

Chapter 6:

Field-Effect Transistors

FET

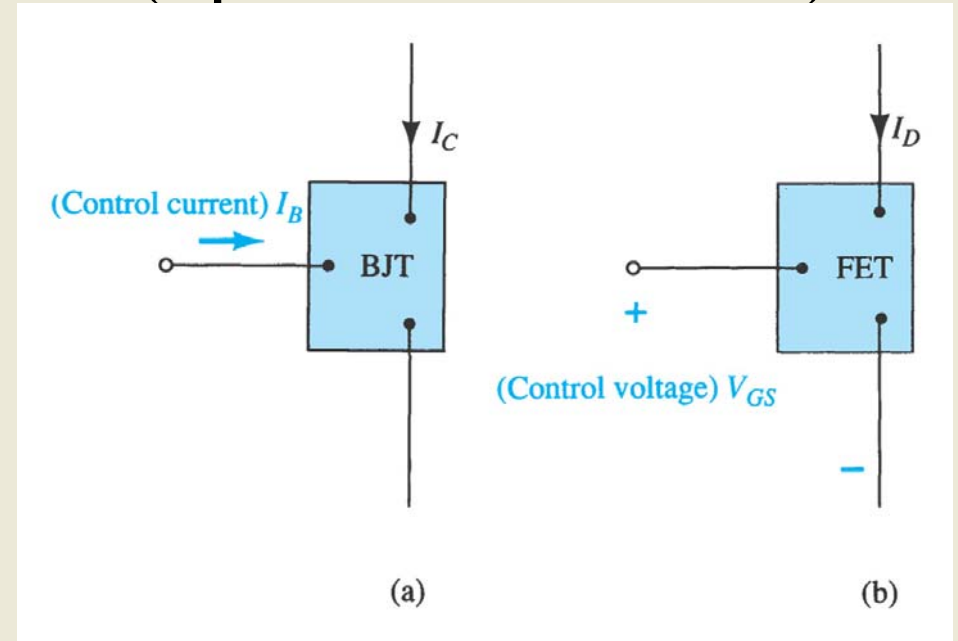
FETs (Field-Effect Transistors) are much like BJT (Bipolar Junction Transistors).

Similarities:

- Amplifiers
- Switching devices
- Impedance matching circuits

Differences:

- FETs are voltage controlled devices whereas BJTs are current controlled devices.
- FETs also have a higher input impedance, but BJTs have higher gains.
- FETs are less sensitive to temperature variations and because of their construction they are more easily integrated on ICs.



FET Types

- **JFET** — Junction Field-Effect Transistor
 - n-channel
 - p-channel
- **MOSFET** — Metal-Oxide Semiconductor Field-Effect Transistor
 - **D-MOSFET** — Depletion MOSFET
 - n-channel
 - p-channel
 - **E-MOSFET** — Enhancement MOSFET
 - n-channel
 - p-channel

6.2 JFET Construction

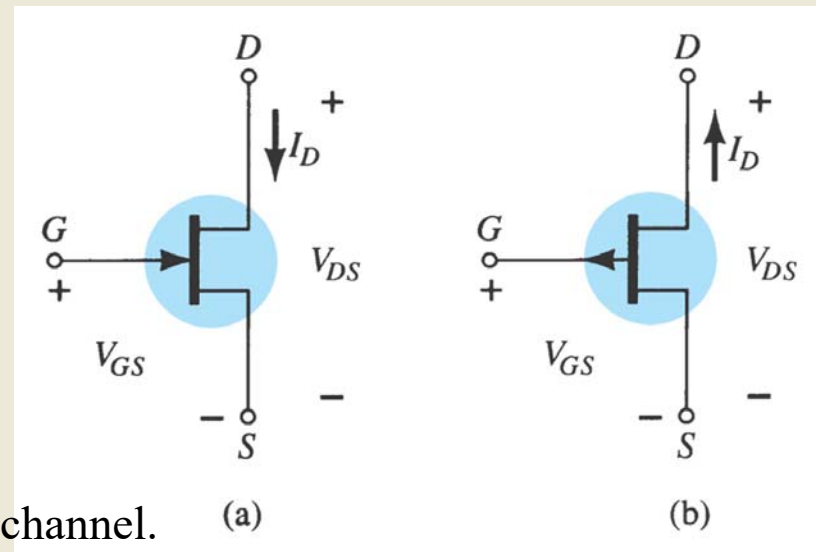
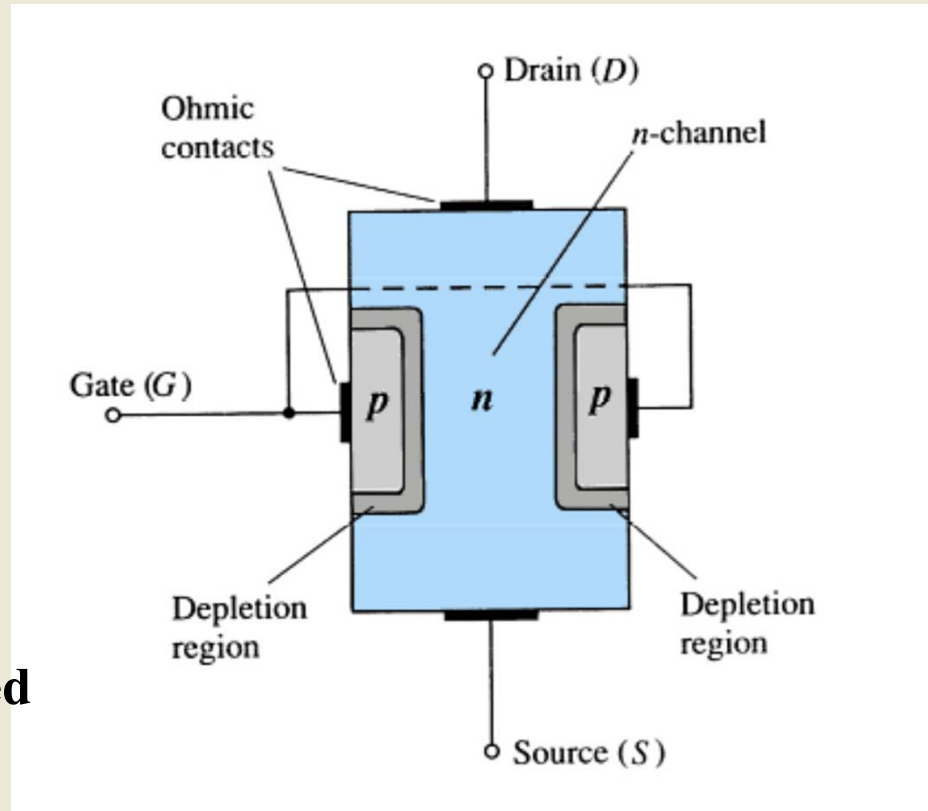
There are two types of JFETs

- ***n*-channel**
- ***p*-channel**

The *n*-channel is more widely used.

There are three terminals.

- **Drain (D)** and **source (S)** are connected to the *n*-channel
- **Gate (G)** is connected to the *p*-type material



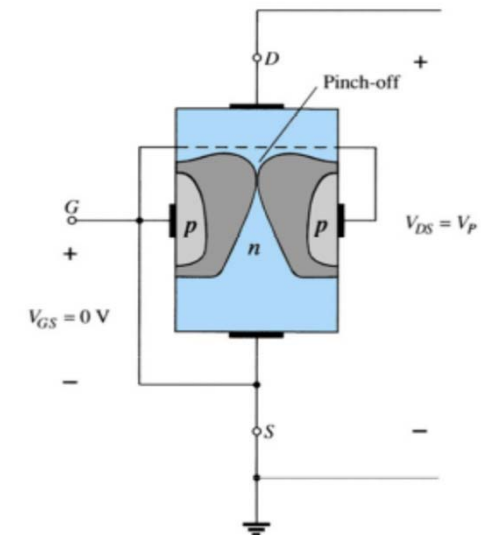
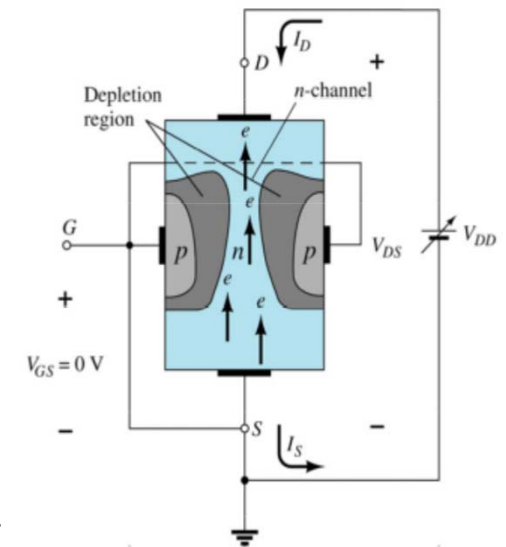
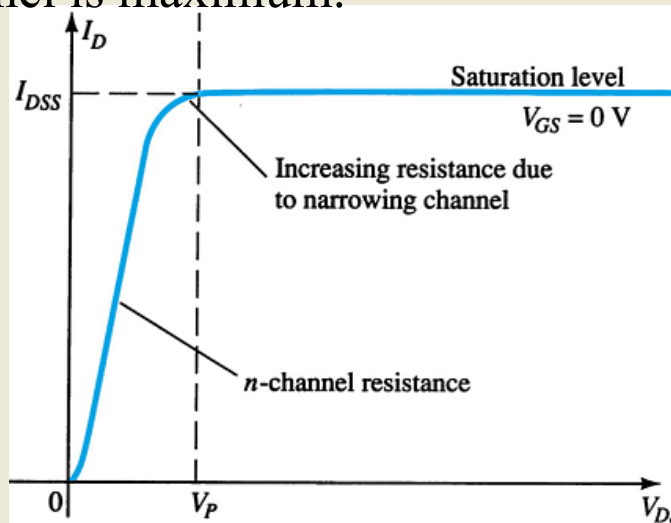
JFET symbols: (a) *n*-channel; (b) *p*-channel.

JFET Operating Characteristics

$V_{GS} = 0$, V_{DS} increasing to some positive value

When $V_{GS} = 0$ and V_{DS} is increased from 0 to a more positive voltage

- The depletion region between p-gate and n-channel increases
- Increasing the depletion region, decreases the size of the n-channel which increases the resistance of the n-channel.
- Even though the n-channel resistance is increasing, the current (I_D) from source to drain through the n-channel is increasing. This is because V_{DS} is increasing.
- If V_{DS} is further increased to a more positive voltage, then the depletion zone gets so large that it **pinches off** the n-channel.
- V_{DS} establishes the pinch-off is denoted as **pinch off voltage: V_p** .
- Any further increase in $V_{DS} > V_p$ does not produce any increase in I_D . I_D is at saturation or maximum referred to as I_{DSS} .
- The ohmic value of the channel is maximum.

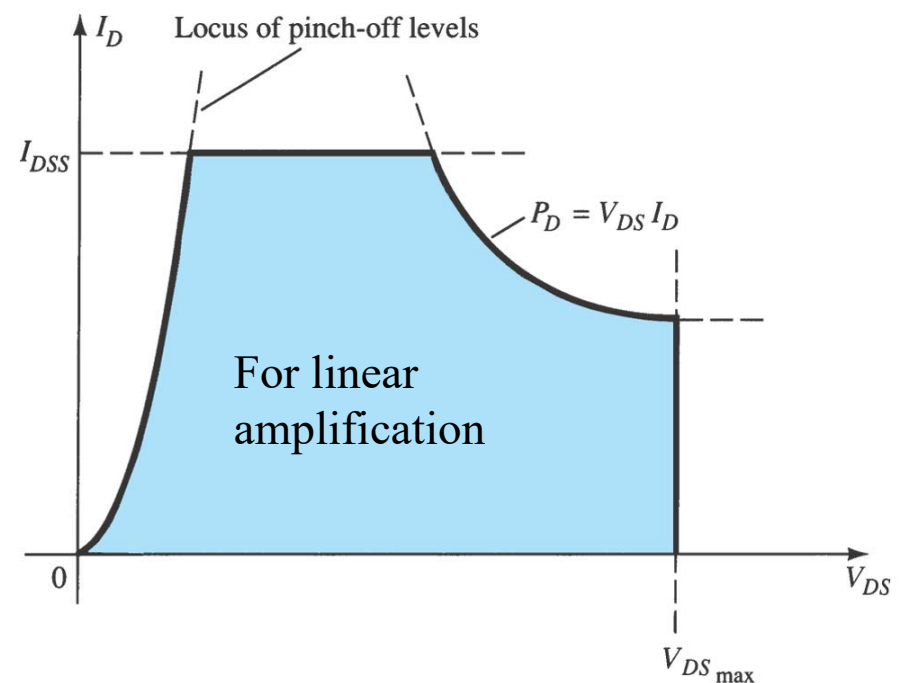
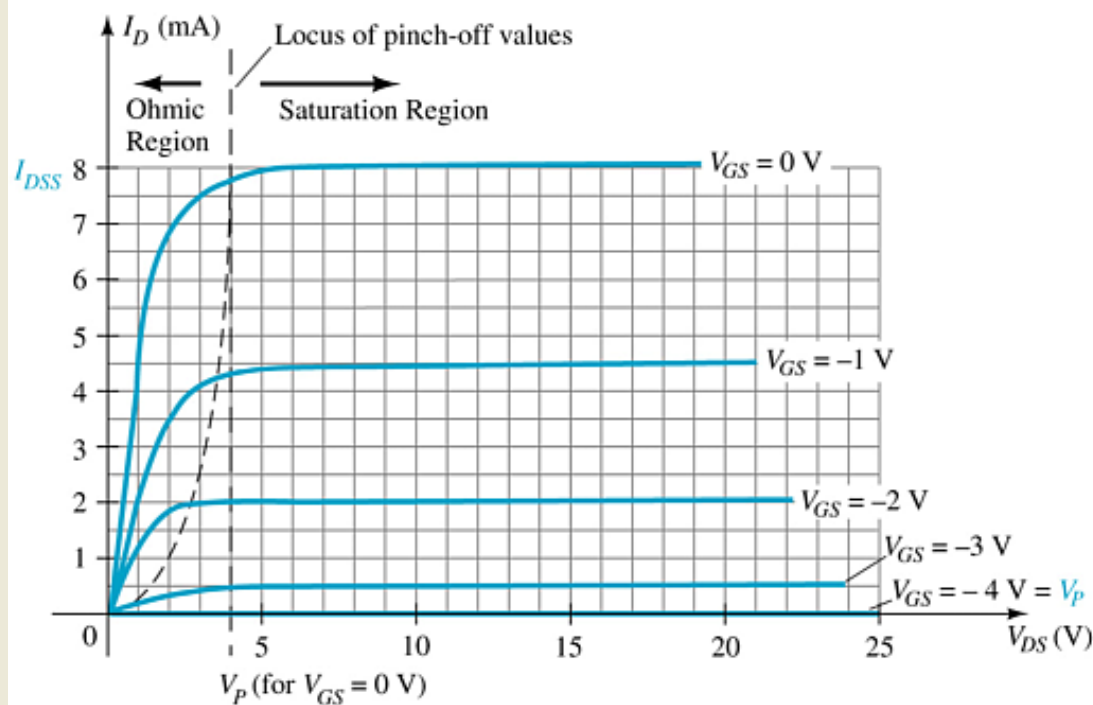


JFET Operating Characteristics

$V_{GS} < 0$, V_{DS} at some positive value: $I_D < I_{DSS}$

As V_{GS} becomes more negative:

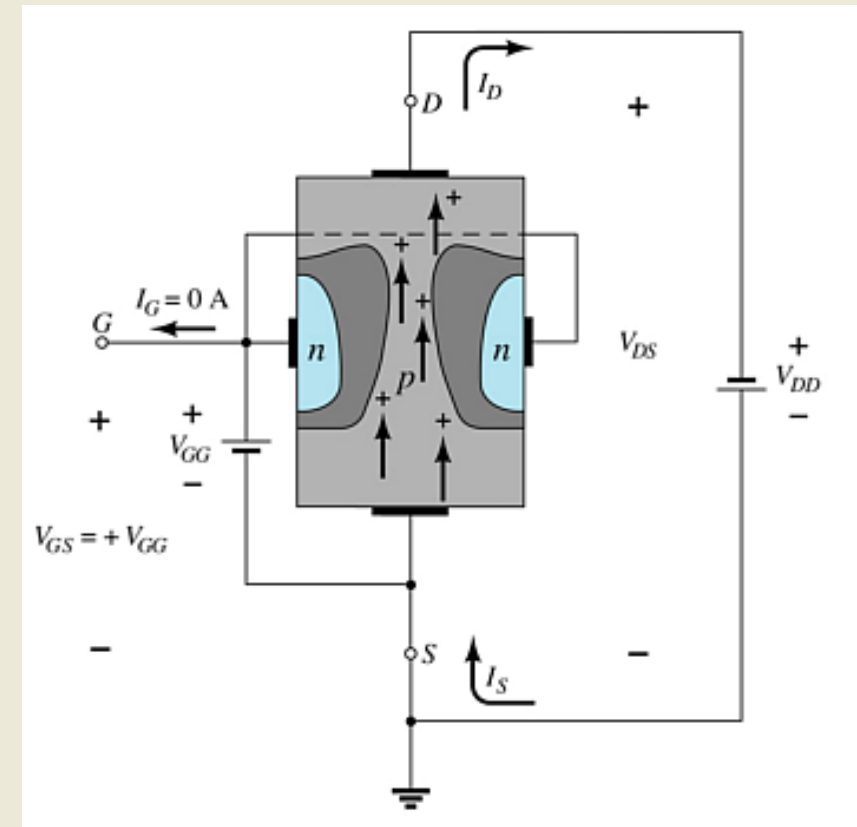
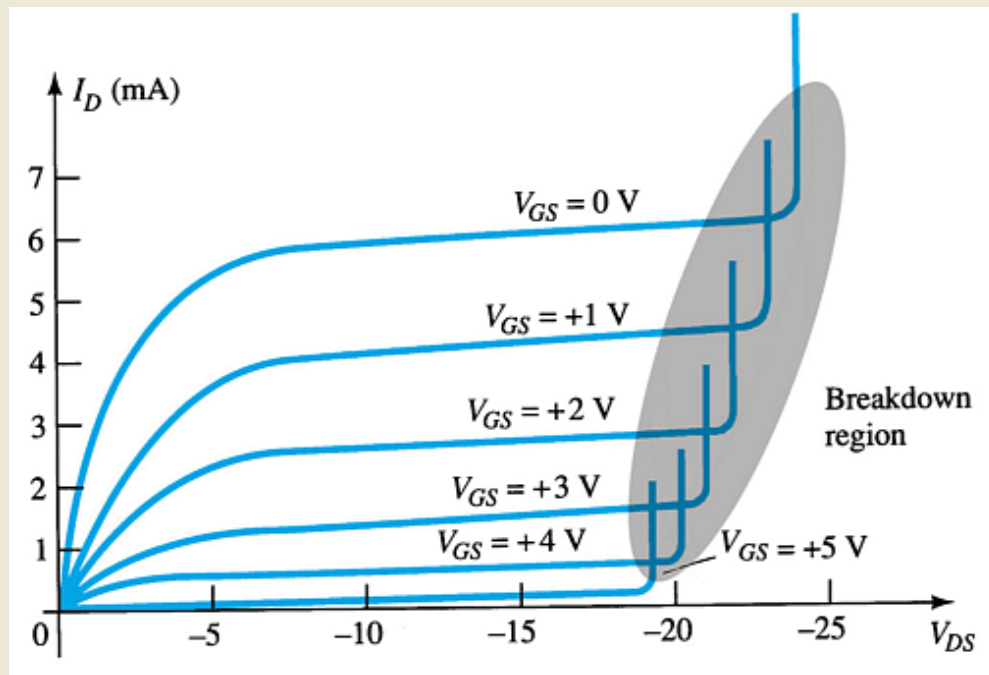
- the depletion region increases.
- The JFET experiences pinch-off at a lower voltage (V_p).
- I_D decreases ($I_D < I_{DSS}$) even though V_{DS} is increased.
- Eventually I_D reaches 0A. V_{GS} at this point is called V_p or $V_{GS(off)}$.



Also note that at high levels of V_{DS} the JFET reaches a breakdown situation. I_D increases uncontrollably if $V_{DS} > V_{DS_{max}}$.

p-Channel JFETs

The *p*-channel JFET behaves the same as the *n*-channel JFET, except the polarities and currents are reversed.



Also note that at high levels of V_{DS} the JFET reaches a breakdown situation— I_D increases uncontrollably if $V_{DS} > V_{DSmax}$.

6.3 JFET Transfer Characteristics

The transfer characteristic of input-to-output is not as straightforward in a JFET as it is in a BJT.

In a BJT, β indicates the relationship between I_B (input) and I_C (output).

In a JFET, the relationship of V_{GS} (input) and I_D (output) is a little more complicated:

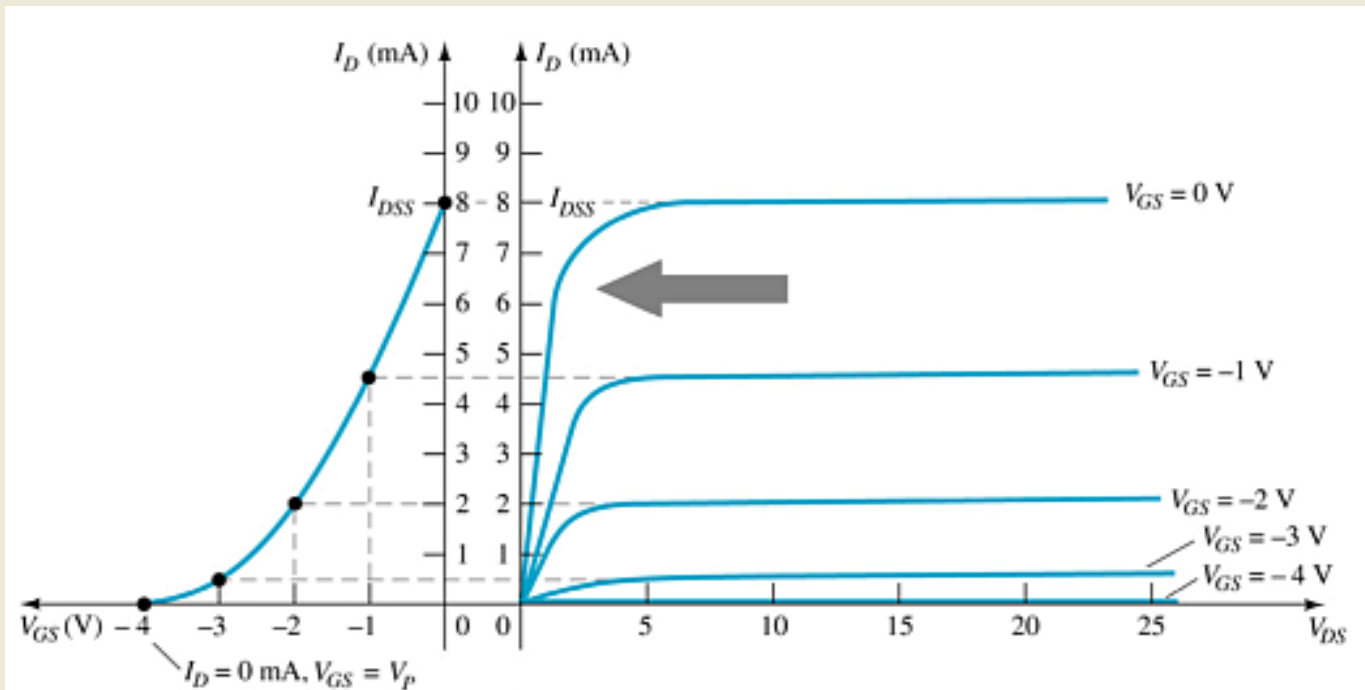
$$I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_P} \right)^2$$

I_{DSS} and V_P ($V_{GS(off)}$) values can be found in a specification sheet

JFET Transfer Curve:

This graph shows the value of I_D for a given value of V_{GS} .

- Applying Shockley's equation (shorthand method)
- from the output characteristics



6.6 MOSFETs

MOSFETs have characteristics similar to JFETs and additional characteristics that make them very useful.

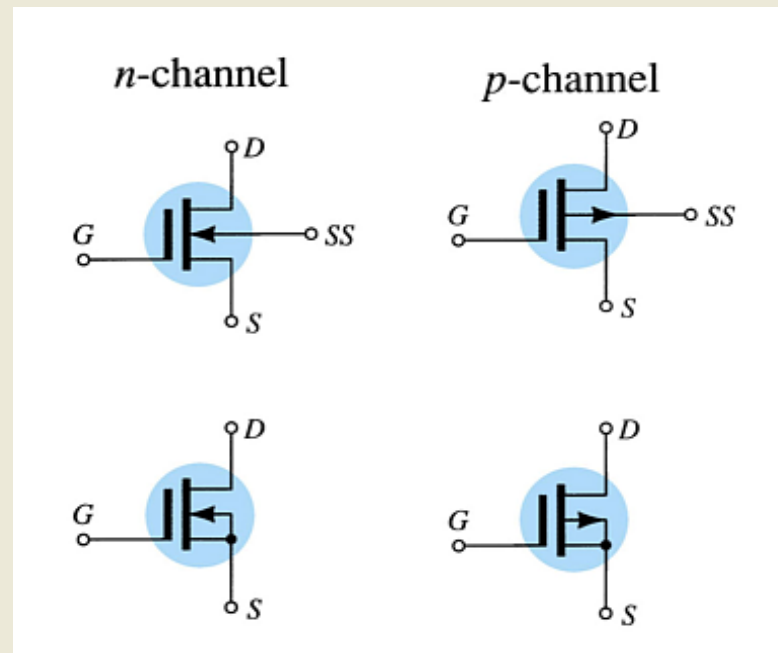
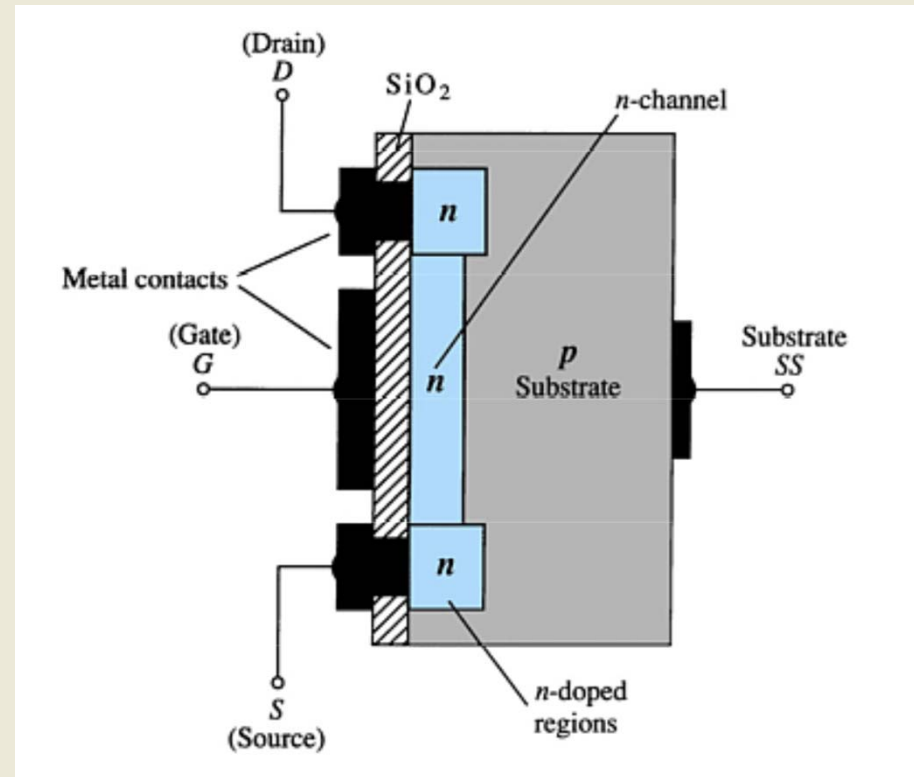
There are two types of MOSFETs:

- **Depletion-Type**
- **Enhancement-Type**

Depletion-Type MOSFET Construction

The **drain** (D) and **source** (S) connect to the n -doped regions. These n -doped regions are connected via an n -channel. This n -channel is connected to the **gate** (G) via a thin insulating layer of SiO_2 .

The n -doped material lies on a p -doped substrate that may have an additional terminal connection called **substrate** (SS).



Basic Depletion-Type MOSFET Operation

A depletion-type MOSFET can operate in two modes:

- Depletion mode
- Enhancement mode

Depletion Mode

The characteristics are similar to a JFET.

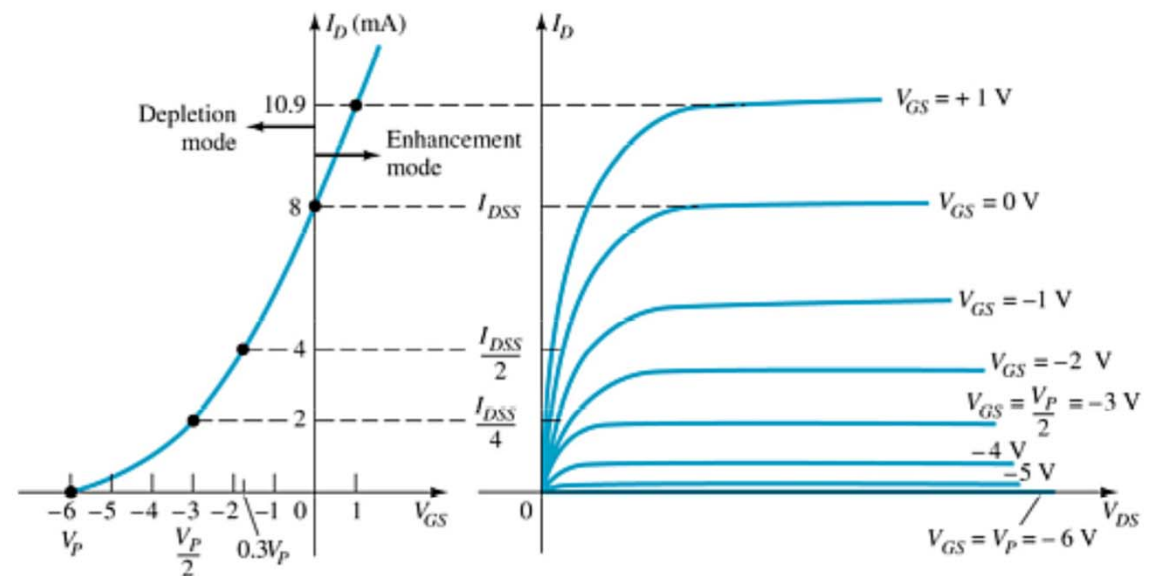
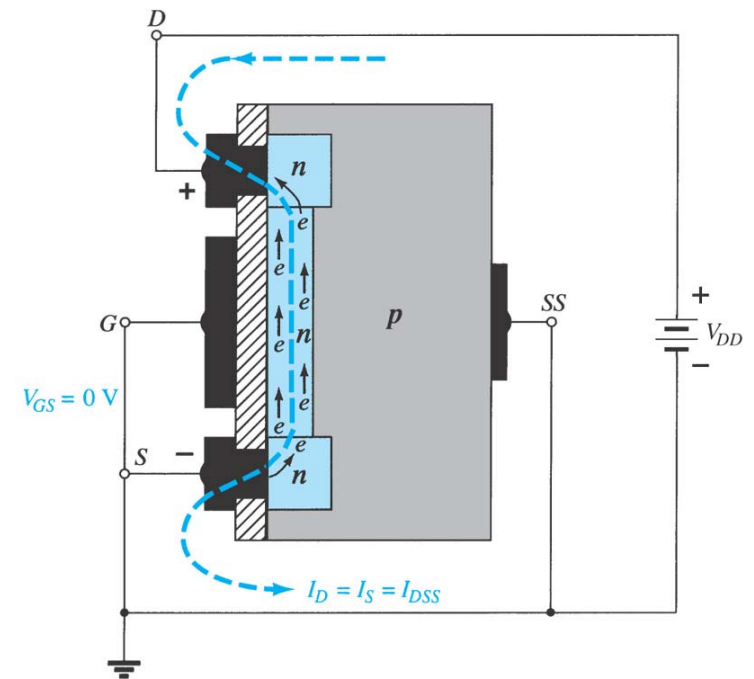
- When $V_{GS} = 0V$, $I_D = I_{DSS}$
- When $V_{GS} < 0V$, $I_D < I_{DSS}$
- The formula used to plot the transfer curve still applies:

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

Enhancement Mode

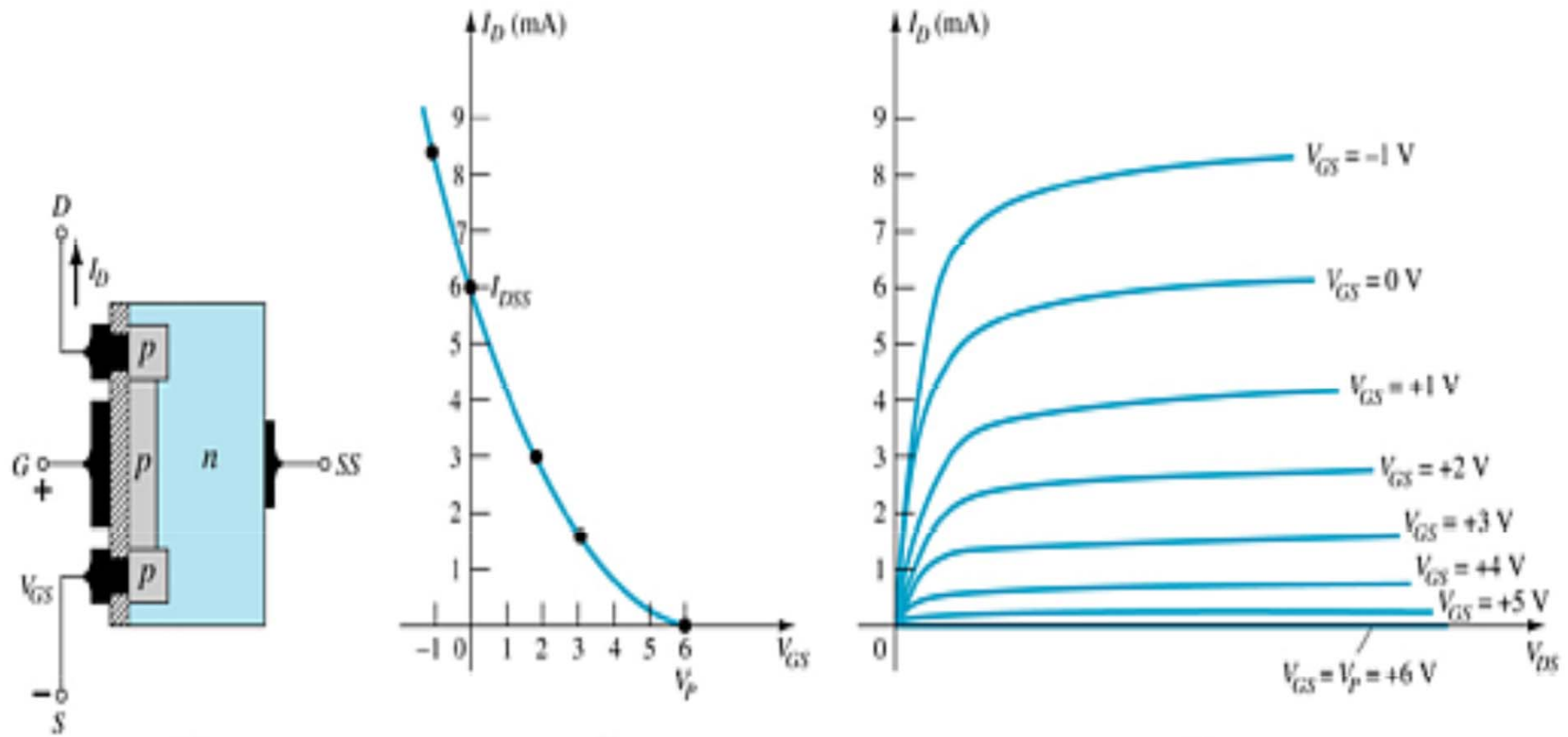
- $V_{GS} > 0V$
- I_D increases above I_{DSS}
- The formula used to plot the transfer curve still applies:

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



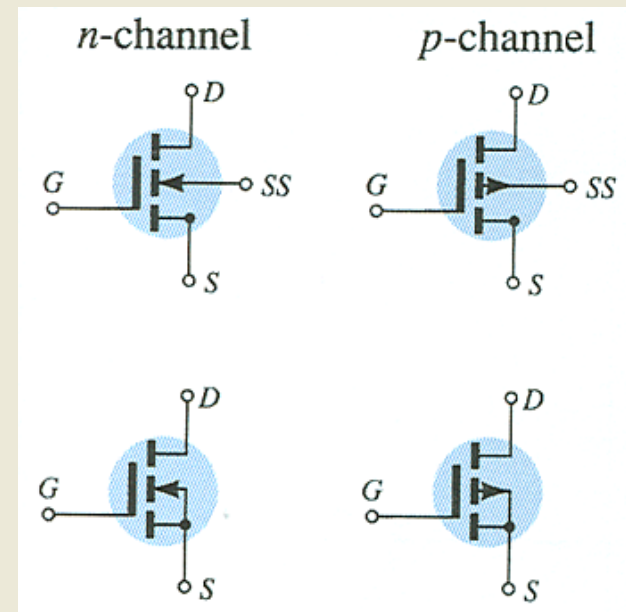
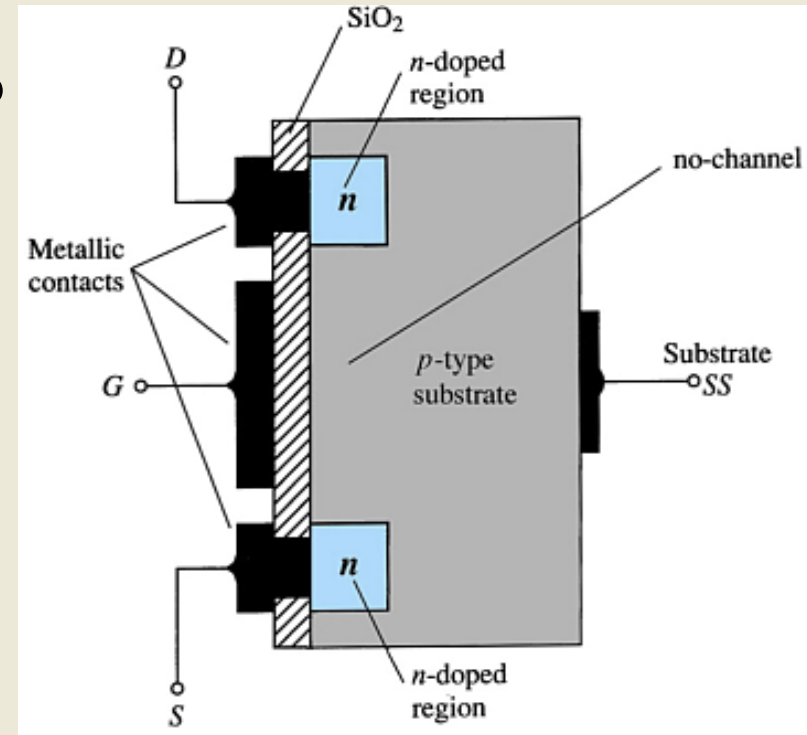
Note that V_{GS} is now a positive polarity

p-Channel Depletion-Type MOSFET



6.7 Enhancement-Type MOSFET Construction

- The **drain** (D) and **source** (S) connect to the *n*-doped regions. These *n*-doped regions are connected via an *n*-channel
- The **gate** (G) connects to the *p*-doped substrate via a thin insulating layer of SiO_2
- There is no channel
- The *n*-doped material lies on a *p*-doped substrate that may have an additional terminal connection called the **substrate** (SS)



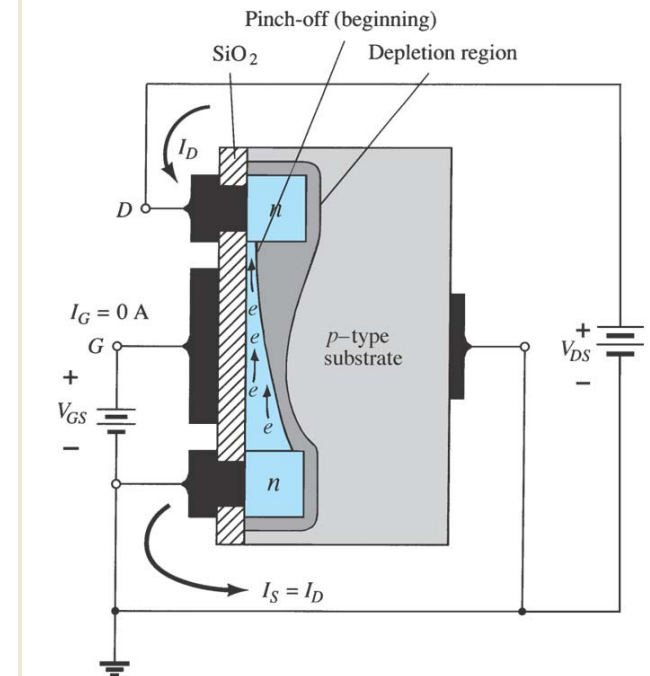
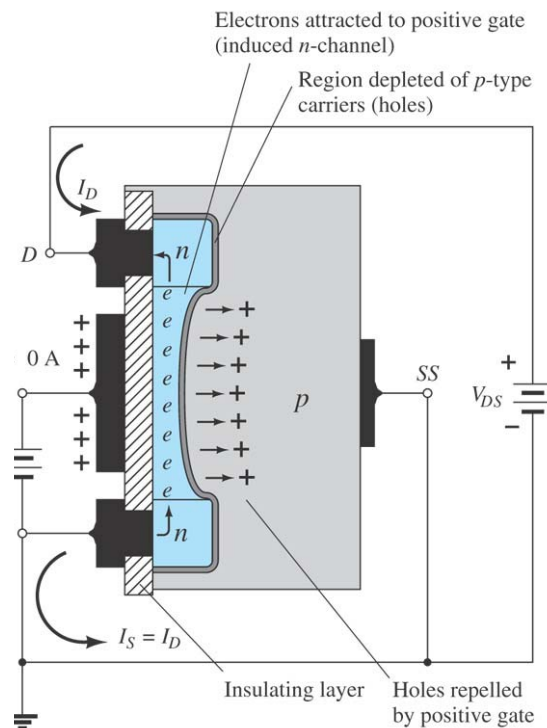
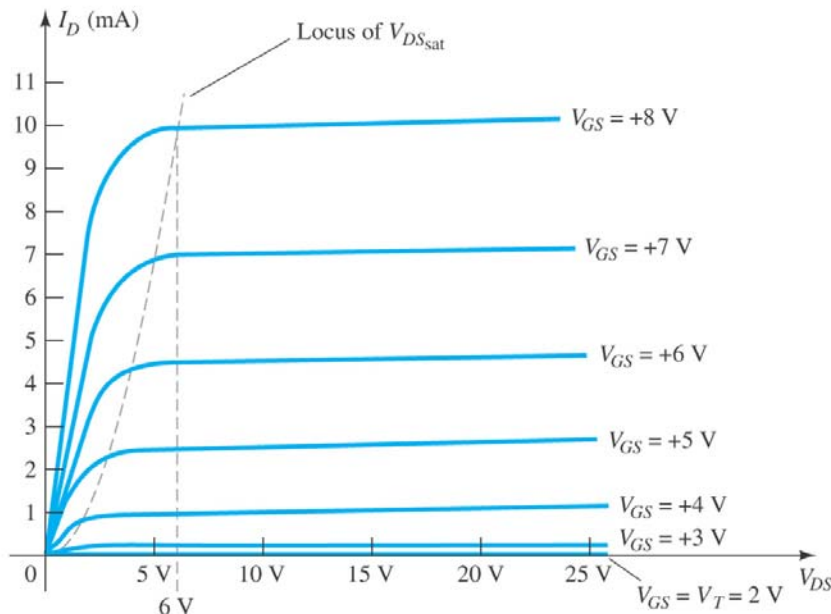
Basic Operation of the Enhancement-Type MOSFET

The enhancement-type MOSFET only operates in the enhancement mode.

- V_{GS} is always positive to form an n-channel. V_{GS} resulting in the significant increase in drain current is called the threshold voltage V_T (or $V_{GS(Th)}$)
- As V_{GS} increases, I_D increases
- As V_{GS} is kept constant and V_{DS} is increased, then I_D saturates (I_{DSS}) due to pinch-off process. And the saturation level, V_{DSsat} is reached

$$V_{GD} = V_{GS} - V_{DS}$$

$$V_{DSsat} = V_{GS} - V_{GD} = V_{GS} - V_T$$



Enhancement-Type MOSFET Transfer Curve

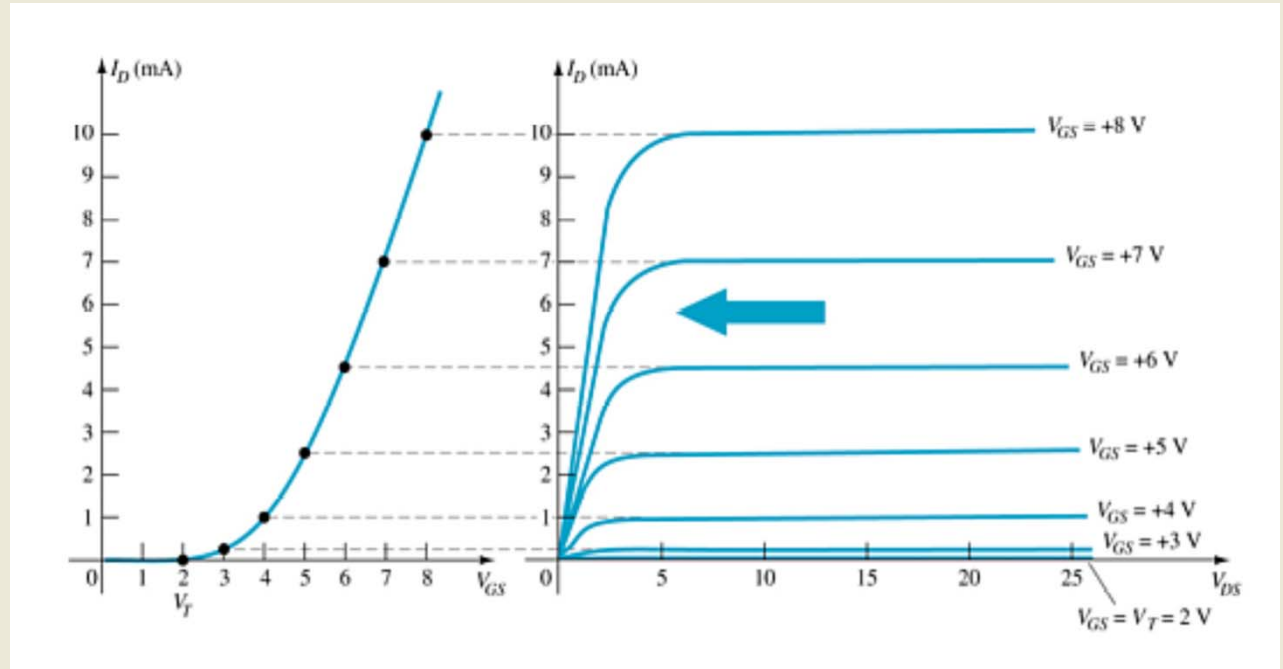
To determine I_D given V_{GS} :

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

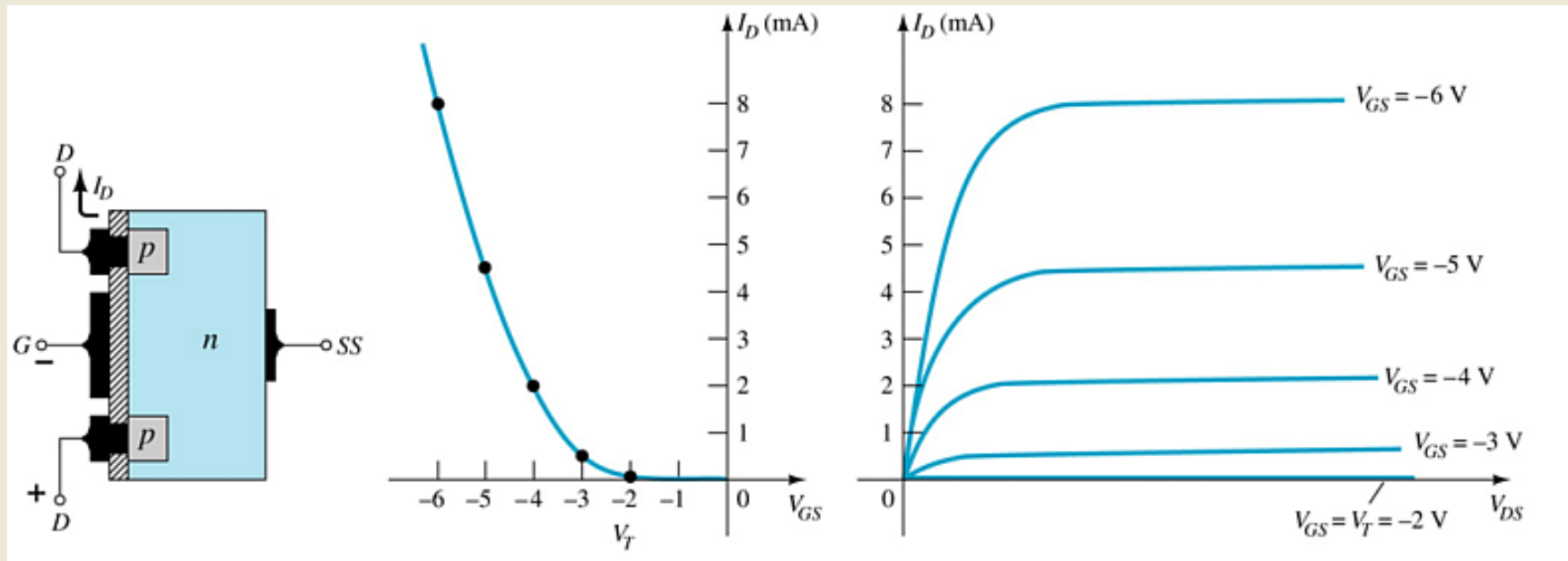
Where:

V_T = threshold voltage
or voltage at which the
MOSFET turns on

k = constant found in
the specification sheet



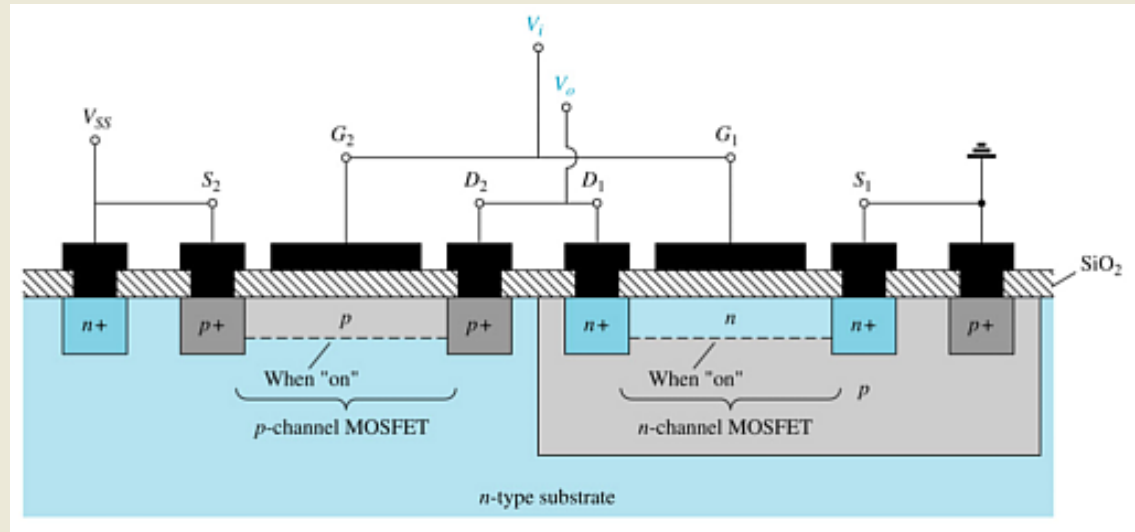
p-Channel Enhancement-Type MOSFETs



The *p*-channel enhancement-type MOSFET is similar to the *n*-channel, except that the voltage polarities and current directions are reversed.

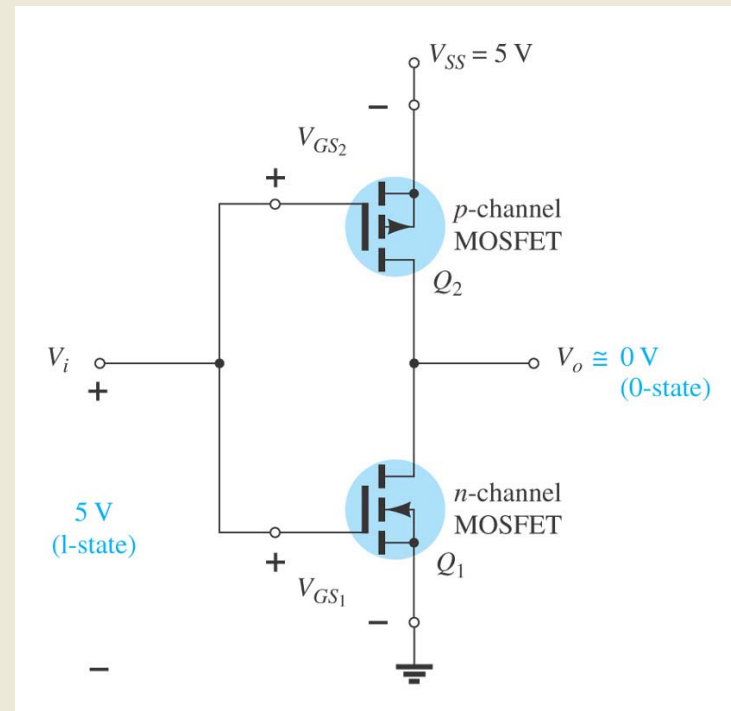
6.8 CMOS Devices

CMOS (complementary MOSFET) uses a *p*-channel and *n*-channel MOSFET on the same substrate.



Advantages

- Useful in logic circuit designs
- Higher input impedance
- Faster switching speeds
- Lower operating power levels



Summary

For all FETs:

$$I_G \cong 0A$$

$$I_D = I_S$$

For JFETs and depletion-type MOSFETs:

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

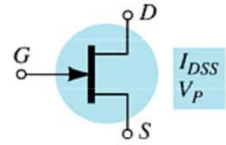
For enhancement-type MOSFETs:

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

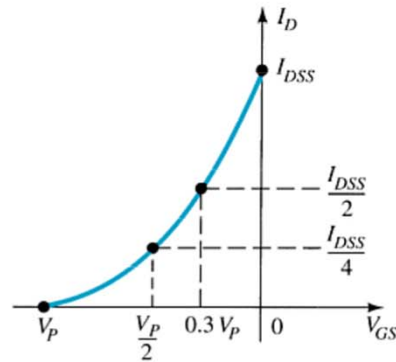
JFETs differ from BJTs

- Nonlinear relationship between input (V_{GS}) and output (I_D)
- FETs are voltage controlled devices whereas BJTs are current controlled devices.
- FETs have a higher input impedance.
- FETs are less sensitive to temperature.

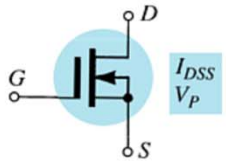
$$I_G = 0A, I_D = I_S$$



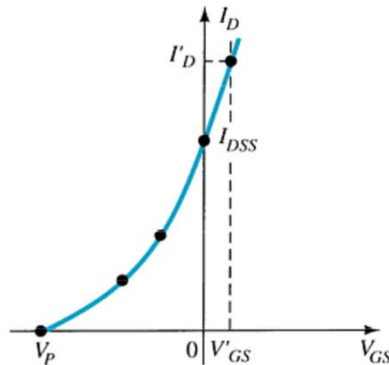
$$I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_P} \right)^2$$



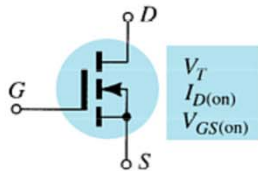
$$I_G = 0A, I_D = I_S$$



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



$$I_G = 0A, I_D = I_S$$



$$I_D = k (V_{GS} - V_{GS(Th)})^2$$

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

