Chapter 3:
Field-Effect Transistors

Comparison between FET and BJT

FETs (Field-Effect Transistors) are much like BJTs (Bipolar Junction Transistors):

Similarities:

- **Amplifiers**
- **Switching devices**
- **Impedance matching circuits**

Differences:

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

FET Types

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

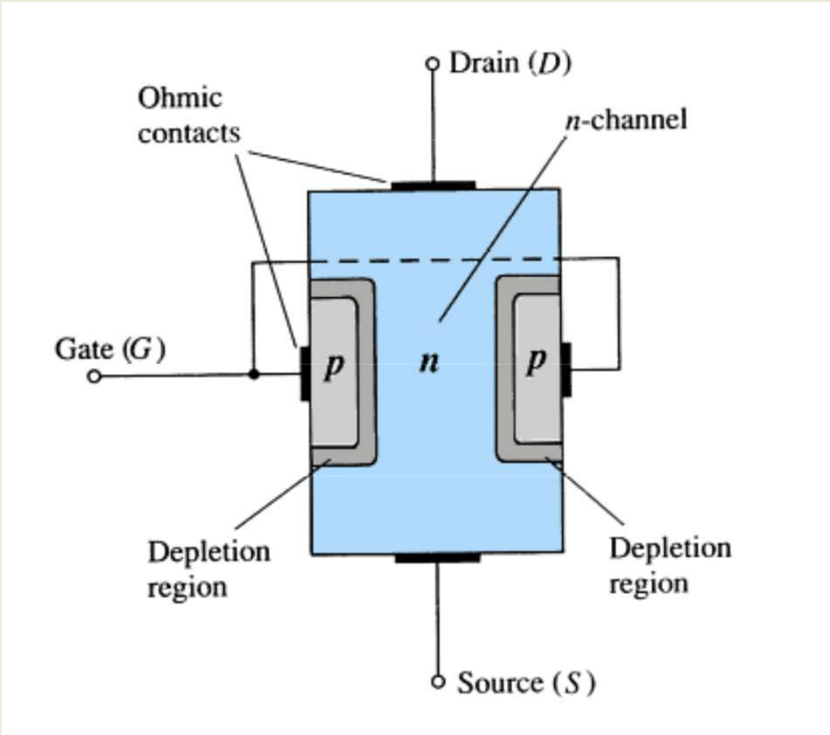
3.2 Characteristics of FET

1.JFET

There are two types of JFETs

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

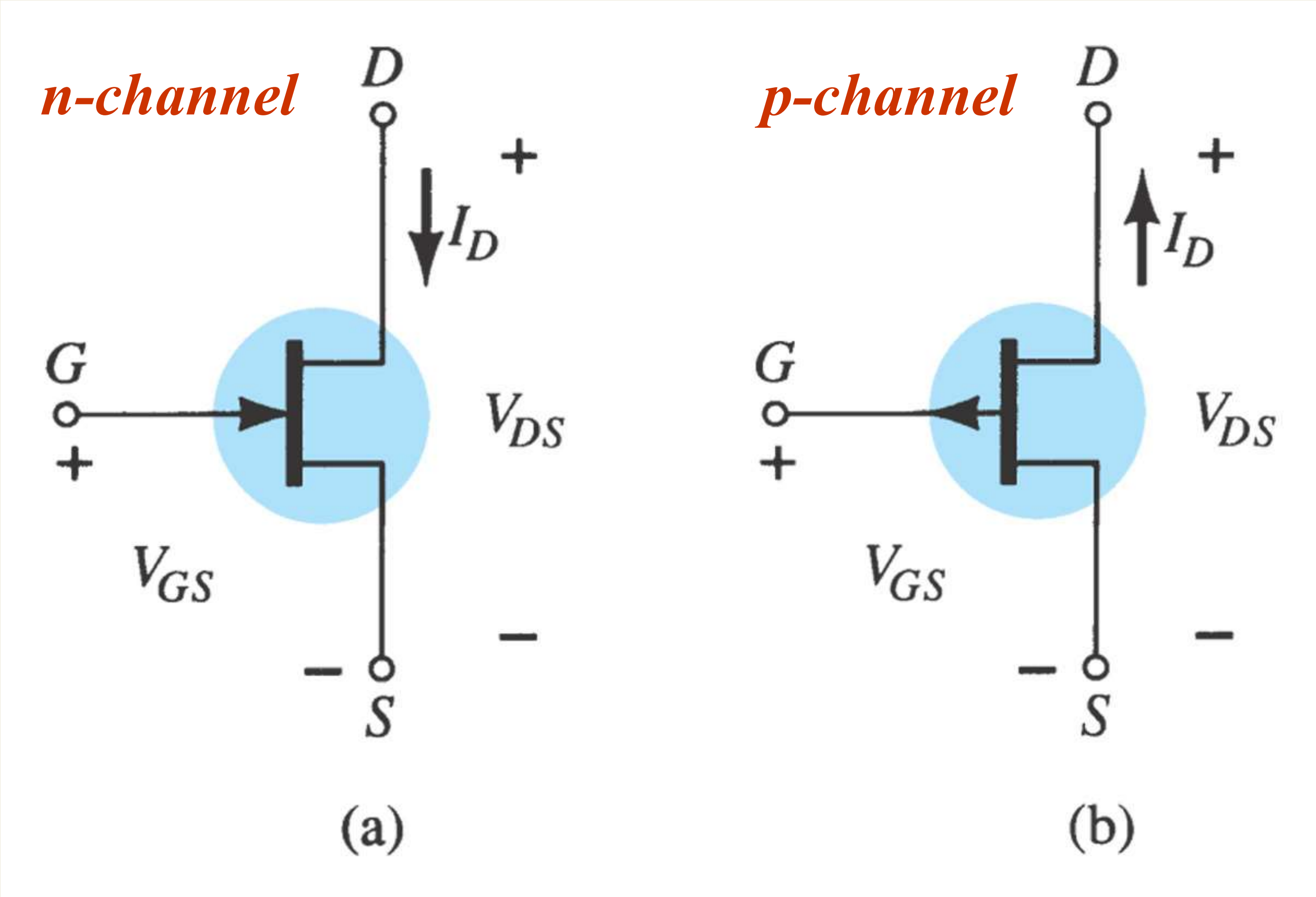
The *n*-channel is more widely used.



There are *three* terminals on JFET:

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

JFET Symbols

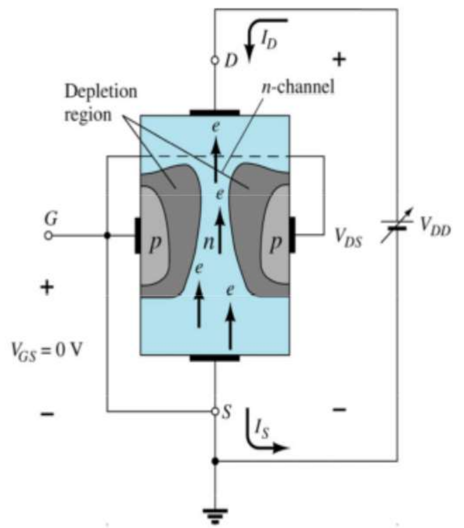


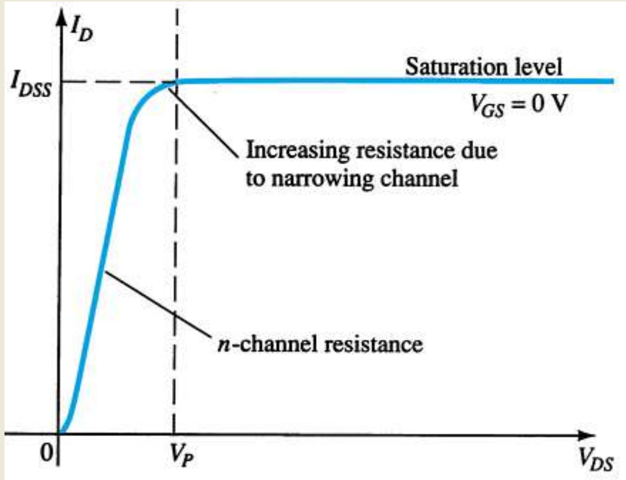
JFET Operating Characteristics

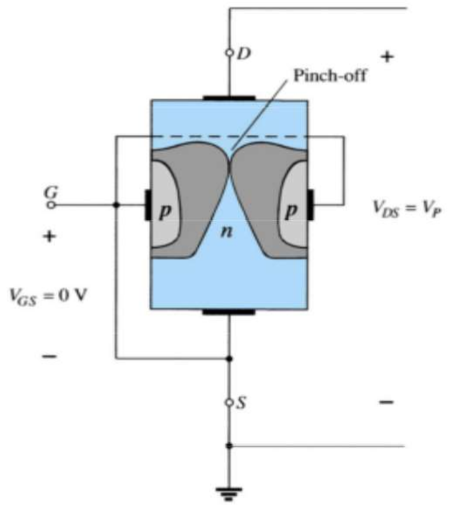
$V_{GS} = 0$, V_{DS} increasing to some positive value

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.





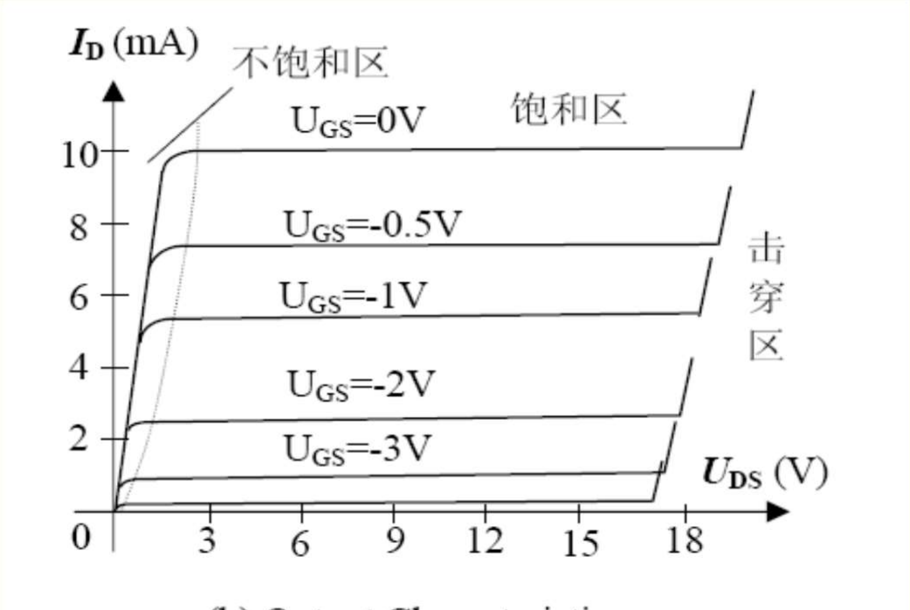


JFET Operating Characteristics

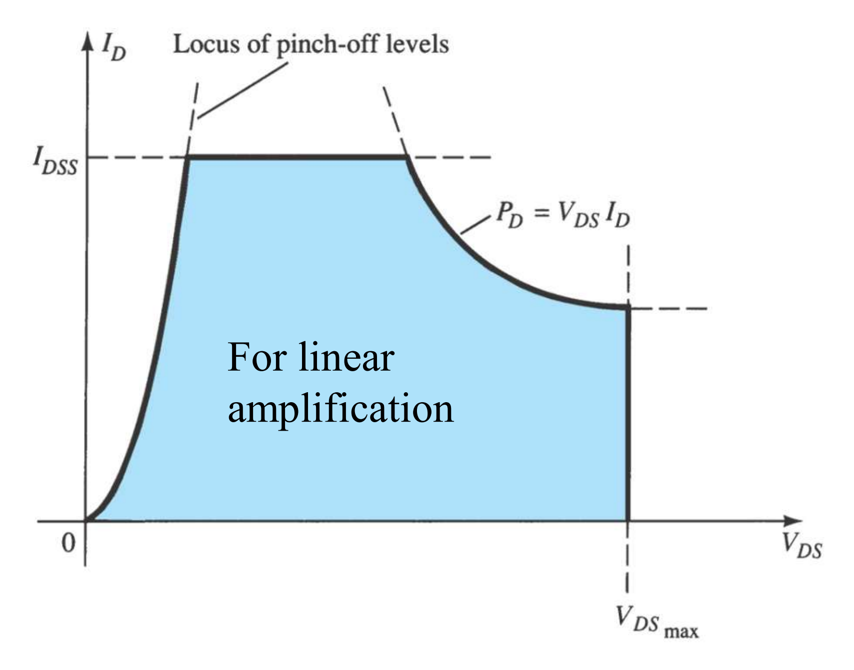
$V_{GS} < 0$, V_{DS} at some positive value: $I_D < I_{DSS}$

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 $V_{GS(off)}$.

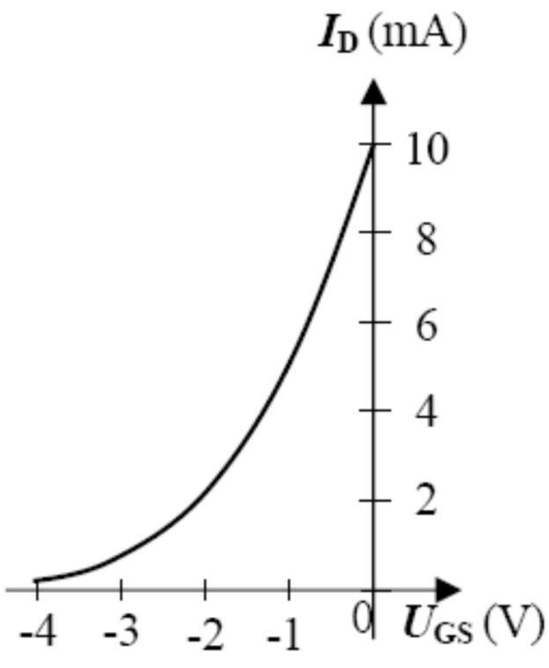


(b) Output Characteristics



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

JFET Transfer Characteristics



(a) Transfer Characteristics

V_{GS} is applied *between the Gate and the Source*

V_{DS} is applied *between the Drain and the Source*

- V_{GS} is a negative voltage, PN junction is reversed
- $I_G \approx 0$
- I_D is controlled by the voltage V_{GS}
- I_D =0mA is defined by V_{GS}= V_P (*pinchoff*)

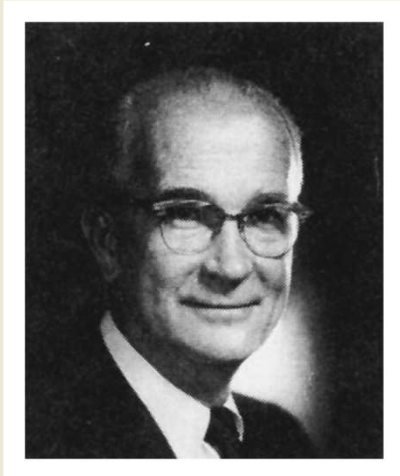
JFET Transfer Characteristics

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 bit more complicated: (*Shockley's Equation*)

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



- *Nonlinear Relationship*
- *Unaffected by the network*

Nobel Prize 1956

Co-inventor of the first transistor and formulator of the "field-effect" theory

MOSFETs

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

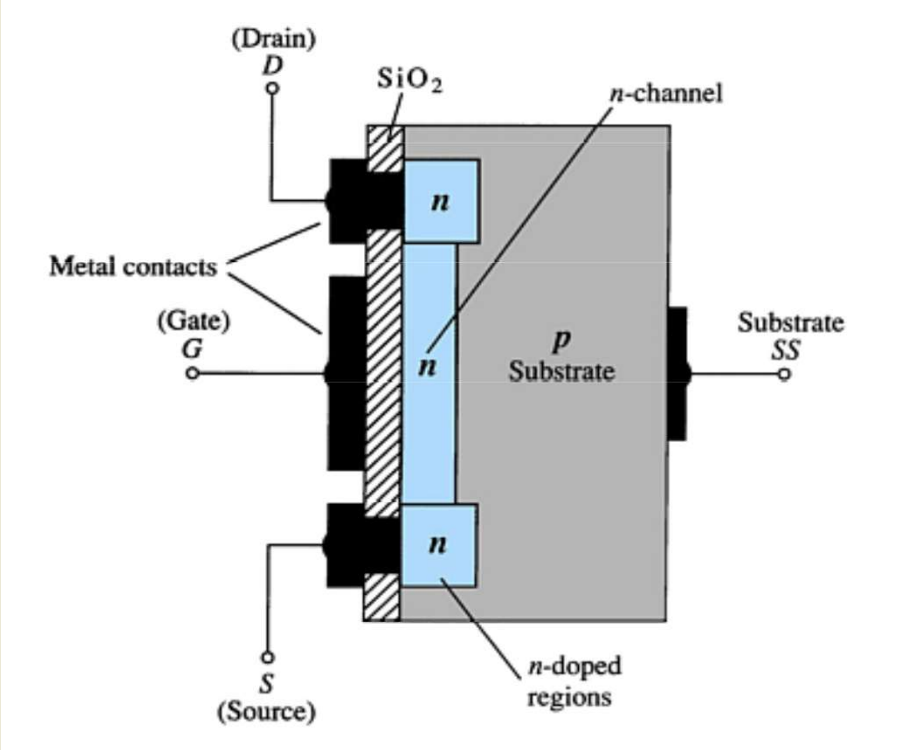
There are two types of MOSFETs:

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

Depletion-type MOSFET

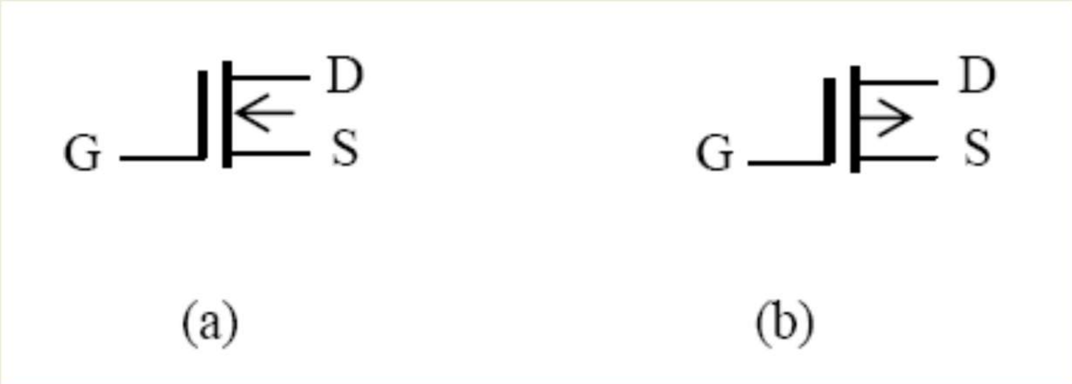
The Drain (D) and Source (S) connect to the *n*-doped regions. These *n*-doped regions are connected via an *n*-channel. This *n*-channel is connected to the Gate (G) via a thin insulating layer of SiO_2.

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



Symbols:

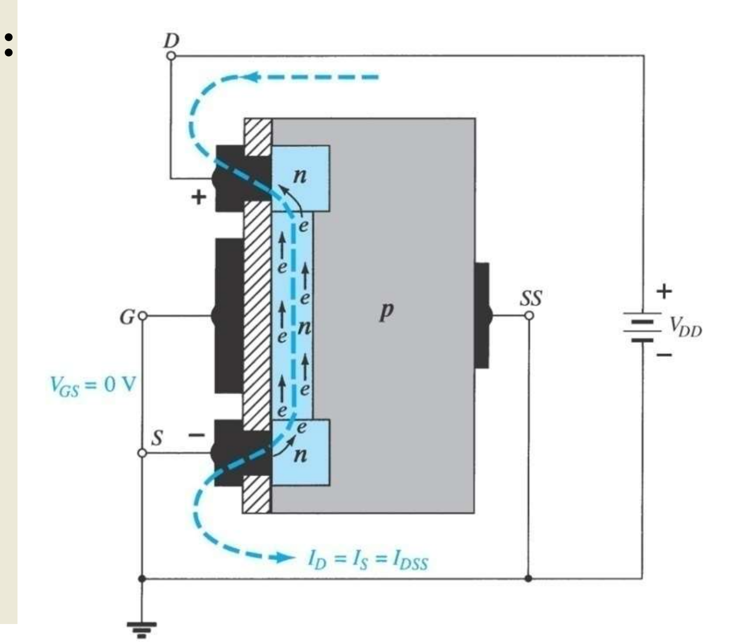
(a) *n-channel*
(b) *p-channel*



Basic Depletion-Type MOSFET Operation

A depletion-type MOSFET can operate in two modes:

- Depletion mode
- Enhancement mode

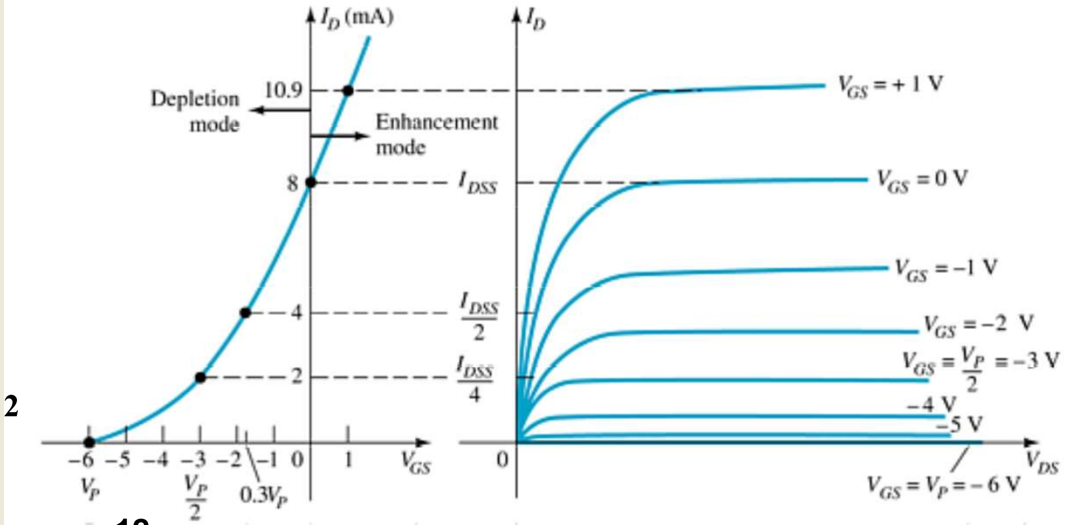


Depletion Mode

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

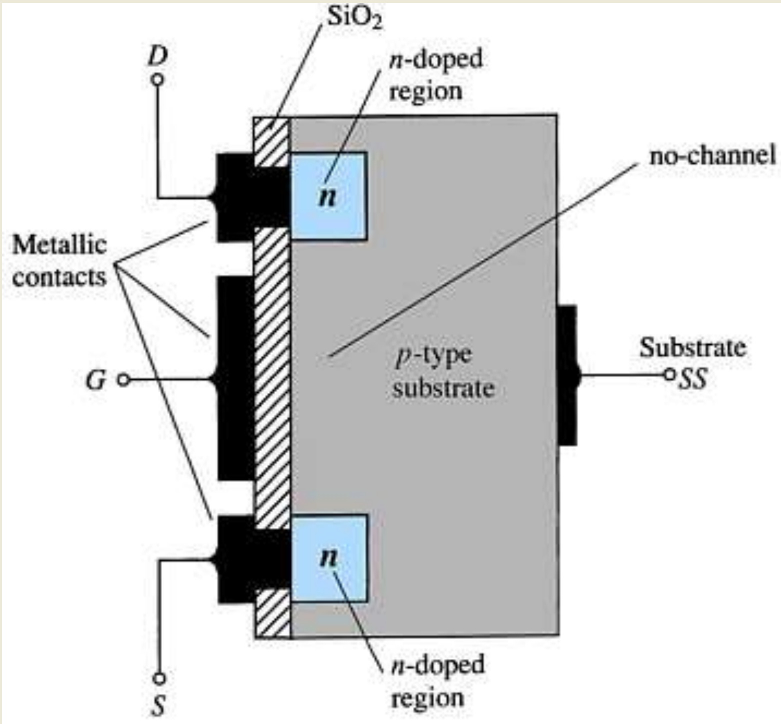
- $V_{GS} > 0V$
- I_D increases above I_{DSS}
- The formula used to plot the transfer curve still applies:

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

Note that V_{GS} is now a positive polarity

Enhancement-type MOSFET

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



Symbols:

(a) ***n-channel***
(b) ***p-channel***

(a) (b)

FET Amplifiers and Analyses

FET Biasing

- Excellent voltage gain
- High input impedance
- Low-power consumption
- Good frequency range

FET Amplifiers

Step 1: DC analysis
Based on DC network:
- V_{GSQ}
- I_{DQ}
- V_{DSQ}

Using V_{GSQ} to determine g_m for AC equivalent model

Step 2: AC analysis
Based on AC network and AC equivalent model:
- Input impedance
- Output impedance
- Voltage gain

Three basic configurations for FET amplifiers

CS: Common Source Configuration

CG: Common Gate Configuration

Source Follower: Common Drain

JFET
- Fixed-Bias
- ***Self-Bias***
- Voltage-Divider Bias

Depletion-Type MOSFET
- ***Self-Bias***
- Voltage-Divider Bias

Enhancement-Type MOSFET
- Voltage-Divider Bias

3.5 Summary

1. A current-controlled device is one in which a current defines the operating conditions of the device, whereas a voltage-controlled device is one in which a particular voltage defines the operating conditions.
2. The maximum current for any JFET is labeled I_{DSS} and occurs when $V_{GS}=0V$.
3. The minimum current for any JFET occurs at pinch-off defined by $V_{GS}=V_P$.
4. The relationship between the drain current and the gate-to-source voltage of a JFET is a nonlinear one defined by Shockley's equation.
5. The transfer characteristics are characteristics of the device itself and are not sensitive to the network in which the JFET is employed.
6. The depletion-type MOSFET has the same transfer characteristics as a JFET for drain currents up to the I_{DSS} level and can exceed the I_{DSS}.
7. The transfer characteristics of the enhancement-type MOSFET can not define by Shockley's equation but rather by a nonlinear equation controlled by V_{GS}.

Chapter 3

➢ **Coursework**

- **Understanding DC & AC analyses for JFET Amplifier**

or

- **Understanding DC & AC analyses for MOSFET Amplifier**