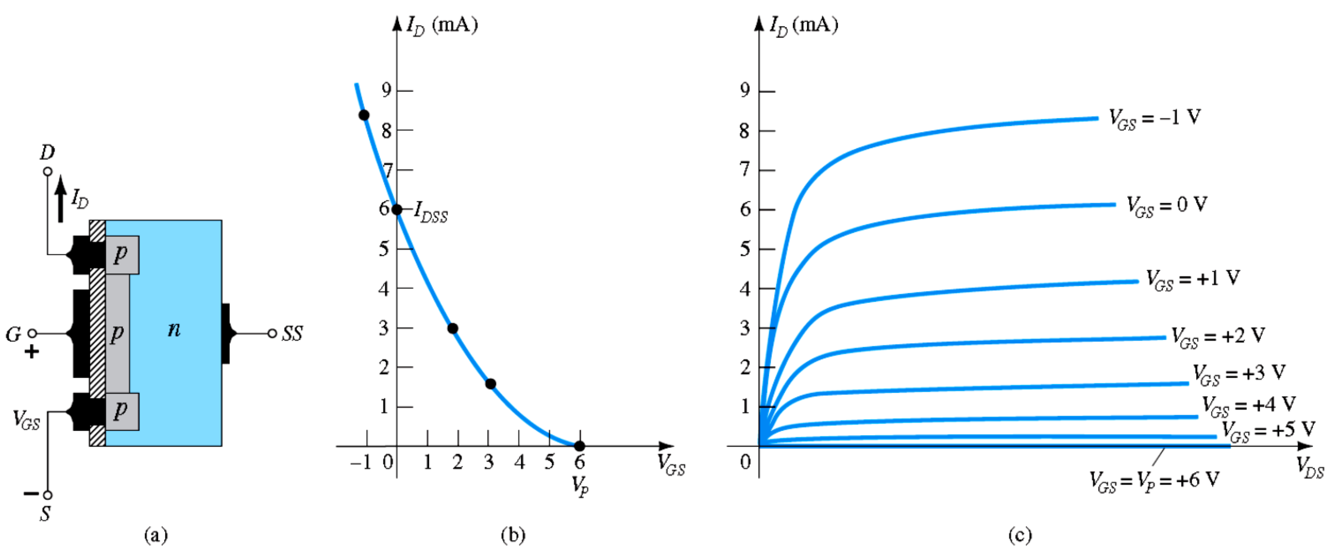
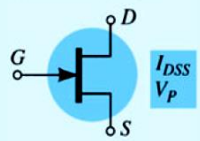
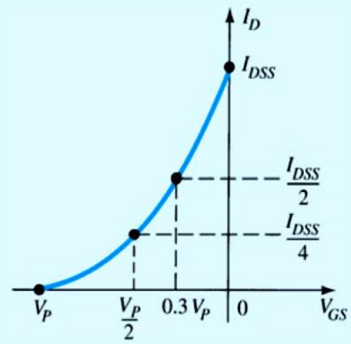
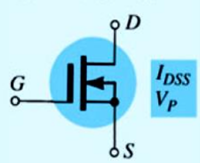
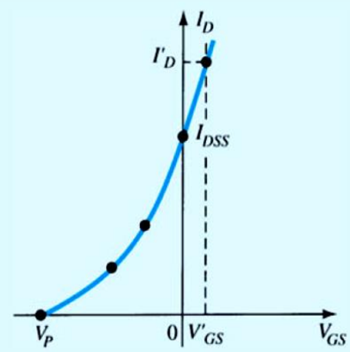
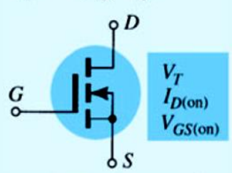
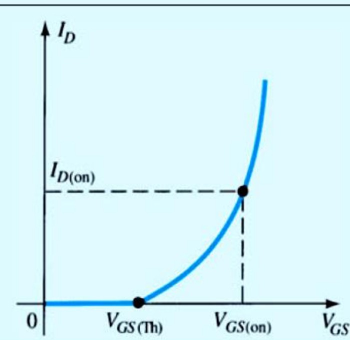



**FIG. 6.29**

*p-Channel depletion-type MOSFET with $I_{DSS}$ = 6 mA and $V_P$ = +6 V.*

# SUMMARY TABLE

**TABLE 6.3**
*Field Effect Transistors*

| Type | Symbol and Basic Relationships | Transfer Curve | Input Resistance and Capacitance |
|---|---|---|---|
| JFET (*n*-channel) | $I_G = 0\text{ A}, I_D = I_S$<br><br>$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$ |  | $R_i > 100\text{ M}\Omega$<br>$C_i$: (1 − 10) pF |
| MOSFET depletion type (*n*-channel) | $I_G = 0\text{ A}, I_D = I_S$<br><br>$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$ |  | $R_i > 10^{10}\ \Omega$<br>$C_i$: (1 − 10) pF |
| MOSFET enhancement type (*n*-channel) | $I_G = 0\text{ A}, I_D = I_S$<br><br>$I_D = k\,(V_{GS} - V_{GS\,(\text{Th})})^2$<br>$k = \frac{I_{D(\text{on})}}{(V_{GS(\text{on})} - V_{GS\,(\text{Th})})^2}$ |  | $R_i > 10^{10}\ \Omega$<br>$C_i$: (1 − 10) pF |