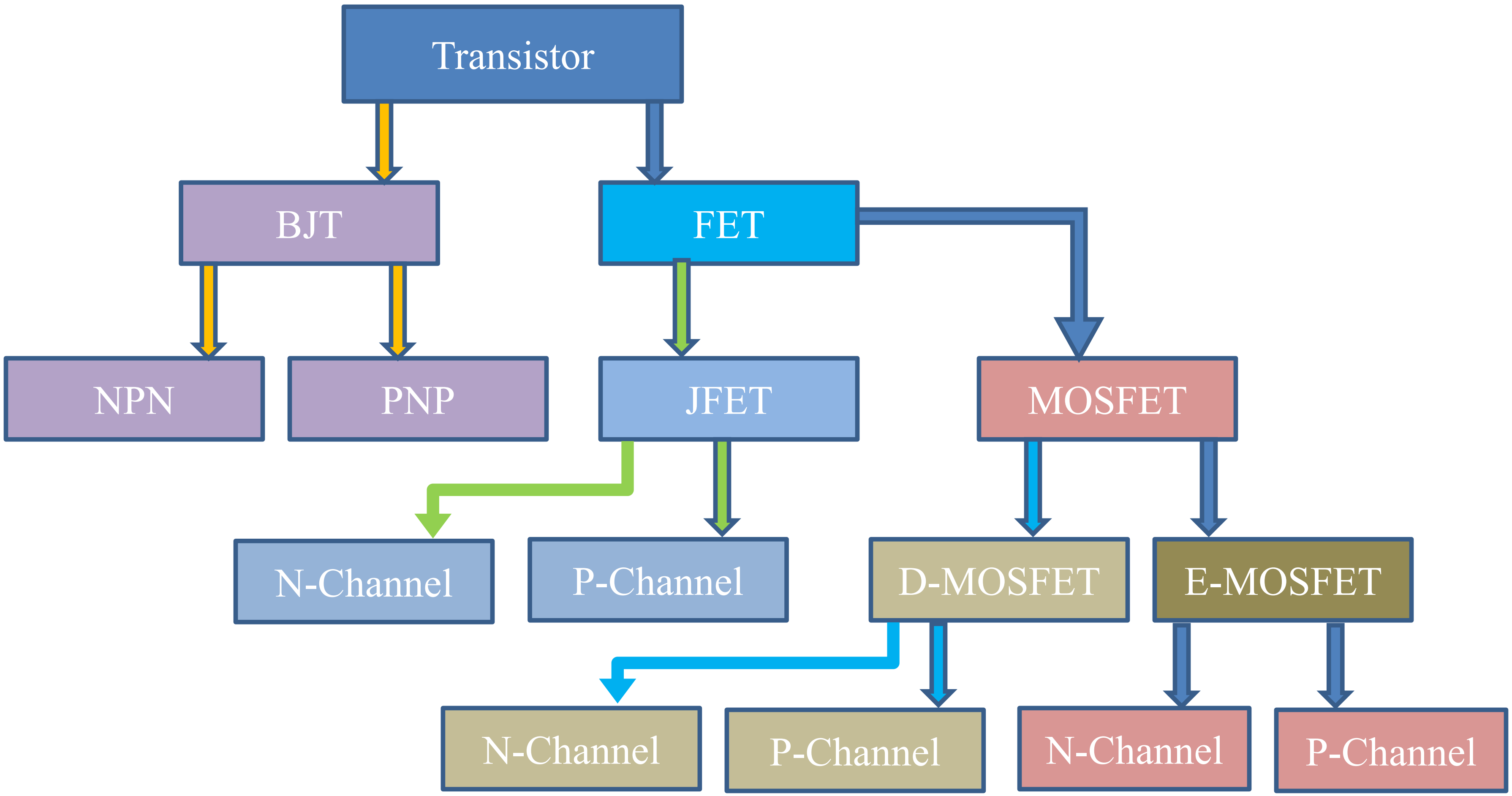
# Field Effect Transistor

Text Book

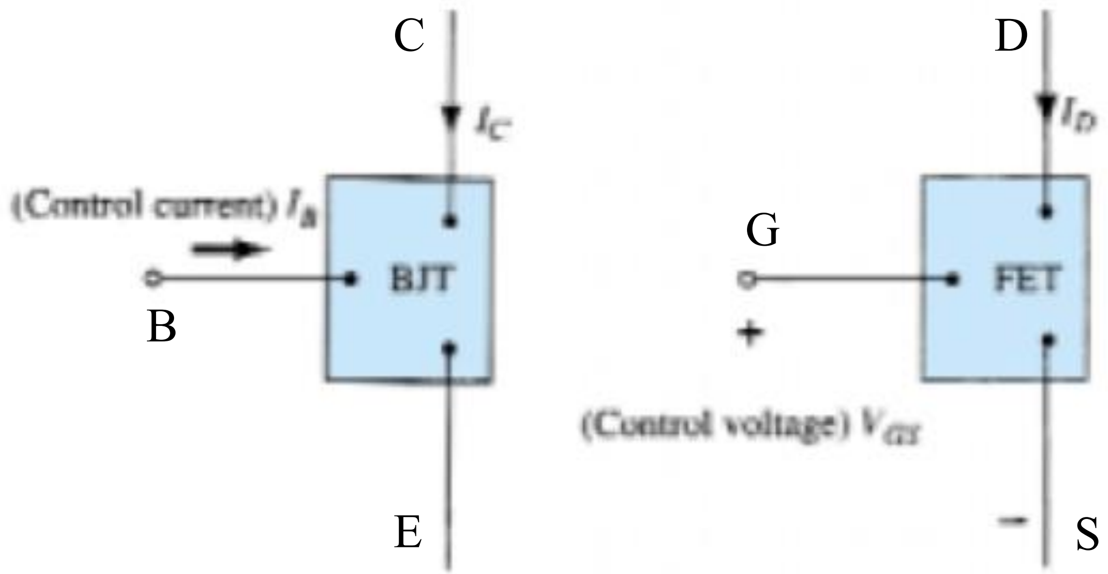
Electronic Devices and Circuit Theory

*by R Boylestad and L Nashelsky*

# Transistor Family



# Field effect transistor (FET)



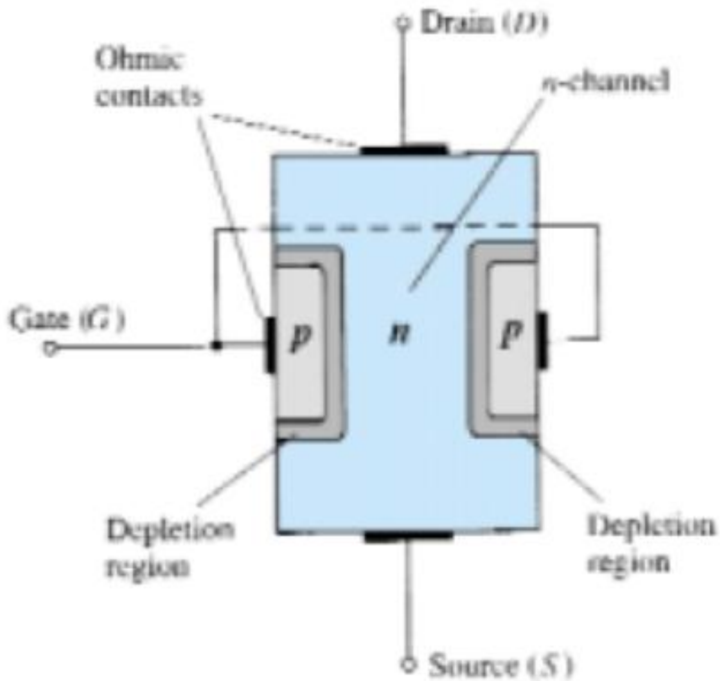
# FET Characteristics

- FET is voltage controlled device
- High input impedance than BJTs
- Voltage gain is less than BJTs
- FETs are more temperature stable than BJTs
- FETs are minimal in size and weight
- Low power consumption
- Output impedance are comparable between FETs and BJTs

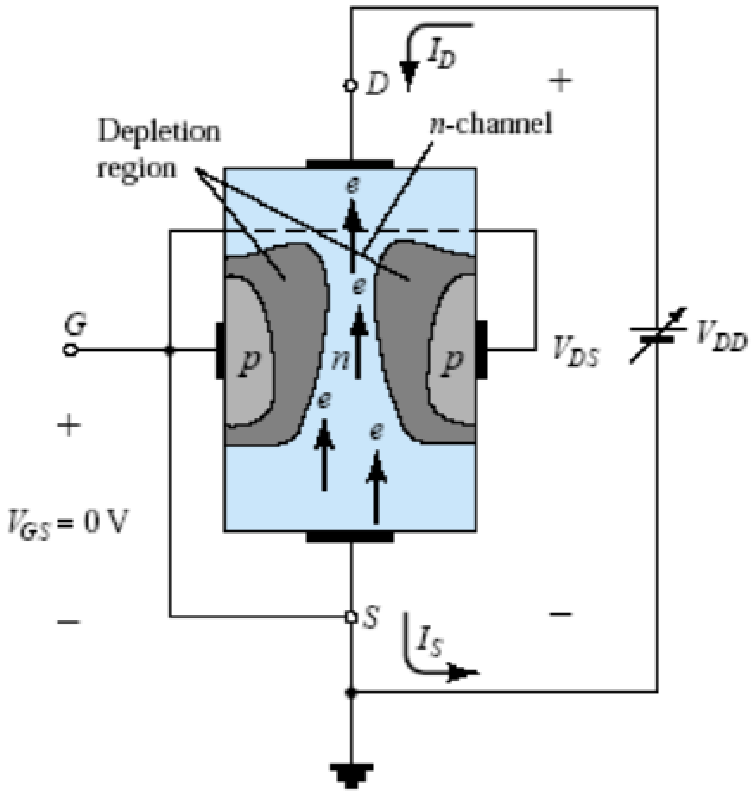
Applications:

- Can be used as linear amplifier or digital device in logic circuits
- Suitable for IC
- Widely used in high frequency applications
- In buffering (interfacing) applications.

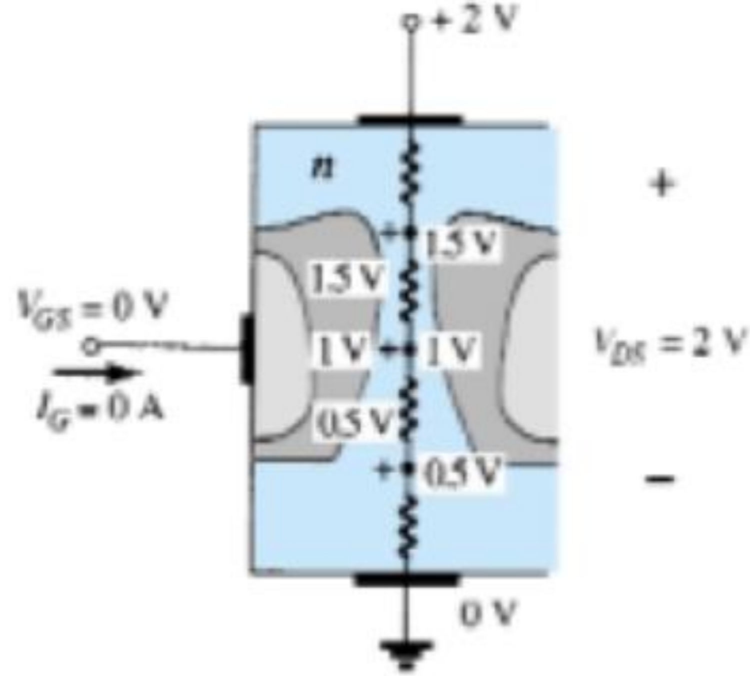
# Construction of JFET (n-ch)




# Operation



$I_D$
D
+
Depletion
region
$n$-channel
e
G
p
n
p
$V_{DS}$
$V_{DD}$
+
e
e
$V_{GS} = 0$ V
–
S
$I_S$
–

+ 2 V
n
+
1.5 V
1.5 V
$V_{GS} = 0$ V
1 V
1 V
$V_{DS} = 2$ V
$I_G = 0$ A
0.5 V
0.5 V
–
0 V

# Pinch-off voltage

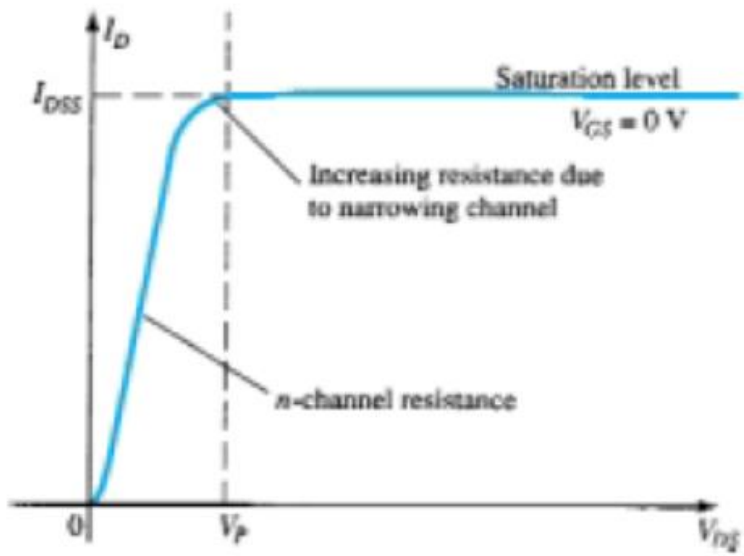



**Figure 5.6** $I_D$ versus $V_{DS}$ for $V_{GS} = 0$ V.

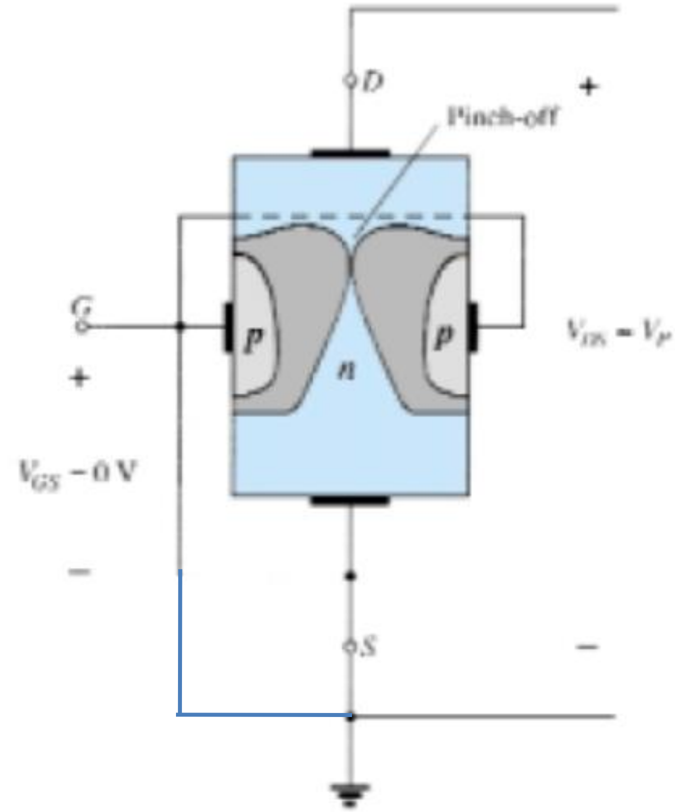
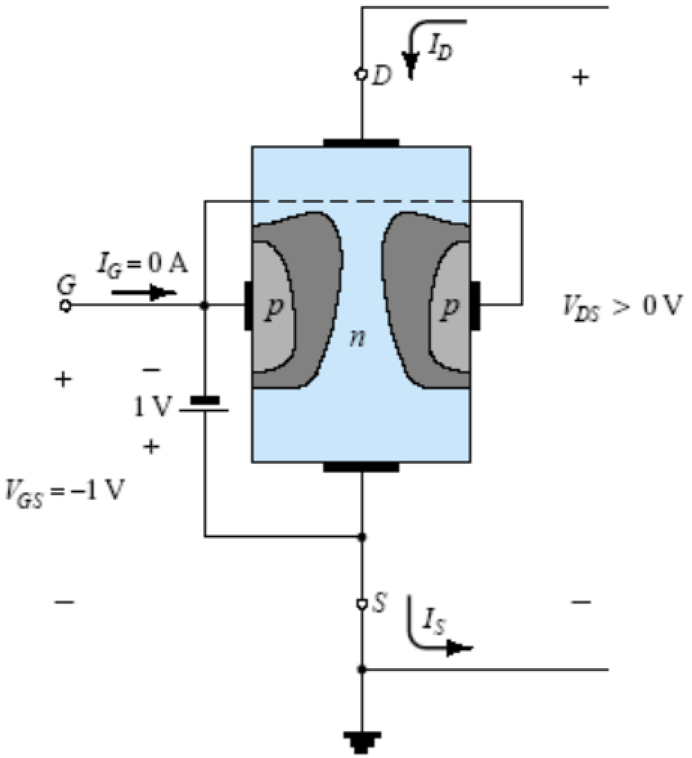



**Figure 5.7** Pinch-off ($V_{GS} = 0$ V, $V_{DS} = V_P$).

# Characteristics



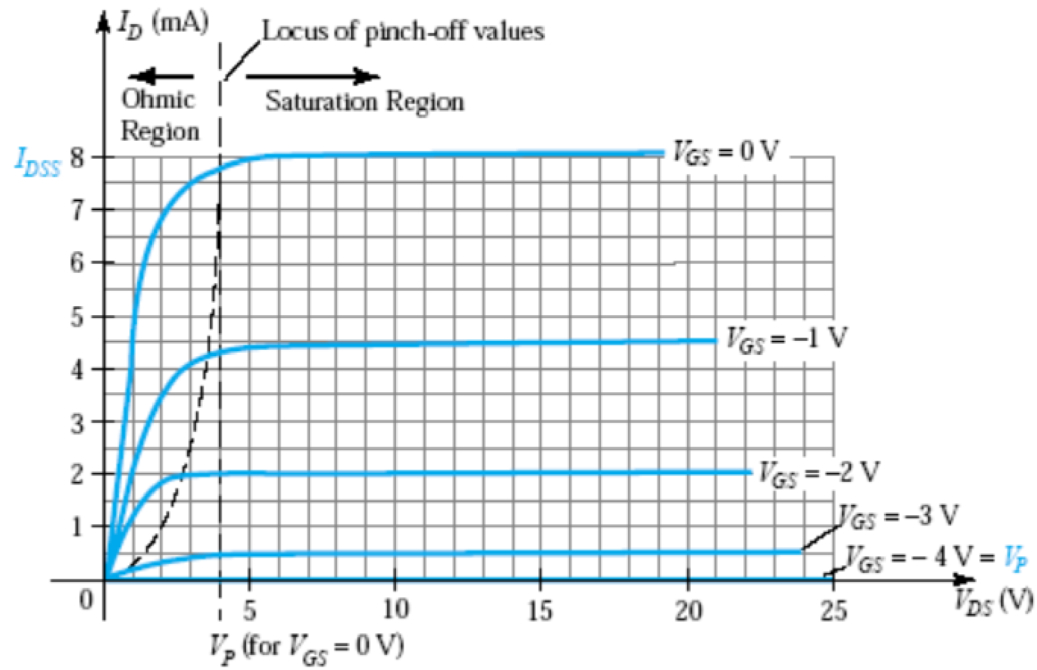
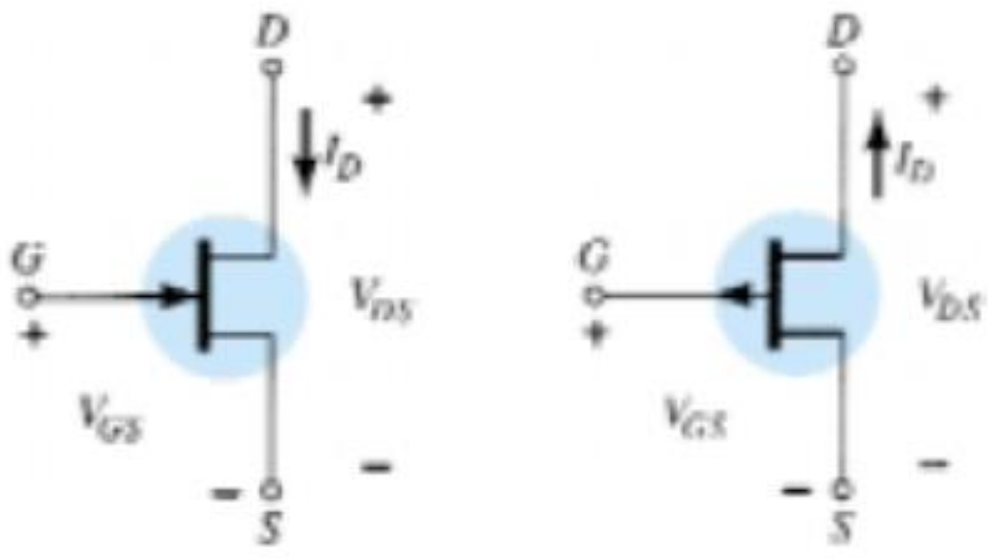




**Figure 5.10** $n$-Channel JFET characteristics with $I_{DSS} = 8$ mA and $V_P = -4$ V.

# Voltage-controlled resistor and Symbols

$$r_d = \frac{r_o}{(1 - V_{GS}/V_P)^2}$$

Symbols




(a) (b)

# Control relations and Transfer characteristics

control variabl

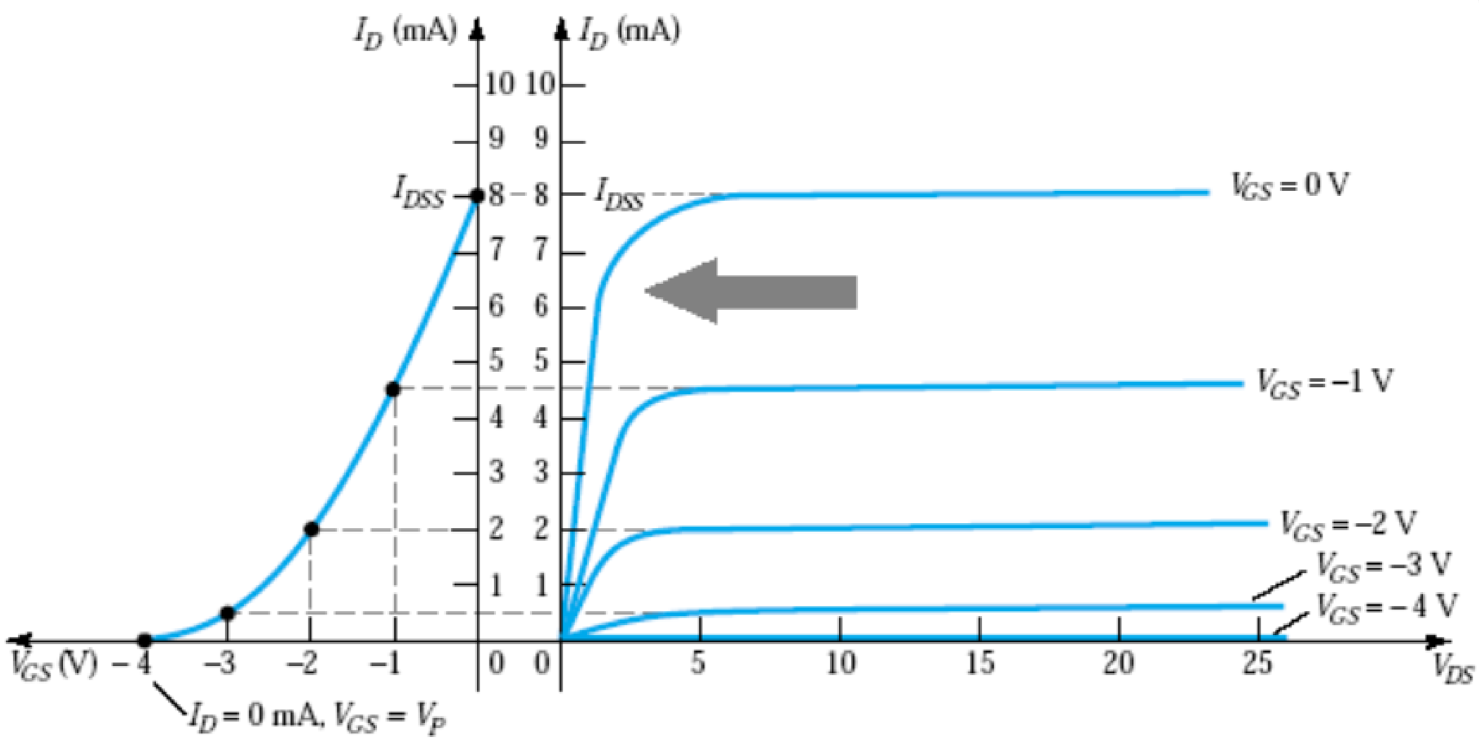
$$\boxed{I_C = f(I_B) = \beta I_B}$$

constant

control variable

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

constants



# Plotting transfer curve

Eq. (5.3): $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$

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

$$\boxed{I_D = I_{DSS}\big|_{V_{GS} = 0\,\mathrm{V}}}$$

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

$$= I_{DSS}(1 - 1)^2 = I_{DSS}(0)$$

$$\boxed{I_D = 0\,\mathrm{A}\big|_{V_{GS} = V_P}}$$

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

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

$$= I_{DSS}(0.25)$$

$$\boxed{I_D = \frac{I_{DSS}}{4}\bigg|_{V_{GS} = V_P/2}}$$

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

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

$$\boxed{V_{GS} \cong 0.3V_P\big|_{I_D = I_{DSS}/2}}$$

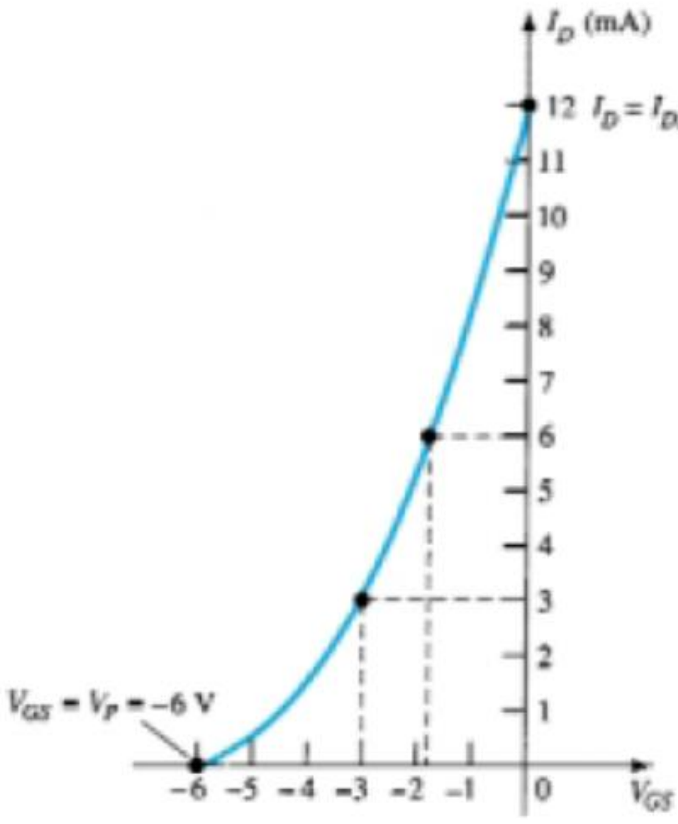
# Four points

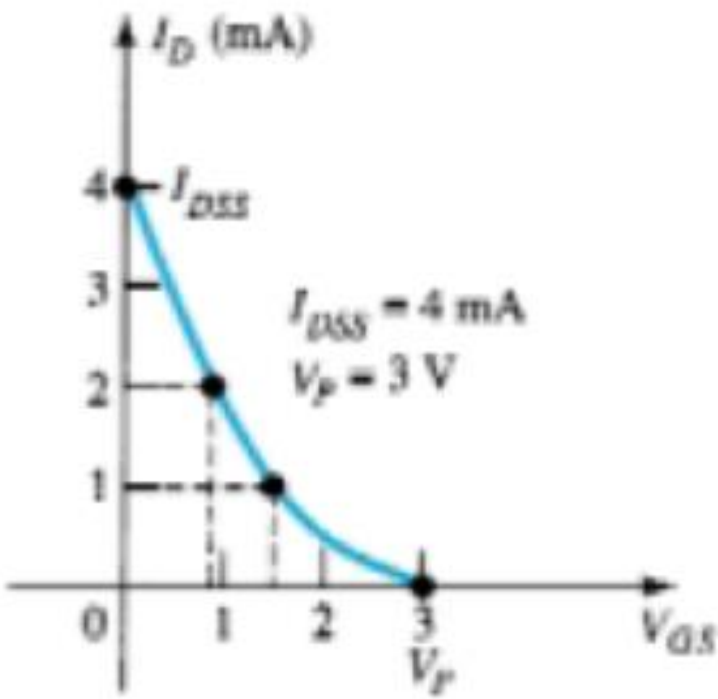
**TABLE 5.1** $V_{GS}$ versus $I_D$ Using Shockley's Equation

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

# Example-1

Plot the transfer characteristics of (i) an n-channel JFET having $I_{DSS}$=12mA and $V_P$=-6V and (ii) a p-channel JFET having $I_{DSS}$=4mA and $V_P$=3V



# Summary

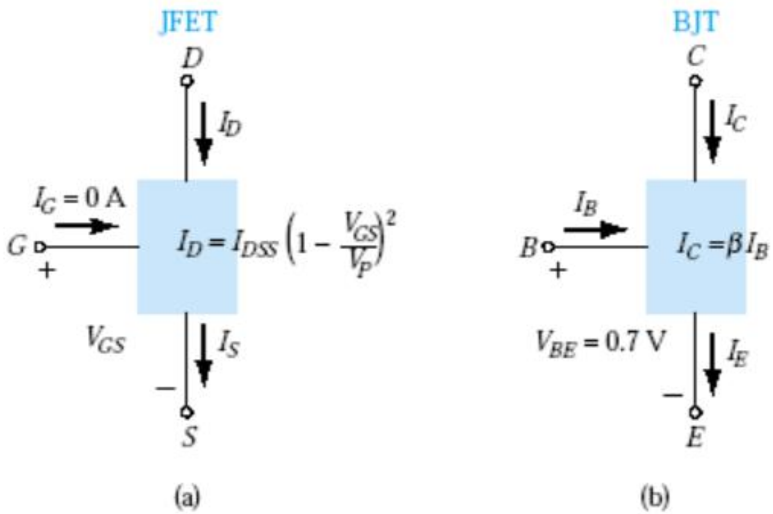



**Figure 5.22** (a) JFET versus (b) BJT.

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

(5.10)

# Depletion type MOSFET (n-ch)

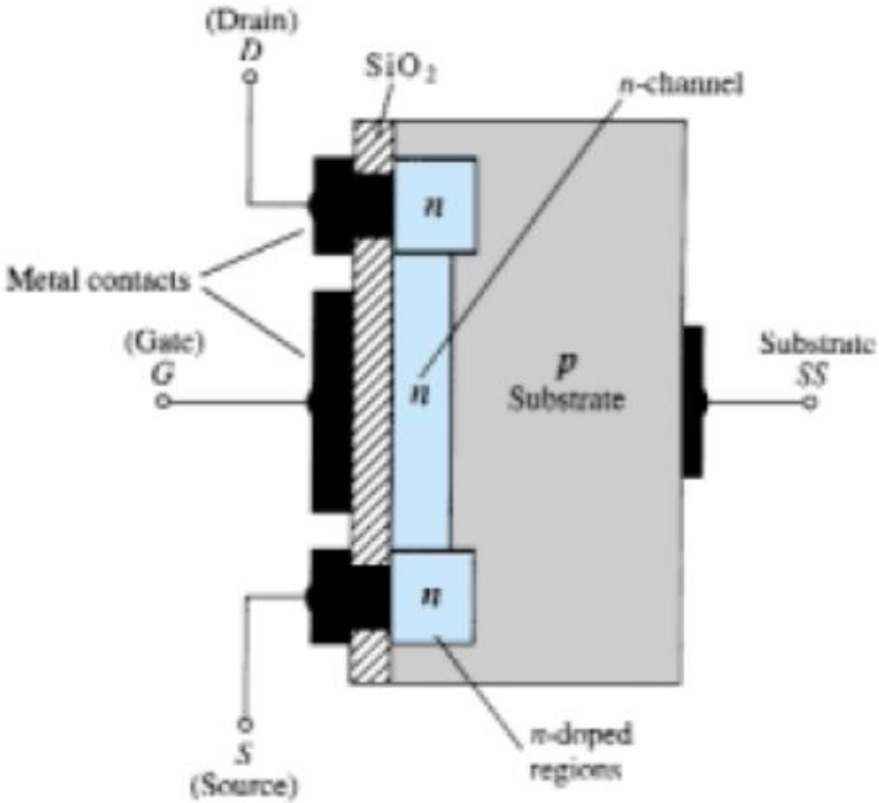



Figure 5.23 *n*-Channel depletion-type MOSFET.

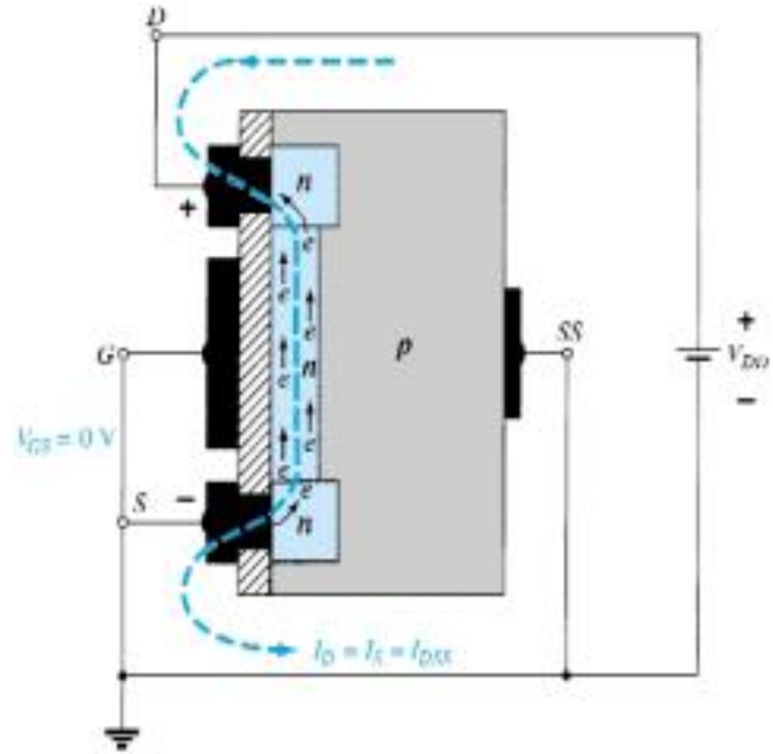
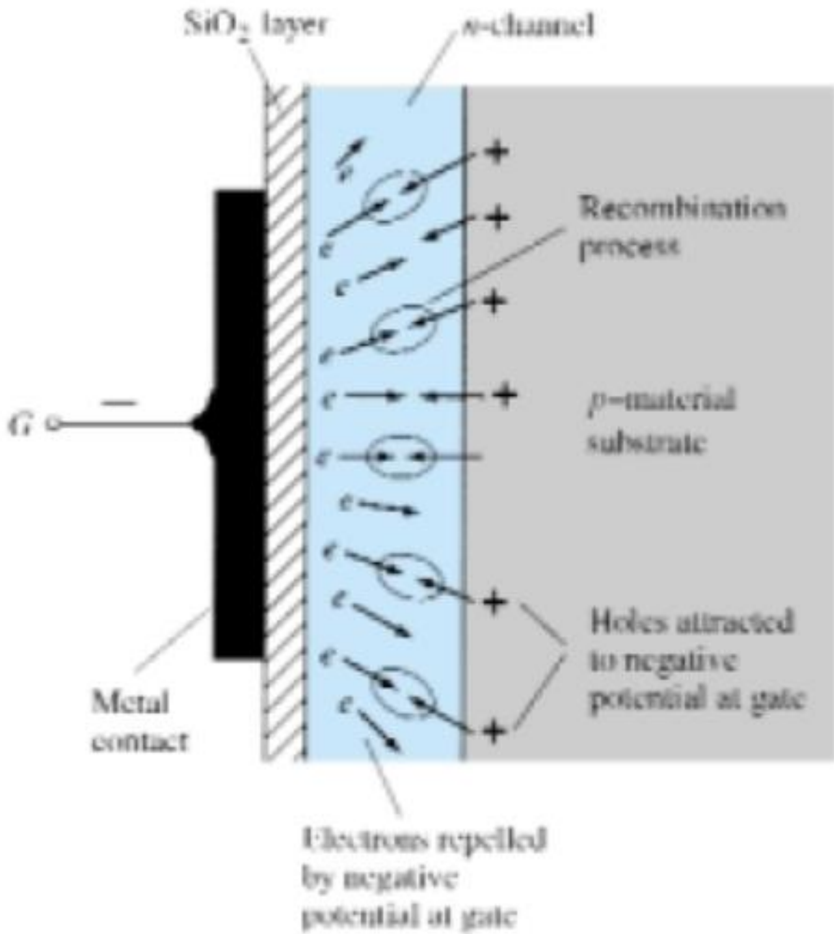


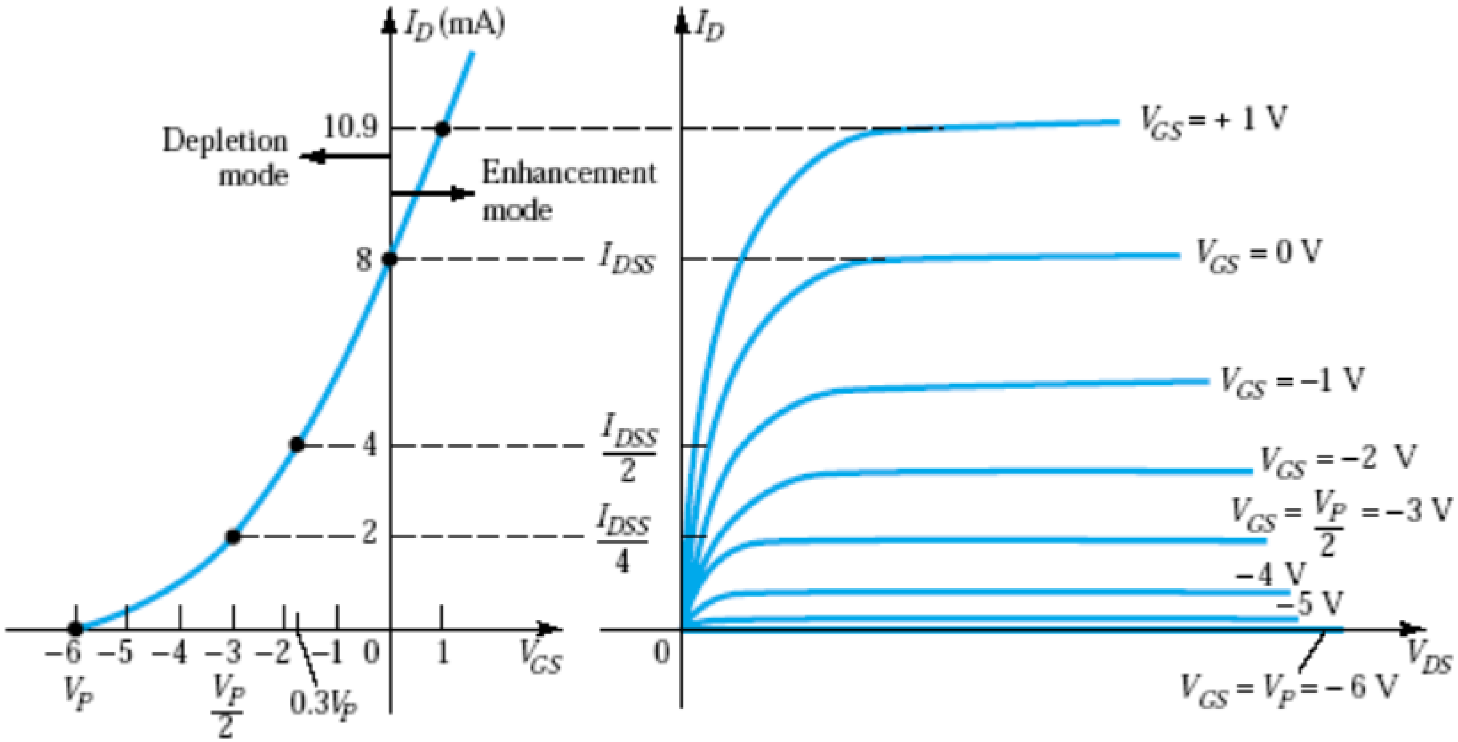

Figure 5.24 *n*-Channel depletion-type MOSFET with $V_{GS}$=0 V and an applied voltage $V_{DD}$.

# Operation

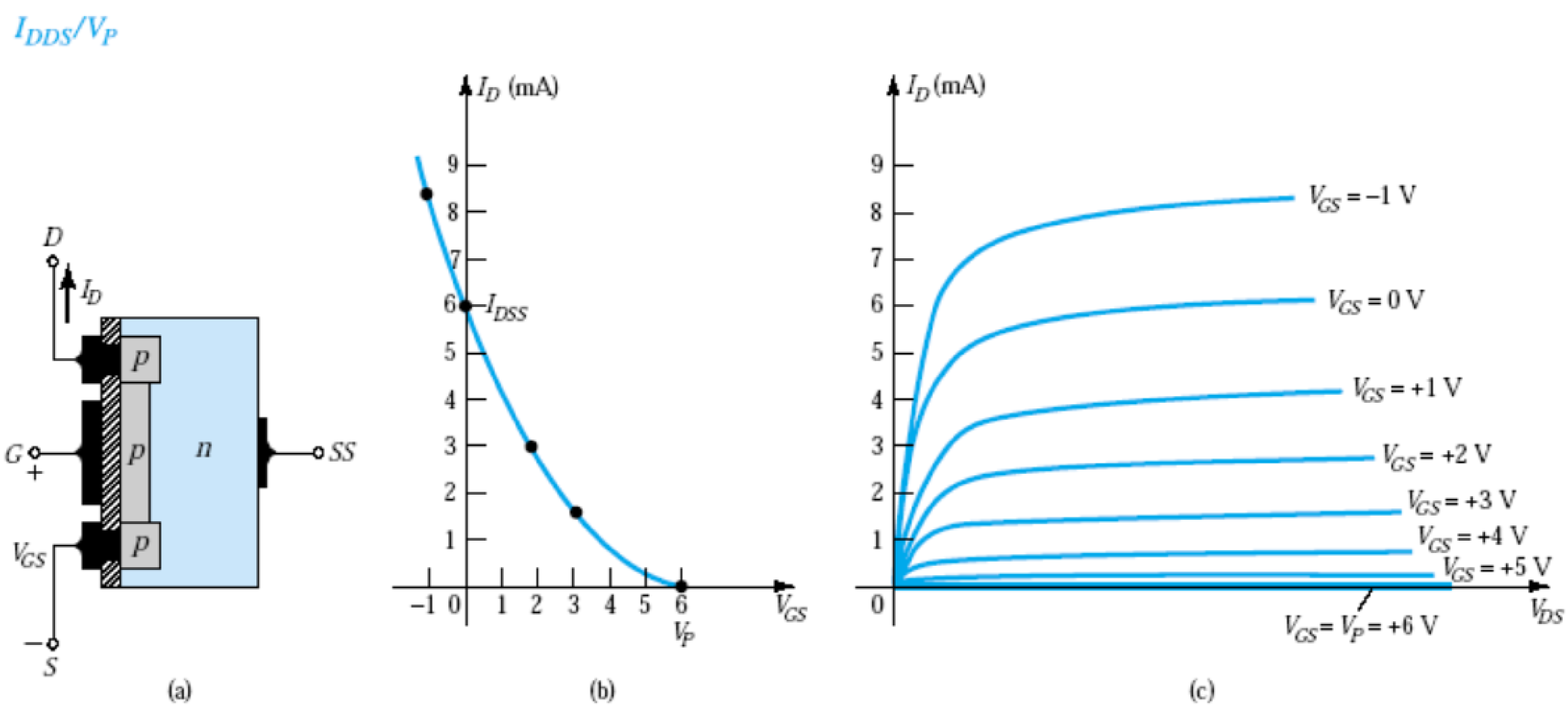


SiO$_2$ layer
n-channel
Recombination process
p-material substrate
Holes attracted to negative potential at gate
Metal contact
Electrons repelled by negative potential at gate
G

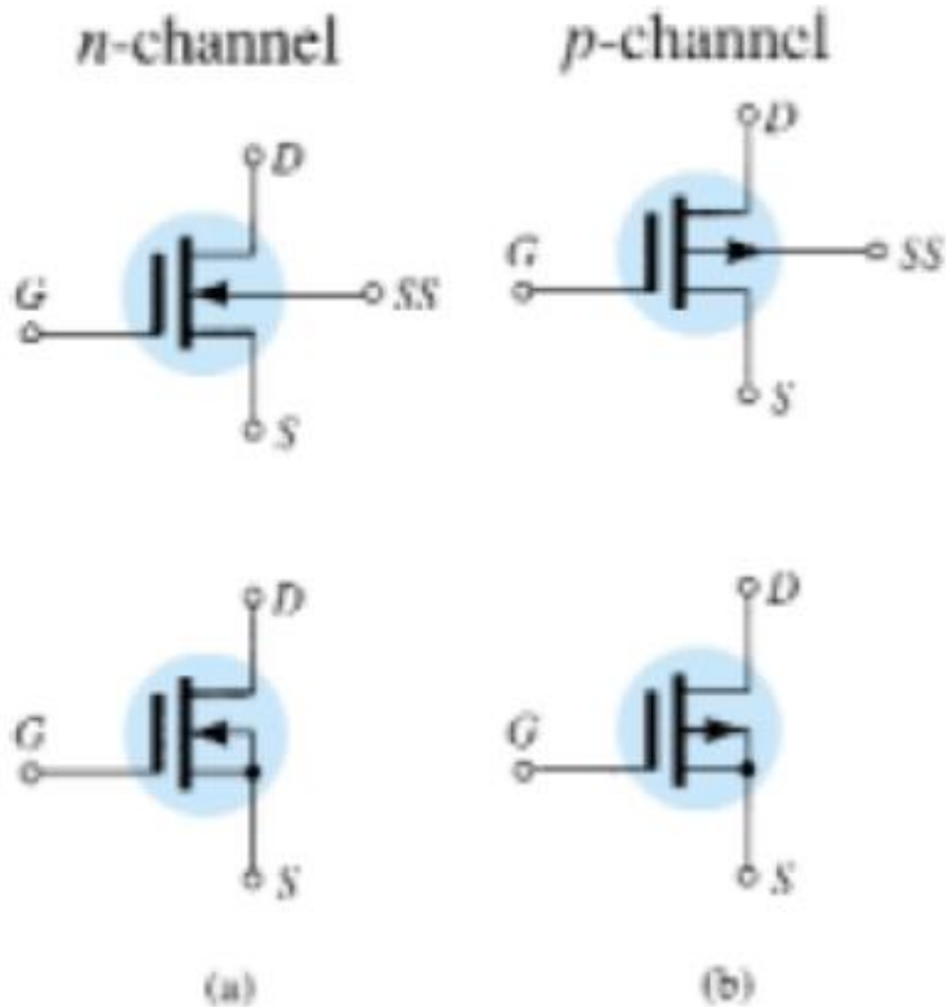
# Characteristics



# Depletion type MOSFET (p- ch)

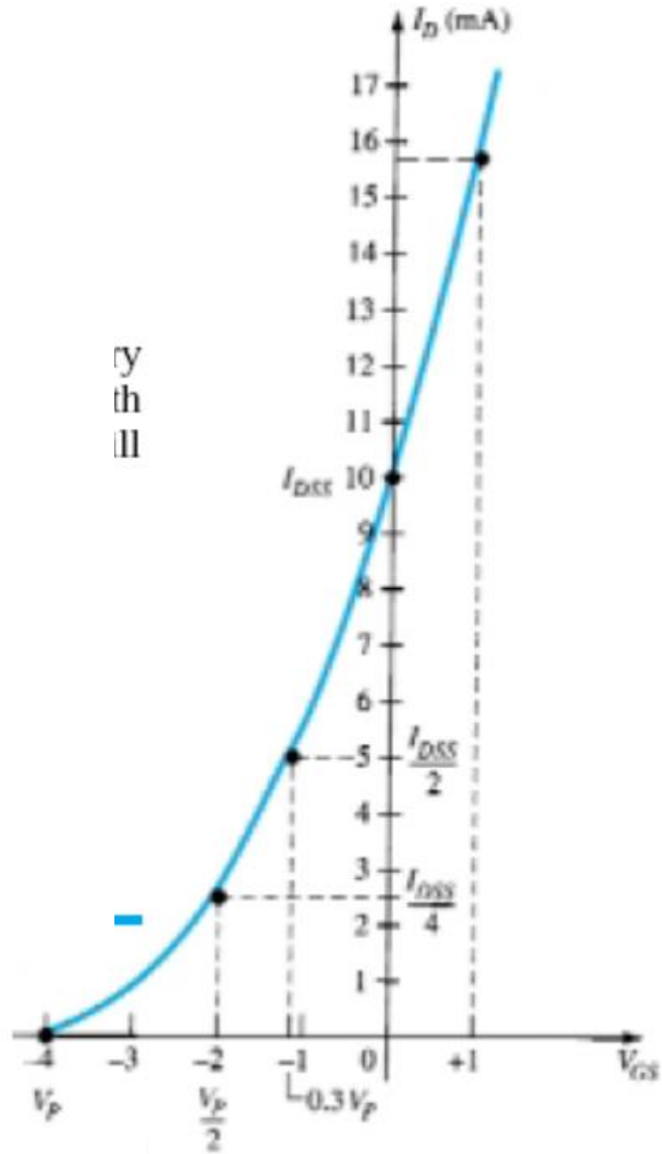


# Circuit symbols

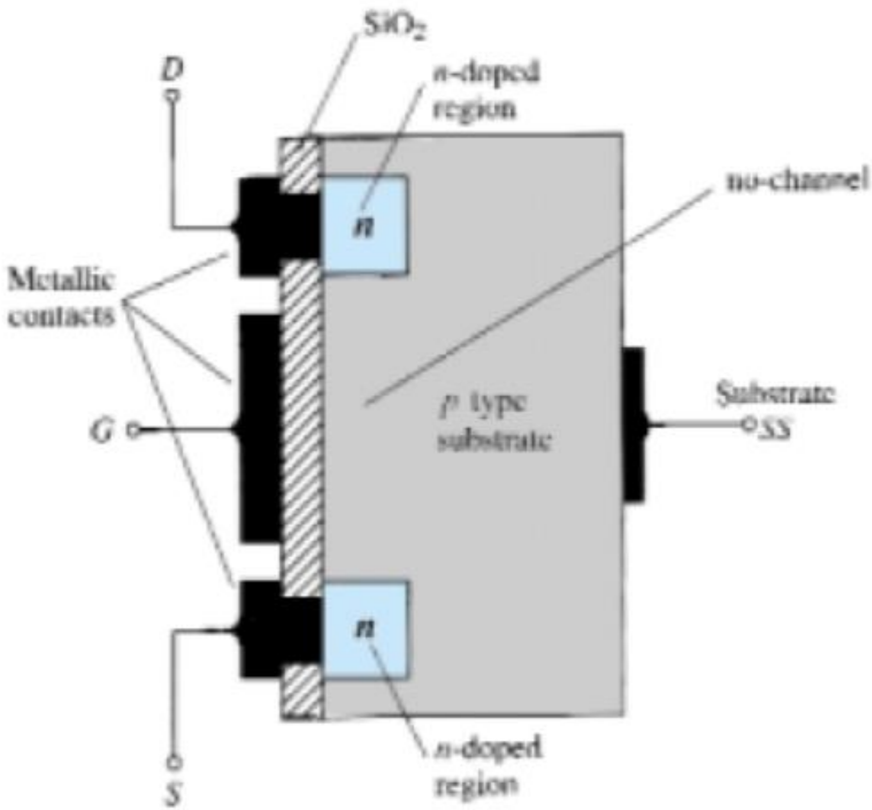


# Example-2

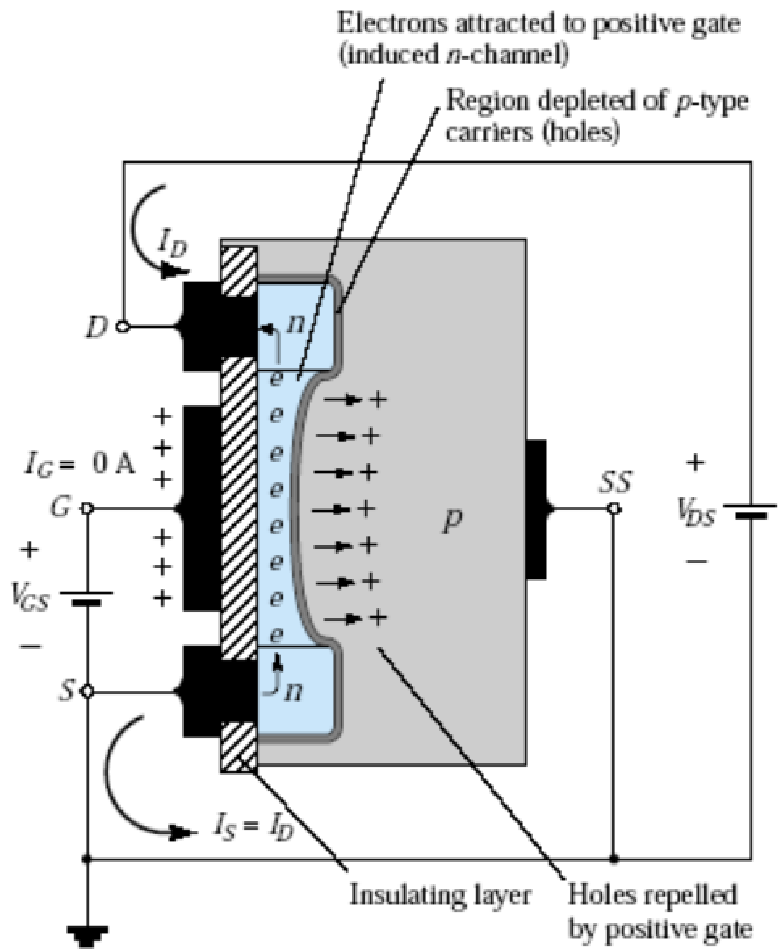
Draw the transfer characteristic of an n-channel depletion type MOSFET having $I_{DSS}$=10mA and $V_P$=-4V.



# Enhancement type MOSFET (n-ch)



# Operation



Electrons attracted to positive gate
(induced n-channel)
Region depleted of p-type
carriers (holes)
$I_D$
D
n
$I_G$ = 0 A
G
+
$V_{GS}$
–
S
n
p
SS
+
$V_{DS}$
–
$I_S = I_D$
Insulating layer
Holes repelled
by positive gate

# Effect of changing $V_{DS}$

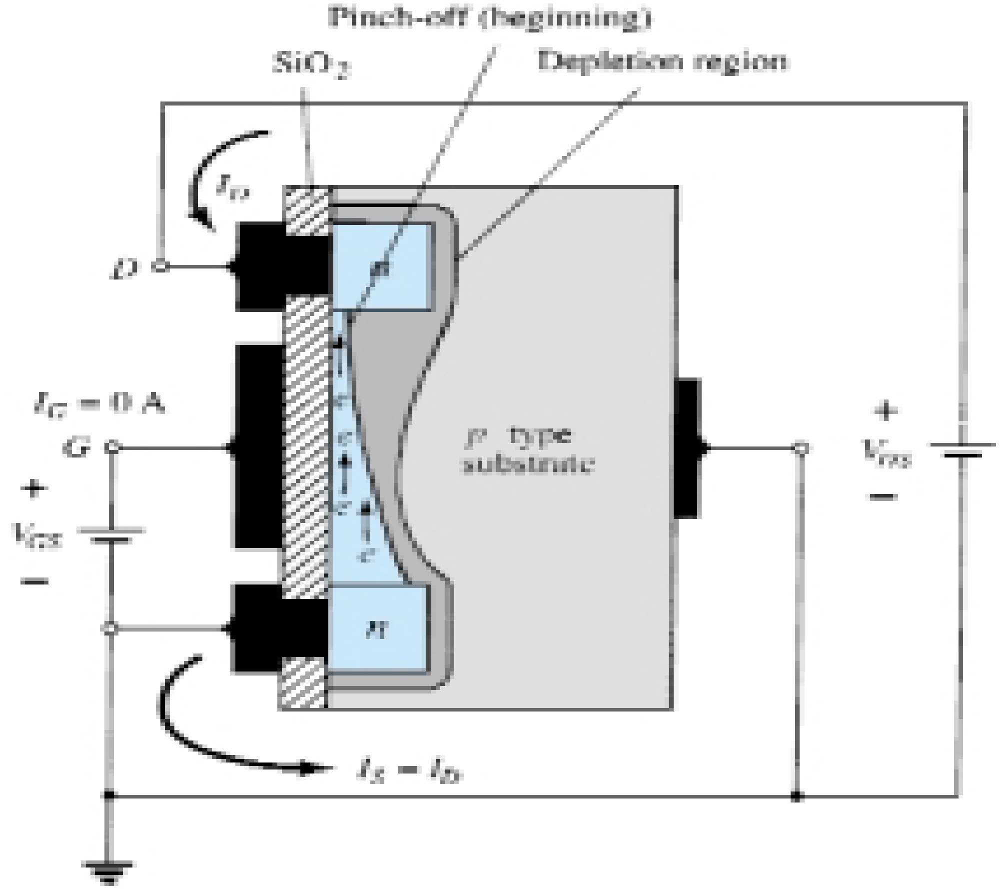
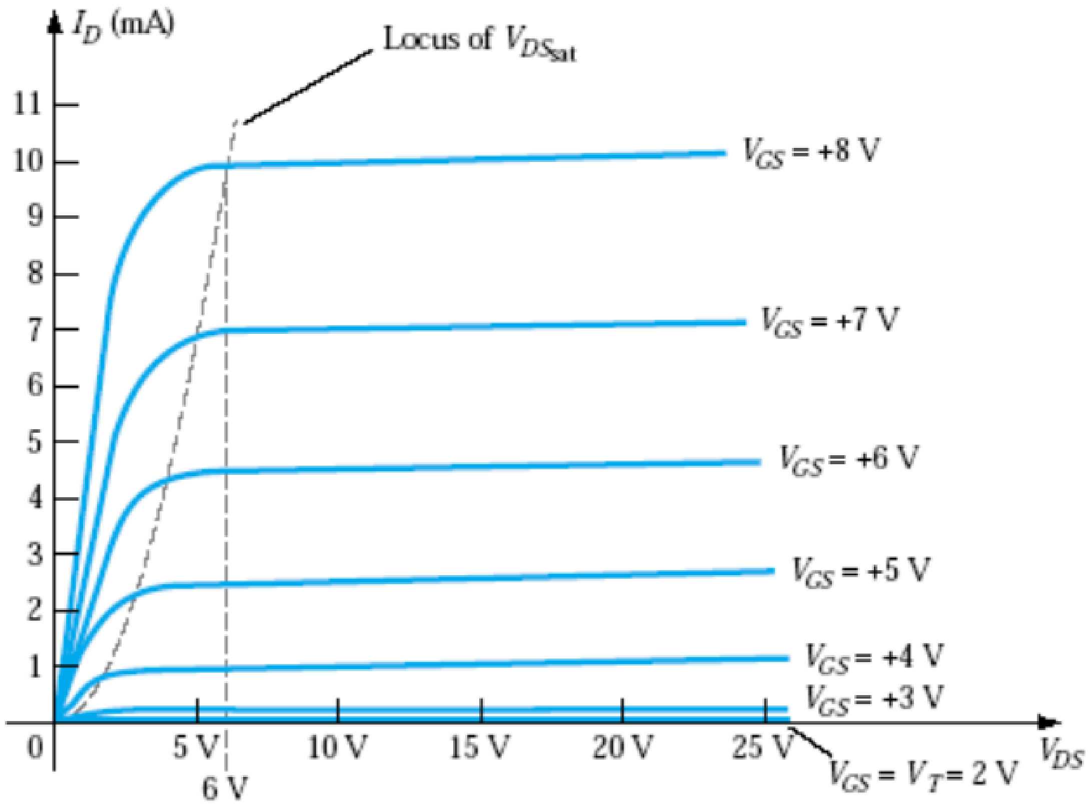



Figure 5.33 Change in channel and depletion region with increasing level of $V_{DS}$ for a fixed value of $V_{GS}$.

# Characteristics



# Shockley equation

$$\boxed{I_D = k(V_{GS} - V_T)^2}$$

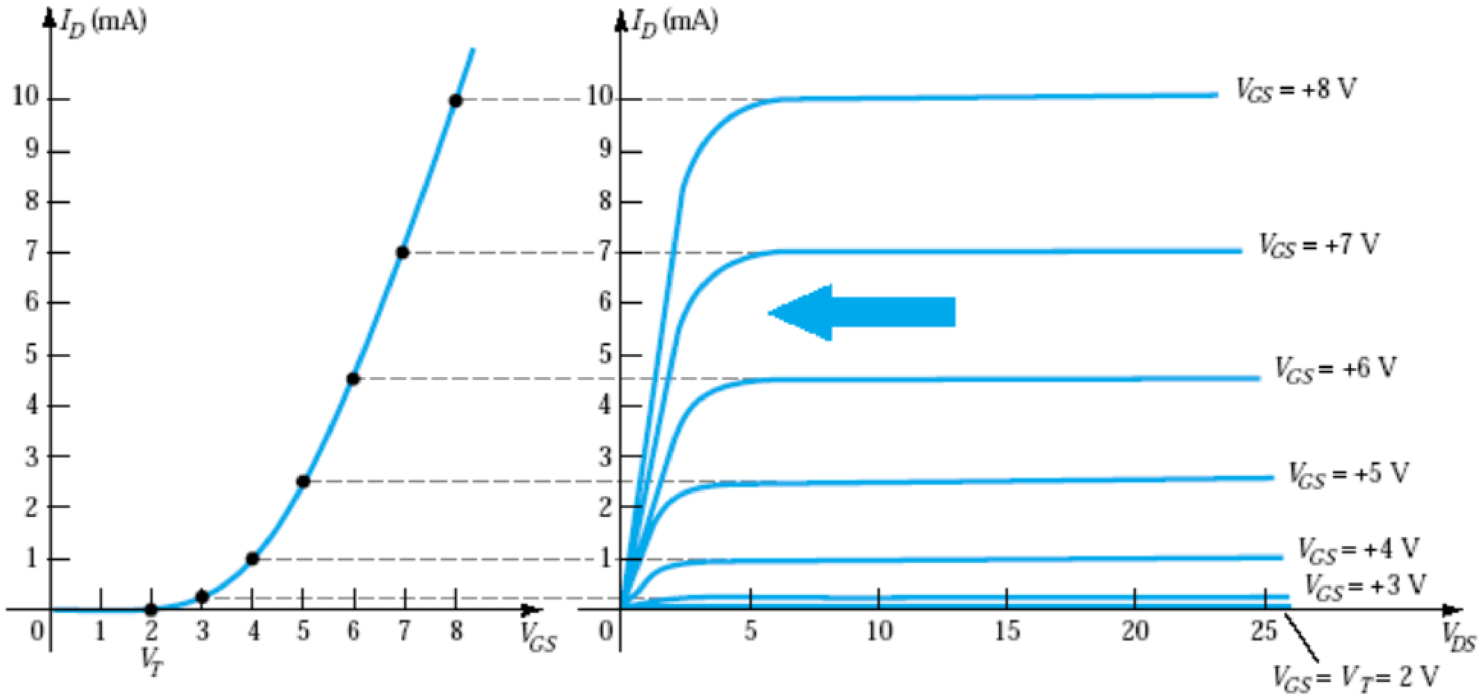
$$\boxed{k = \frac{I_{D(\text{on})}}{(V_{GS(\text{on})} - V_T)^2}}$$

$I_{D(\text{on})} = 10\text{ mA}$ when $V_{GS(\text{on})} = 8\text{ V}$ from the characteristics of Fig.

$$k = \frac{10\text{ mA}}{(8\text{ V} - 2\text{ V})^2} = \frac{10\text{ mA}}{(6\text{ V})^2} = \frac{10\text{ mA}}{36\text{ V}^2}$$

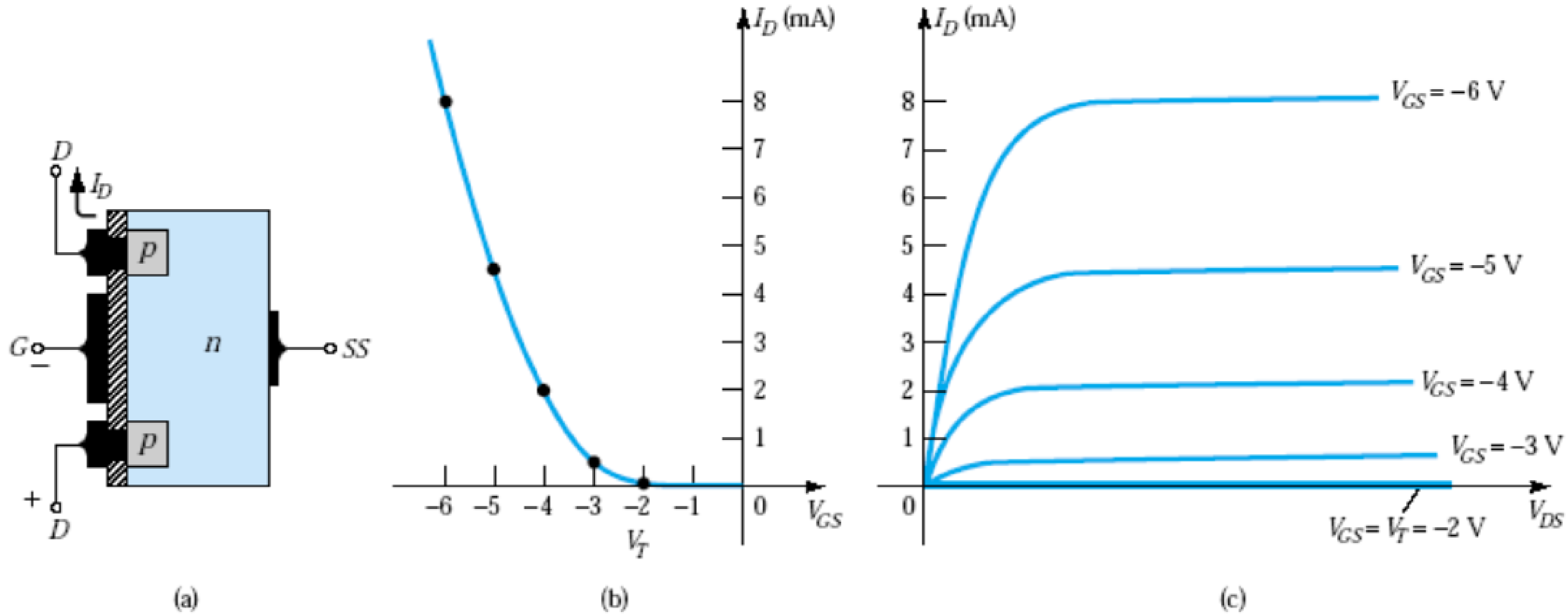
$$= \mathbf{0.278 \times 10^{-3}\ A/V^2}$$

# N-Channel E-MOSFET

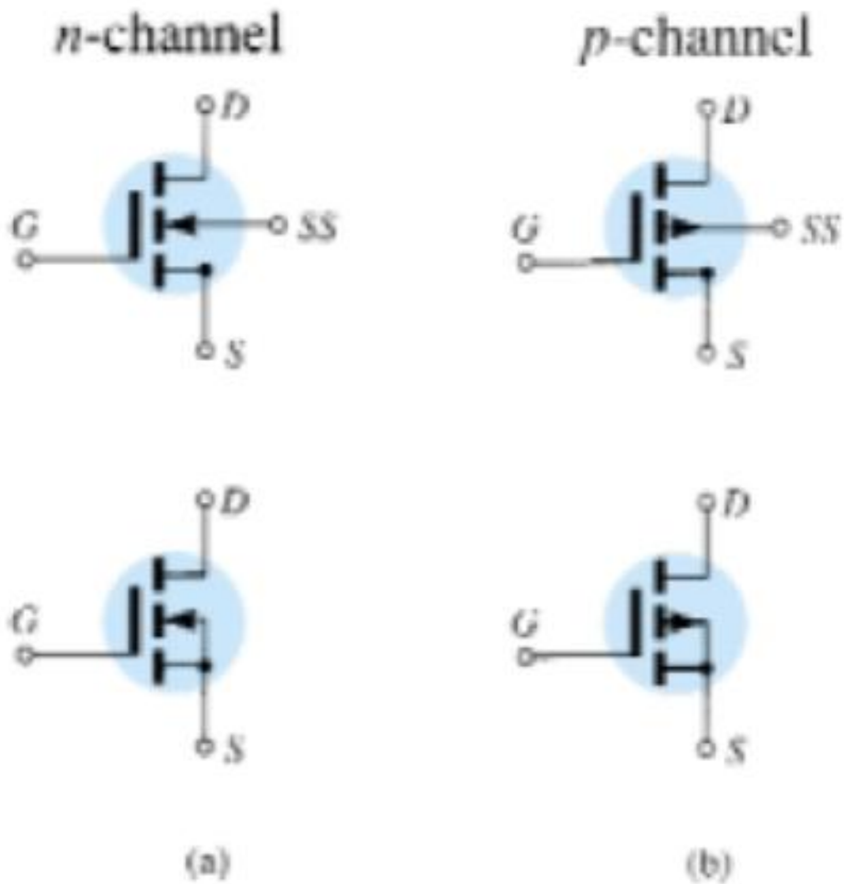


# Enhancement type MOSFET (p- ch)

$I_{DDS}/V_P$

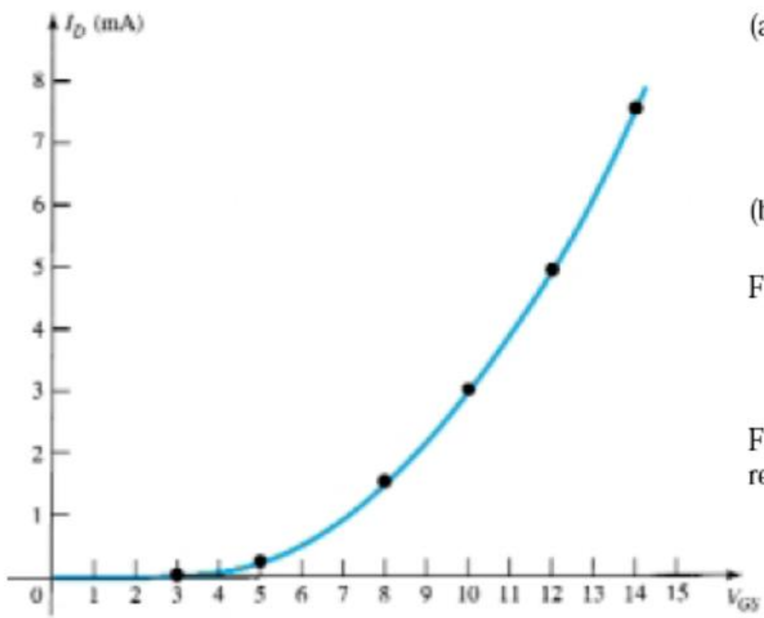


# Circuit symbols



# Example-3

Plot the transfer characteristic of an n-channel enhancement type MOSFET having $V_{GS(TH)}$=3V, and given $I_{D(on)}$ =3mA and $V_{GS(on)}$=10V




(a) Eq. (5.14): $k = \dfrac{I_{D(\text{on})}}{(V_{GS(\text{on})} - V_{GS(\text{Th})})^2}$

$$= \frac{3\text{ mA}}{(10\text{ V} - 3\text{ V})^2} = \frac{3\text{ mA}}{(7\text{ V})^2} = \frac{3 \times 10^{-3}}{49}\text{ A/V}^2$$

$$= \mathbf{0.061 \times 10^{-3}\ A/V^2}$$

(b) Eq. (5.13): $I_D = k(V_{GS} - V_T)^2$

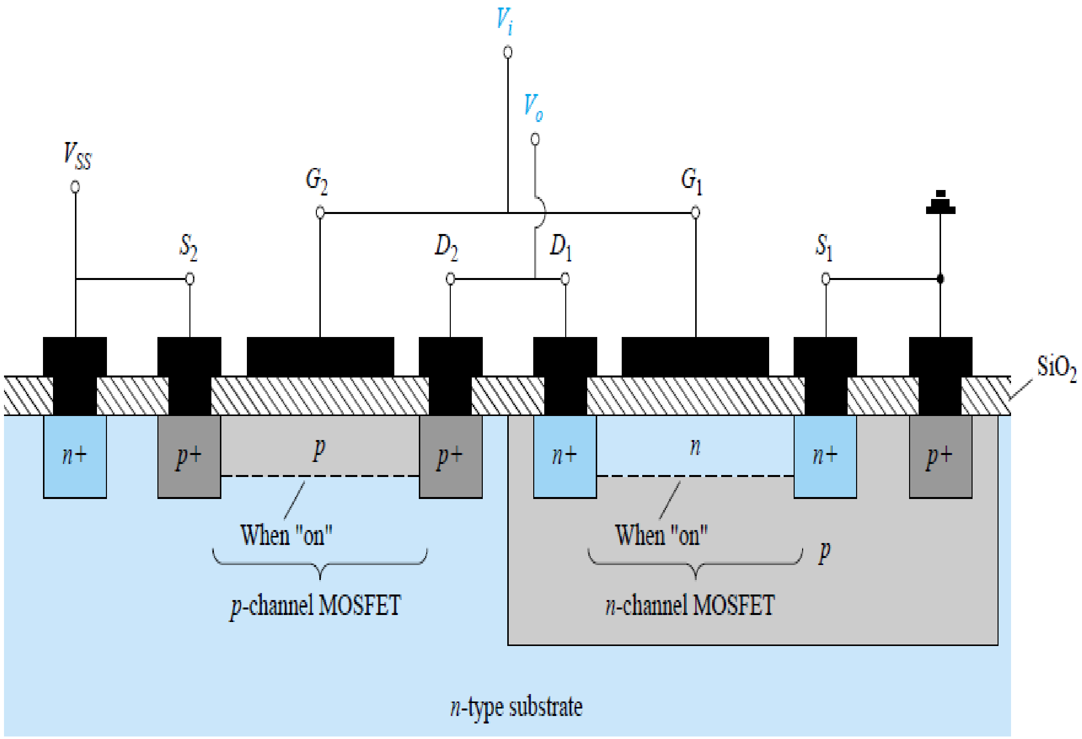
$$= 0.061 \times 10^{-3}(V_{GS} - 3\text{ V})^2$$

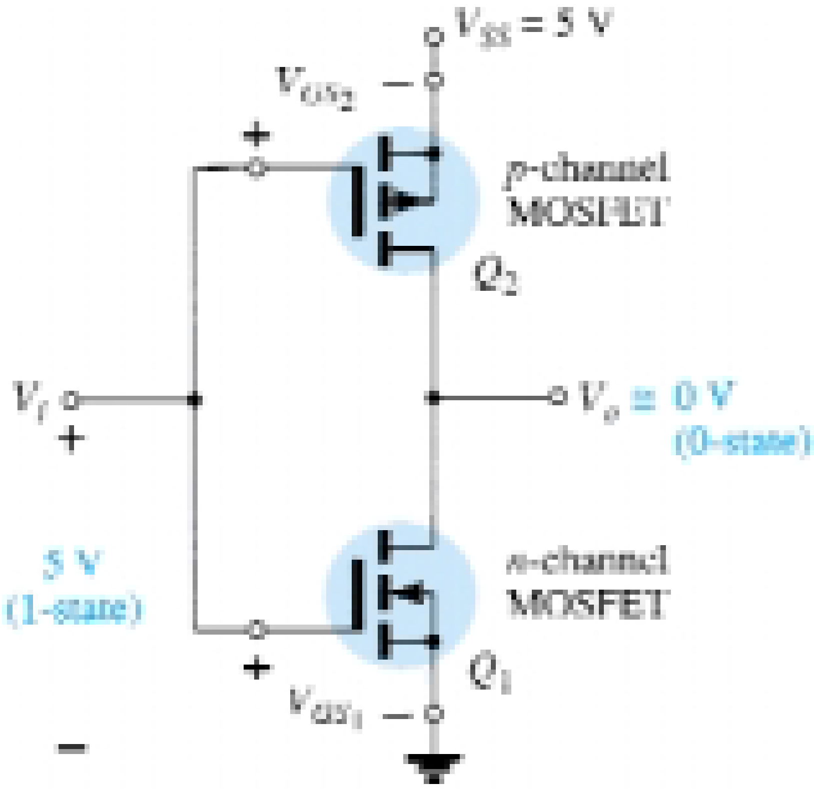
For $V_{GS} = 5$ V,

$$I_D = 0.061 \times 10^{-3}(5\text{ V} - 3\text{ V})^2 = 0.061 \times 10^{-3}(2)^2$$

$$= 0.061 \times 10^{-3}(4) = 0.244\text{ mA}$$

For $V_{GS}$ = 8, 10, 12, and 14 V, $I_D$ will be 1.525, 3 (as defined), 4.94, and 7.38 mA, respectively. The transfer characteristics are sketched in Fig. 5.40.




CMOS with the connections indicated in next Fig.

CMOS inverter.

Practice yourself and send me your feedback, if any.