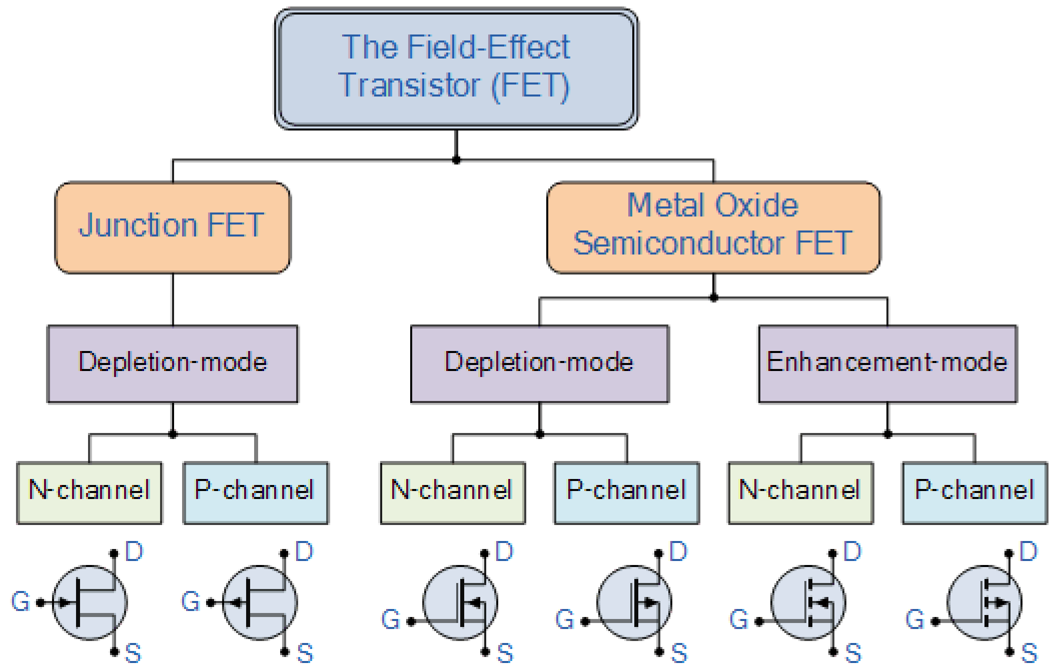
UNIT IV

UNIT IV Field Effect Transistor (FET)

JFET- Construction, Principle of Operation, Pinch-Off Voltage, Volt- Ampere Characteristic, Comparison of BJT and FET, FET as Voltage Variable Resistor, MOSFET, MOSFET as a capacitor.

4.1 Introduction to Field Effect Transistor

- A field effect transistor is a voltage controlled device i.e. the output characteristics of the device are controlled by input voltage. There are two basic types of field effect transistors:
  - Junction field effect transistor (JFET)
  - Metal oxide semiconductor field effect transistor (MOSFET)



4.2 Junction Field Effect Transistor (JFET)

- A JFET is a three terminal semiconductor device in which current conduction is by one type of carrier i.e. electrons or holes.
- It has three terminals namely Source (S), Drain (D) and Gate (G).
- The current conduction is controlled by means of an electric field between the gate and the conducting channel of the device.
- The JFET has high input impedance and low noise level.
- There are two types of JFET's namely N-channel JFET's and P-channel JFET's.
- Generally N-channel JFETs are more preferred than P-channel.

4.2.1 Symbols of JFET

- The symbol of N-channel and P-channel JFETs are shown in the figure 4.1.

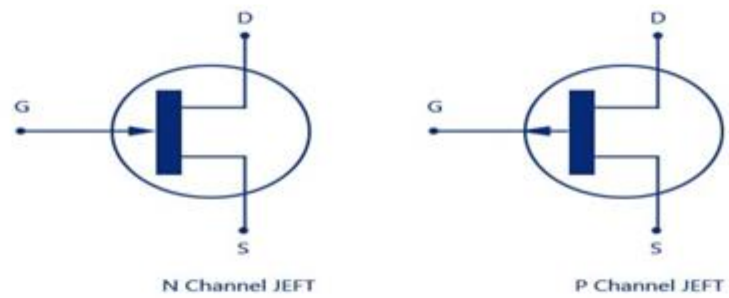


Fig. 4.1 Symbols of N - channel and P- channel JFET

- The vertical line in the symbol may be thought as channel and source S and drain D connected to the line.
- Note that the direction of the arrow at the gate indicates the direction in which the gate current flows.

4.2.2 Construction of JFET

- In an N-channel JFET an N-type silicon bar, referred to as the channel, has two smaller pieces of P-type silicon material diffused on the opposite sides of its middle part, forming P-N junctions, as illustrated in figure 4.2.

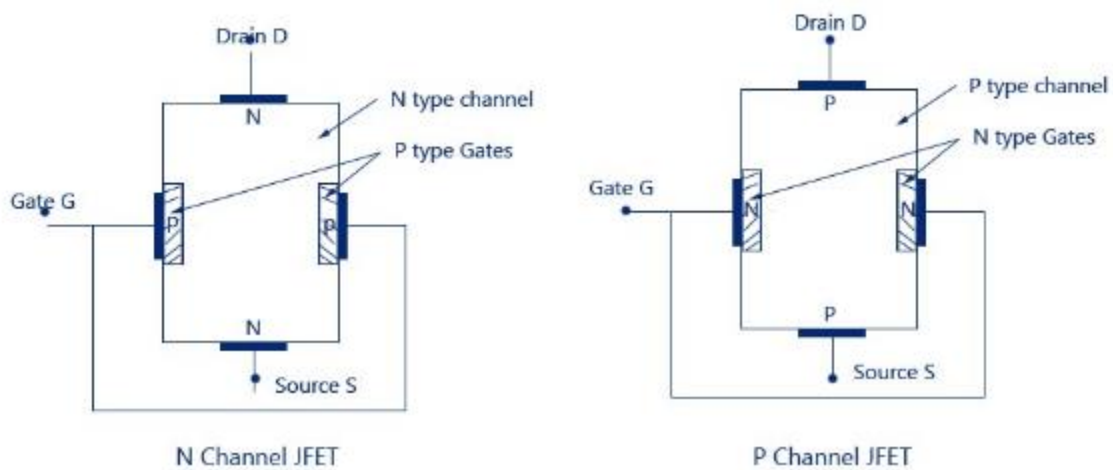


Fig. 4.2 Construction of JFET

- The two P-N junctions forming diodes or gates are connected internally and a common terminal, called the gate terminal, is brought out.
- Ohmic contacts (direct electrical connections) are made at the two ends of the channel—one lead is called the Source terminal S and the other Drain terminal D.
- **Source** – The terminal through which the majority carriers enter the channel, is called the source terminal S
- **Drain** – The terminal, through which the majority carriers leave the channel, is called the drain terminal D

- **Channel** – The region between the source and drain, sandwiched between the two gates is called the channel and the majority carriers move from source to drain through this channel.
- The silicon bar behaves like a resistor between its two terminals D and S.
- The gate terminal is used to control the flow of current from source to drain.
- In the figure above, the gate is P-region, while the source and the drain are N-regions.
- Because of this, a JFET is similar to two diodes.
- The gate and the source form one of the diodes, and the drain form the other diode.
- These two diodes are usually referred as the gate-source diode and the gate-drain diode.
- Since JFET is a silicon device, it takes only 0.7 volts for forward bias to get significant current in either diode.

4.2.3 Polarities of JFET

- Fig.4.3 shows the n-channel JFET polarities and the p-channel JFET polarities.
- In each case, the voltage between the gate and source is such that the gate is reverse biased.
- The source and the drain terminals are interchangeable.

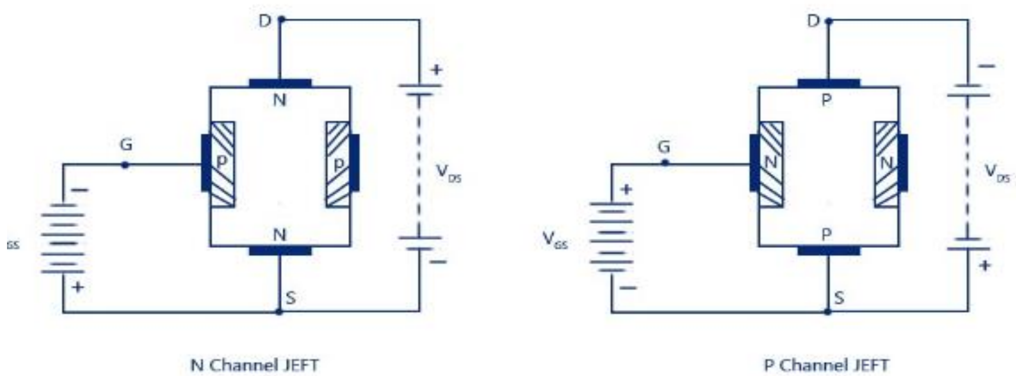


Fig. 4.3 Polarities of JFET

4.2.4 Principle of operation n channel JFET

- The working of JFET can be explained as follows.

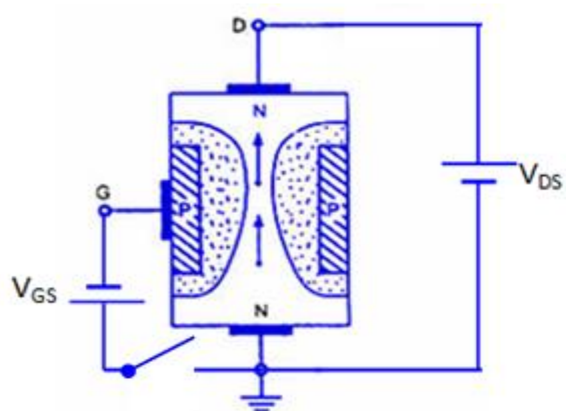


Fig. 4.4 Operation of JFET when V_{GS}=0

Case-i:

- When a voltage V_{DS} is applied between drain and source terminals and voltage on the gate is zero as shown in fig.4.4, then two pn junctions at the sides of the bar establish depletion layers.
- The electrons will flow from source to drain through a channel between the depletion layers.
- The size of the depletion layers determines the width of the channel and hence current conduction through the bar.

Case-ii:

- When a reverse voltage V_{GS} is applied between gate and source terminals, then width of depletion layer is increased which is shown in fig. 4.4.
- This reduces the width of conducting channel, thereby increasing the resistance of n-type bar.
- Consequently, the current from source to drain is decreased.
- On the other hand, when the reverse bias on the gate is decreased, the width of the depletion layer also decreases.
- This increases the width of the conducting channel and hence source to drain current

4.2.5 Principle of operation p channel JFET

- A p channel JFET operates in the same manner as an n-channel JFET except that channel current carries will be the holes instead of electrons and polarities of V_{GS} and V_{DS} are reversed.

4.3 Volt-Ampere characteristics of JFET

- There are two types of static characteristics viz.
  - Output or drain characteristics
  - Transfer characteristics

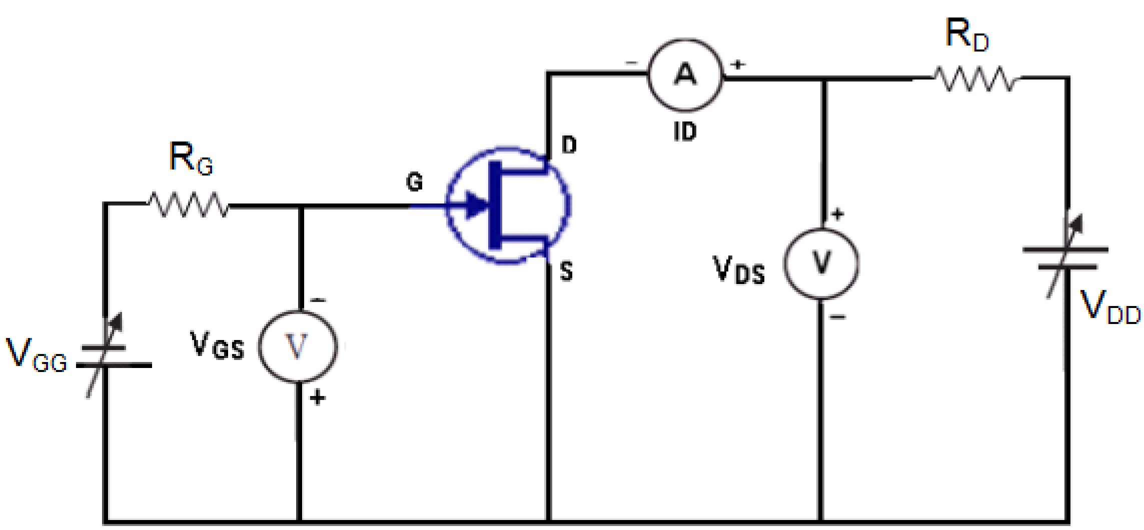


Fig. 4.5 Characteristics of JFET

4.3.1 Output or Drain Characteristics

- The curve drawn between drain current I_D and drain-source voltage V_{DS} by keeping gate-to source voltage V_{GS} as constant as shown in figure 4.6.

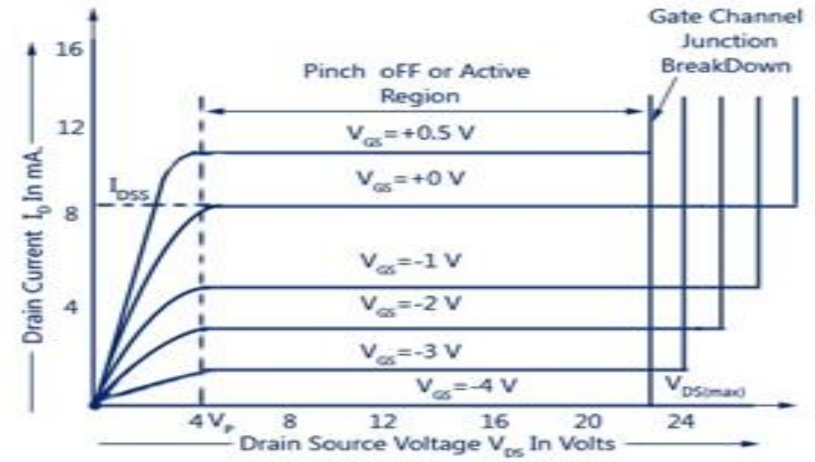


Fig. 4.6 Waveforms of Drain characteristics of JFET

Pinch-off voltage

The value of voltage V_{DS} at which the channel is pinched off (i.e. all the free charges from the channel get removed) and the drain current I_D attains a constant value is called as pinch-off voltage V_P.

- For small applied voltage V_{DS}, the n-type bar acts as a simple semiconductor resistor and the drain current increases linearly with the increase in V_{DS}, upto the knee point.
- So with the increase in V_{DS}, the conducting portion of the channel begins to constrict more at the drain end. Eventually a voltage V_{DS} is reached at which the channel is pinched off.
- The drain current I_D no longer increases with the increase in V_{DS}. It approaches a constant saturation value.
- The drain current in the pinch-off region with V_{GS} = 0 is referred to the drain-source saturation current (I_{DSS}).
- Drain current in the pinch-of region is given by Shockley's equation

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

$$I_D = I_{DSS}\left[1 - \frac{V_{GS}}{\mathrm{Vp}}\right]^2$$

Where

I_D = Drain current at given VGS
I_{DSS} = Drain-source saturation current
V_{GS} = Gate-source Voltage
$V_{GS(off)}$ = Gate-source cut off voltage
V_P = Pinch off voltage

4.3.2 Transfer characteristics

- The transfer characteristics for a JFET can be determined experimentally, keeping drain-source voltage V_{DS} as constant and determining drain current I_D for various values of gate-source voltage, V_{GS}.
- The circuit diagram is shown in fig. 4.5.

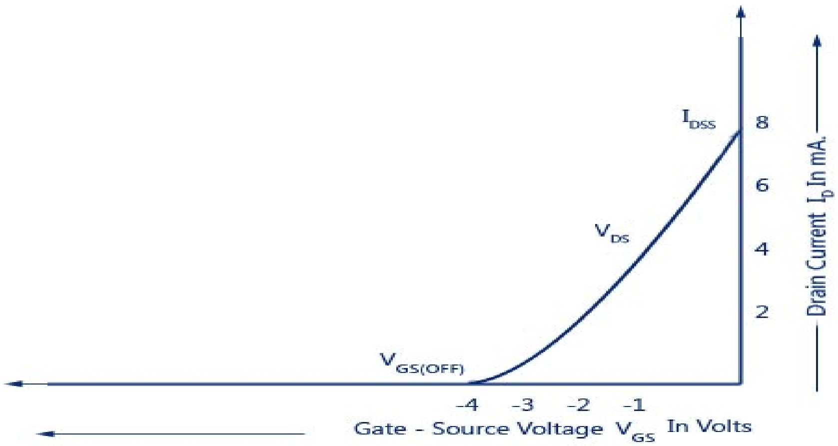


Fig. 4.7 Transfer characteristics

- The curve is plotted between gate-source voltage, V_{GS} and drain current, I_D, as illustrated in fig. 4.7.
- It is observed that
    - Drain current decreases with the increase in negative gate-source bias
    - Drain current, $I_D = I_{DSS}$ when $V_{GS} = 0$
    - Drain current, $I_D = 0$ when $V_{GS} = V_p$

4.5 JFET parameters

- The JFET parameters are the major components of low frequency small signal model for JFET.
- The change in the drain current due to change in gate to source voltage can be determined using the transconductance factor g_m. It is given as

$$\boxed{g_m = \frac{\Delta I_d}{\Delta V_{GS}}}$$

- Another important parameter of JFET is drain resistance r_d. It is given by

$$\boxed{r_d = \left.\frac{\Delta V_{DS}}{\Delta I_D}\right|_{V_{GS}=\text{ constant}}}$$

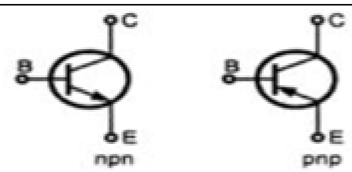
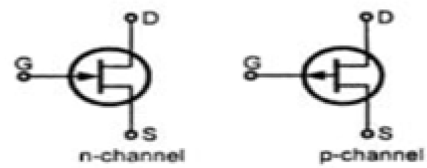
- The amplification factor μ of an FET is defined as

$$\boxed{\mu = \left.\frac{\Delta V_{DS}}{\Delta V_{gS}}\right|_{I_D=\text{const}}}$$

- The parameters g_m, r_d and μ are related by,

$$\boxed{\mu = r_d\, g_m}$$

4.6 Comparison BJT and FET

S. No.	Parameter	BJT	FET
1	Control Element	Current controlled device.	Voltage controlled device
2	Device type	Bipolar device	Unipolar device
3	Types	npn & pnp	n-channel & p-channel
4	Symbols		
5	Configurations	CE, CB, CC	CS, CG, CD
6	Input Resistance	Low	High
7	Size	Bigger	Smaller
8	Sensitivity	High	Low
9	Thermal Stability	Less	More
10	Thermal runaway	Exists	Does not exists
11	Thermal noise	More	Less

4.8 FET as Voltage Variable Resistor

- Let us consider the drain characteristics of FET as shown in the Fig. 4.14.

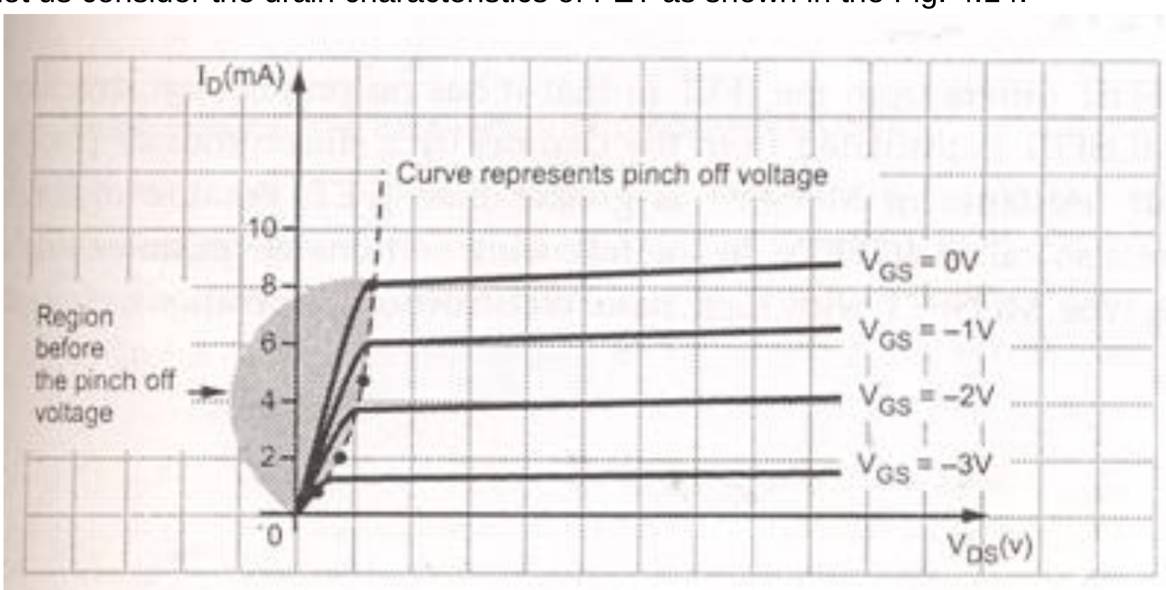


Fig. 4.14 Drain characteristics of FET

- In this characteristic we can see that in the region before pinch off voltage, drain characteristics is Linear, i.e., FET operation is linear.
- In this region the FET is useful as a voltage-controlled resistor, i.e., the drain to source resistance is controlled by the bias voltage V_{GS}.
- The operation of FET in this region is useful in most Linear applications of FET.
- In such an application the FET is also referred to as a Voltage Variable Resistor (VVR) or Voltage Dependent Resistor (VDR).
- The variation of the r_d with V_{GS} can be closely approximated by the empirical expression,

$$r_d = \frac{r_0}{1 - KV_{GS}}$$

Where r_o = drain resistance at zero gate bias, and K = a constant, dependent upon FET type.

- Thus, small signal FET drain resistance r_d varies with applied gate voltage V_{GS} and FET acts like a variable passive resistor.
- For example, the VVR can be used in Automatic Gain Control (AGC) circuit of a multistage amplifier.

4.9 Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

- The field effect transistor that can be operated to enhance the width of the channel. Such a FET is called MOSFET.
- The MOSFET differs from the JFET in that it has no p-n junction structure.
- The gate of the MOSFET is insulated from the channel by a silicon dioxide (SiO_2) layer. So MOSFETs are also called as Insulate Gate FET (IGFET)
- Due to this the input resistance of MOSFET is greater than JFET.

4.9.1 Types of MOSFETs

- **Depletion mode MOSFET or D-MOSFET:**
- **Enhancement mode MOSFET or E-MOSFET:**

4.10 D-MOSFET

- There are two types of D-MOSFETs such as:
  - n-channel D-MOSFET
  - p-channel D-MOSFET

4.10.1 Construction of n-channel D-MOSFET

- A thin layer of metal oxide, usually silicon dioxide (SiO2) is deposited over a small portion of the channel. A metallic gate is deposited over the oxide layer.
- As SiO2 is an insulator, therefore, gate is insulated from the channel.
- The substrate is connected to the source internally so that a MOSFET has three terminals such as Source (S), Gate (G) and Drain (D).

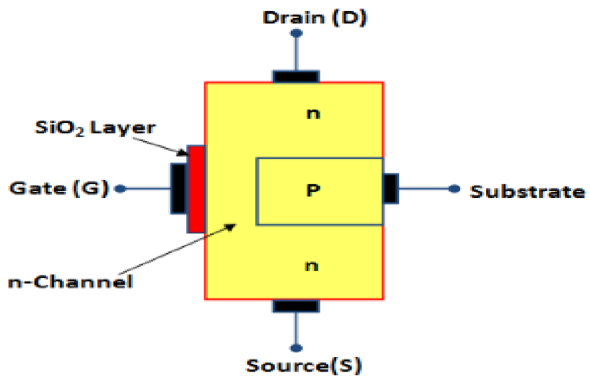


Fig. 4.15 construction of n-channel D-MOSFET

- Since the gate is insulated from the channel, we can apply either negative or positive voltage to the gate.
- Therefore, D-MOSFET can be operated in both depletion-mode and enhancement-mode.
- The p-type substrate constricts the channel between the source and drain so that only a small passage remains at the left side.
- Electrons flowing from source (when drain is positive w.r.t. source) must pass through this narrow channel.

4.10.2 Symbol for n-channel D-MOSFET

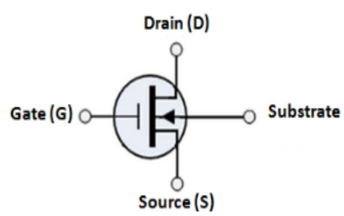


Fig. 4.16 Symbol for n-channel D-MOSFET

- The symbol for n channel D MOSFET is shown in Fig. 4.16 which is having four terminals.
- The substrate is connected to the source as shown in Fig. 4.17. This gives rise to a three terminal device.

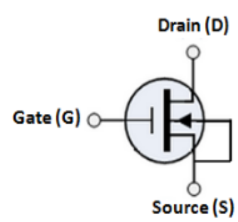


Fig. 4.17 Symbol for n-channel D-MOSFET

4.10.3 Operation of n-channel D- MOSFET

- Fig.4.18 (a) shows the circuit for operation of n-channel D-MOSFET.

- The gate forms a small capacitor. One plate of this capacitor is the gate and the other plate is the channel with metal oxide layer as the dielectric.
- When gate voltage is changed, the electric field of the capacitor changes which in turn changes the resistance of the n-channel.
- Gate voltage is negative, hence there are electrons on the gate as shown in fig. 4.18 (b).
- Since the gate voltage is negative, it induces positive charges (free holes) in the channel by the capacitor action as shown in fig. 4.18 (b).
- These free holes are added to free electrons in the channel, thus the total number of free electrons in the n–channel is decreased.
- Hence a negative gate voltage decreases the conductivity of the channel.

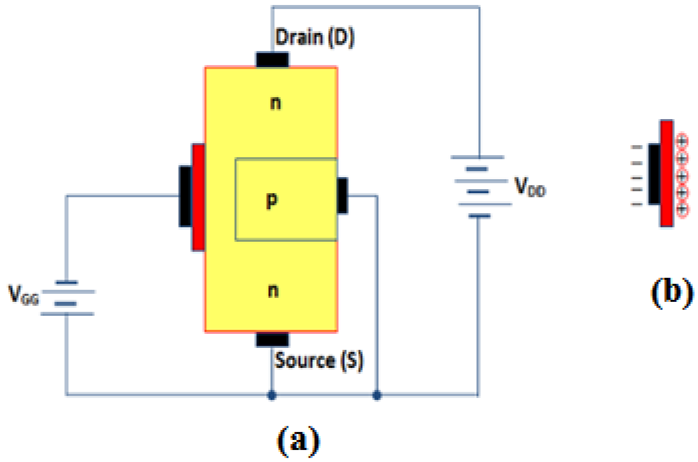


Fig. 4.18 (a) Operation of n channel D- MOSFET (b) Capacitor

- The greater the negative voltage on the gate, the lesser is the current from source to drain.
- Thus by changing the negative voltage on the gate, we can vary the resistance of the n-channel and hence the current from source to drain.
- In a D-MOSFET, the source to drain current is controlled by the electric field of capacitor formed at the gate.
- D-MOSFET has very low input capacitance, which makes the D-MOSFET useful in high frequency applications.

4.10.4 Volt-Ampere characteristics of D-MOSFET

- There are two types of static characteristics viz.
    - Output or drain characteristics
    - Transfer characteristics
- In general, any MOSFET is seen to exhibit three operating regions viz.,
- **Cut-Off Region:**
    - Cut-off region is a region in which the MOSFET will be OFF as there will be no current flow through it.
    - In this region, MOSFET behaves like an open switch and is thus used when they are required to function as electronic switches.

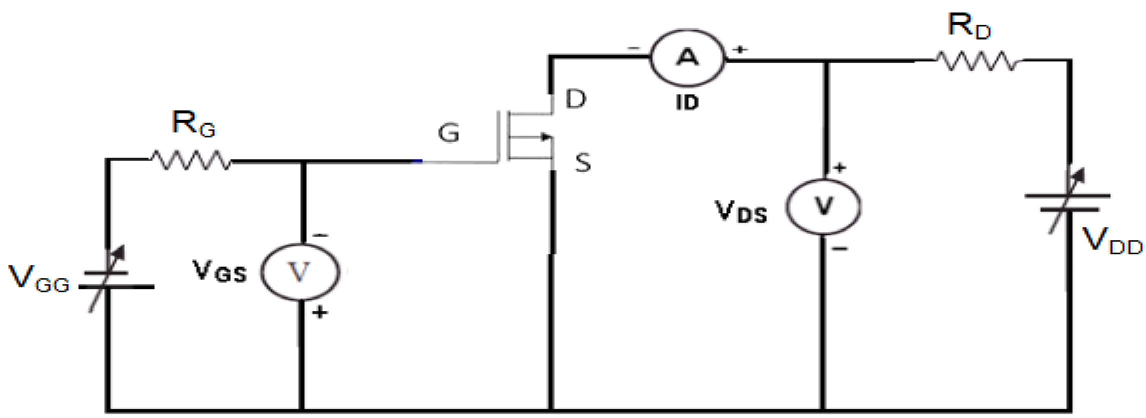


Fig. 4.19 Characteristics of D-MOSFET

- **Ohmic or Linear Region:**
  - Ohmic or linear region is a region where in the current I_{DS} increases with an increase in the value of V_{DS}.
  - When MOSFETs are made to operate in this region, they can be used as amplifiers.
- **Saturation Region:**
  - In saturation region, the MOSFETs have their I_{DS} constant inspite of an increase in V_{DS} and occur once when V_{DS} exceeds the value of pinch-off voltage V_P.
  - Under this condition, the device will act like a closed switch through which a saturated value of I_{DS} flows.
  - As a result, this operating region is chosen whenever MOSFETs are required to perform switching operations.

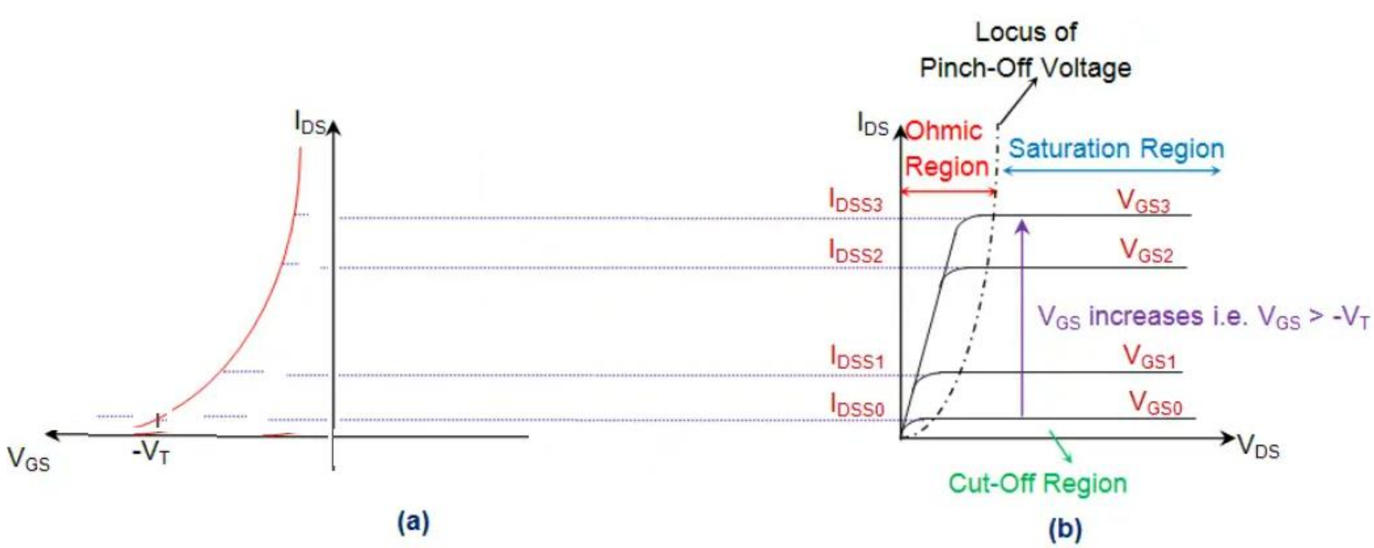


Fig. 4.20 n-channel Depletion-type MOSFET a) transfer characteristics b) output characteristics

- The transfer characteristics of n-channel depletion MOSFET shown by Figure 4.20 (a) indicate that the device has a current flowing through it even when V_{GS} is 0V.

- This indicates that these devices conduct even when the gate terminal is left unbiased, which is further emphasized by the V_{GS0} curve of Figure 4.20 (b).
- Under this condition, the current through the MOSFET is seen to increase with an increase in the value of V_{DS} (Ohmic region) until V_{DS} becomes equal to pinch-off voltage V_P.
- After this, I_{DS} will get saturated to a particular level I_{DSS} (saturation region of operation) which increases with an increase in V_{GS} i.e. $I_{DSS3} > I_{DSS2} > I_{DSS1}$, as $V_{GS3} > V_{GS2} > V_{GS1}$.
- Further, the locus of the pinch-off voltage also shows that V_P increases with an increase in V_{GS}.
- However it is to be noted that, if one needs to operate these devices in cut-off state, then it is required to make V_{GS} negative and once it becomes equal to $-V_T$, the conduction through the device stops ($I_{DS} = 0$) as it gets derived of its n-type channel (Figure 4.20 a).

4.11 E-MOSFET

- There are two types of E-MOSFETs such as:
  - n-channel E-MOSFET
  - p-channel E-MOSFET

4.11.1 Construction of n-channel E-MOSFET

- Fig.4.21 shows the constructional details of n-channel E-MOSFET.
- Its gate construction is similar to that of D-MOSFET.
- The E-MOSFET has no channel between source and drain. The substrate extends completely to the SiO_2 layer so that no channel exists.

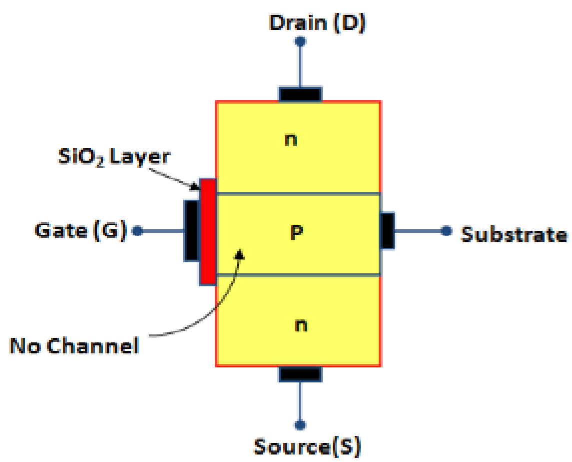


Fig. 4.21 Construction of n-channel E-MOSFET

- The E-MOSFET requires a proper gate voltage to form a channel, called induced channel between the source and the drain.
- It operates only in the enhancement mode and has no depletion mode.
- Only by applying VGS of proper magnitude and polarity, the device starts conducting.
- The minimum value of V_{GS} of proper polarity that turns on the E-MOSFET is called threshold voltage [$V_{GS(th)}$].

- The n-channel device requires positive V_{GS} ($\geq V_{GS(th)}$) and the p-channel device requires negative V_{GS} ($\geq V_{GS(th)}$).

4.11.2 Symbol of n-channel E-MOSFET

- Fig. 4.22 shows the schematic symbols for n-channel E-MOSFET.

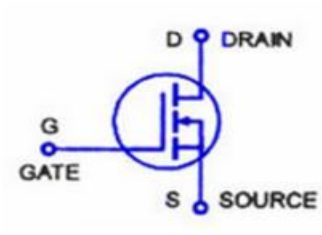


Fig. 4.22 Symbol of n-channel E-MOSFET

4.11.3 Operation of n-channel E-MOSFET

- Fig. 4.23 (a) shows the circuit of operation of n-channel E-MOSFET.
- Again the gate acts like a capacitor. Since the gate is positive, it induces negative charges in the n-channel as shown in fig. 4.23 (b).
- These negative charges are the free electrons drawn into the channel.
- Because these free electrons are added to those already in the channel, the total number of free electrons in the channel is increased.

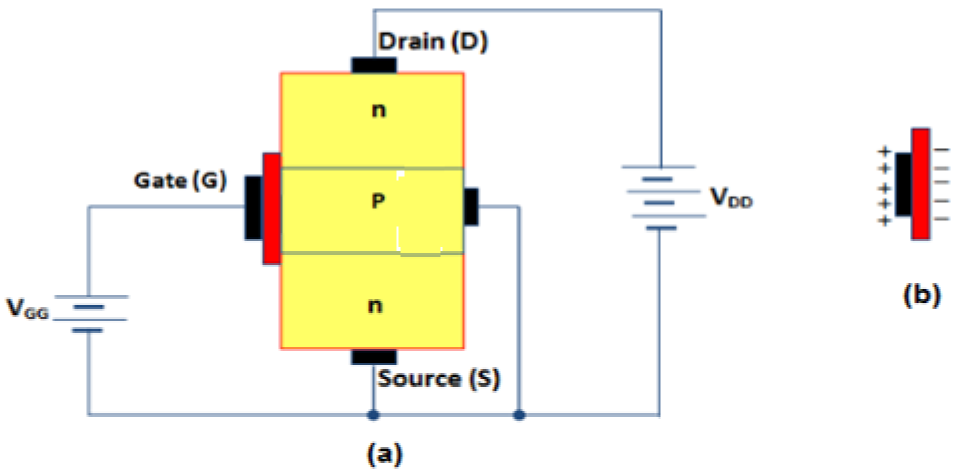


Fig. 4.23 (a) Operation of n-channel E-MOSFET (b) Capacitor

- Thus a positive gate voltage enhances or increases the conductivity of the channel.
- The greater the positive voltage on the gate, greater the conduction from source to drain.
- Thus by changing the positive voltage on the gate, we can change the conductivity of the channel.
- Because the action with a positive gate depends upon enhancing the conductivity of the channel, the positive gate operation is called enhancement mode.
- When V_{GS}= 0V, as shown in fig. 4.23 (a), there is no channel connecting source and drain.

- The p-substrate has only a few thermally produced free electrons (minority carriers) so that drain current is almost zero. For this reason, E-MOSFET is normally OFF when V_{GS} = 0V.
- When V_{GS} is positive, i.e gate is made positive as shown in fig. 4.23 (b), it attracts free electrons into the p region. The free electrons combine with the holes next to the SiO_2 layer.
- If V_{GS} is positive enough, all the holes touching the SiO_2 layer are filled and free electrons begin to flow from the source to drain.
- The effect is same as creating a thin layer of n-type material i.e. inducing a thin n-layer adjacent to the SiO_2 layer.
- Thus the E-MOSFET is turned ON and drain current I_D starts flowing from the source to the drain.
- The minimum value of V_{GS} that turns the E-MOSFET ON is called threshold voltage [$V_{GS(th)}$].
- When V_{GS} is less than $V_{GS(th)}$, there is no induced channel and the drain current I_D is zero.
- When V_{GS} is equal to $V_{GS(th)}$, the E-MOSFET is turned ON and the induced channel conducts drain current from the source to the drain.
- Beyond $V_{GS(th)}$, if the value of V_{GS} is increased, the newly formed channel becomes wider, causing to I_D to increase.
- If the value of V_{GS} decreases not less than $V_{GS(th)}$, the channel becomes narrower and I_D will decrease.

4.11.4 Volt-Ampere characteristics of E-MOSFET

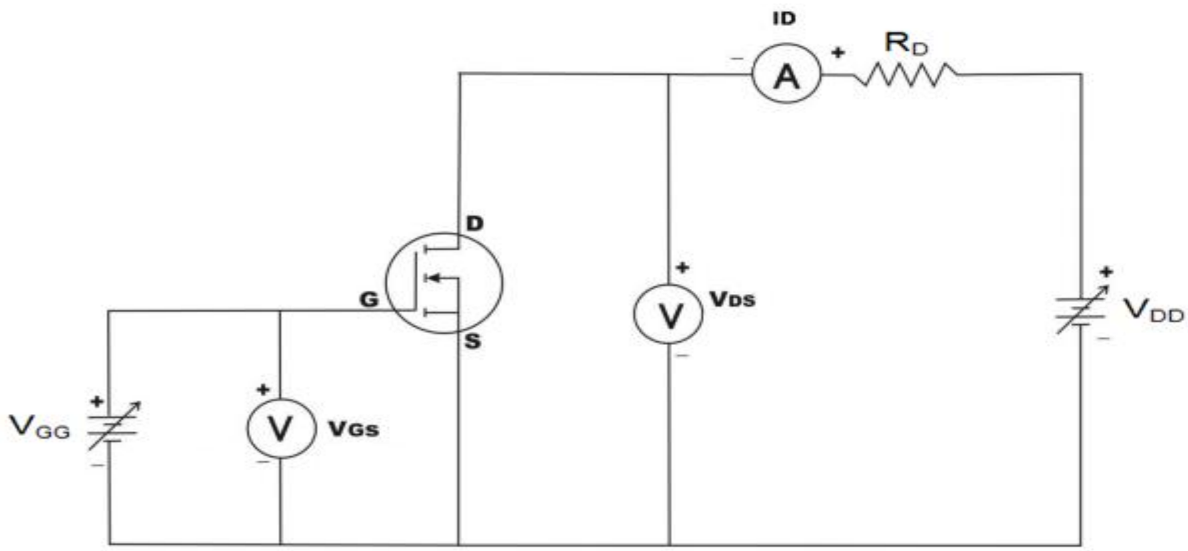


Fig. 4.24 Characteristics of E-MOSFET

- Figure 4.25 (a) shows the transfer characteristics (drain-to-source current I_{DS} versus gate-to-source voltage V_{GS}) of n-channel Enhancement-type MOSFETs.
- From this, it is evident that the current through the device will be zero until the V_{GS} exceeds the value of threshold voltage V_T.
- This is because under this state, the device will be void of channel which will be connecting the drain and the source terminals.

- Under this condition, even an increase in V_{DS} will result in no current flow as indicated by the corresponding output characteristics (I_{DS} versus V_{DS}) shown by Figure 4.25 (b).
- As a result this state represents nothing but the cut-off region of MOSFET's operation.
- Next, once V_{GS} crosses V_T, the current through the device increases with an increase in I_{DS} initially (Ohmic region) and then saturates to a value as determined by the VGS (saturation region of operation) i.e. as VGS increases, even the saturation current flowing through the device also increases.
- This is evident by Figure 4.25 (b) where I_{DSS2} is greater than I_{DSS1} as $V_{GS2} > V_{GS1}$, I_{DSS3} is greater than I_{DSS2} as $V_{GS3} > V_{GS2}$, so on and so forth.
- Further, Figure 4.25 (b) also shows the locus of pinch-off voltage (black discontinuous curve), from which V_P is seen to increase with an increase in V_{GS}.

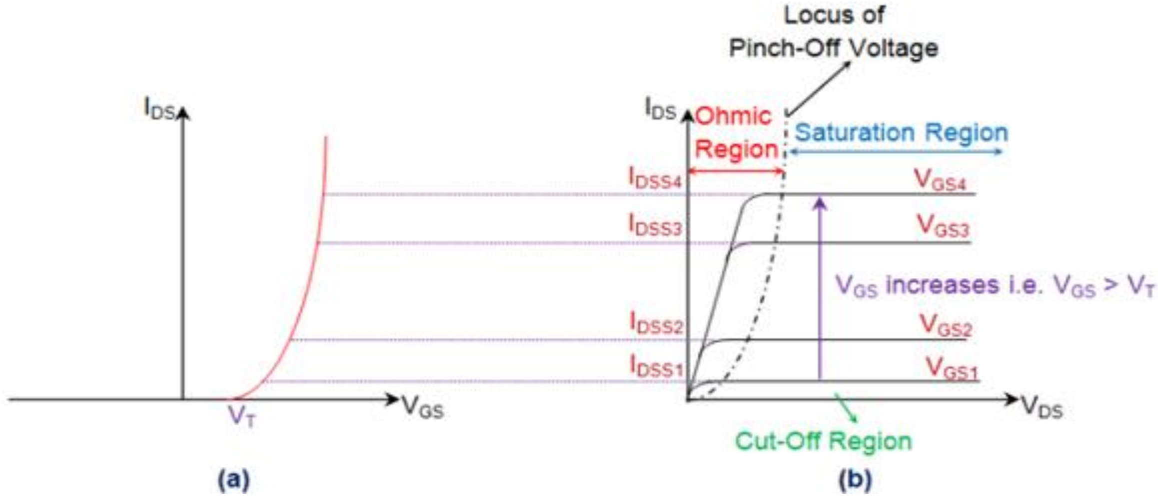


Fig. 4.25 n-channel Enhancement type MOSFET a) transfer characteristics b) output characteristics

4.12 MOSFET as a capacitor

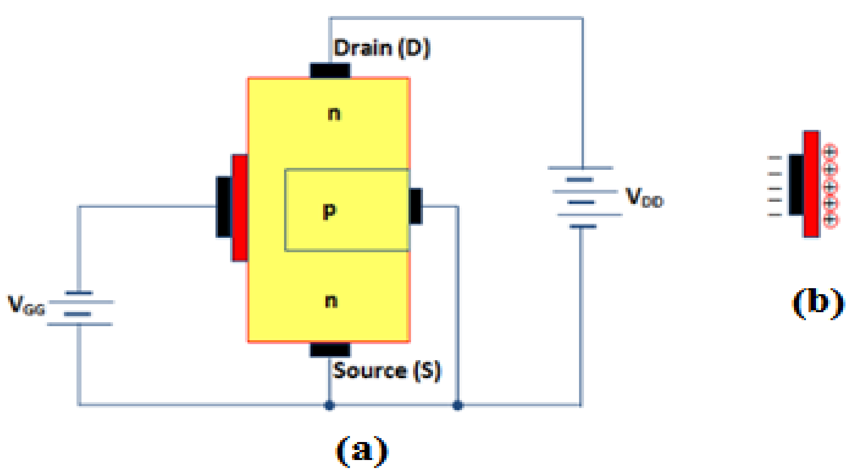


Fig. 4.26 MOSFET act as a Capacitor

- The gate of MOSFET forms a small capacitor which is shown in Fig. 4.26 (a).
- One plate of this capacitor is the gate terminal and the other plate is the channel (Area between Source and Drain) with metal oxide layer as the dielectric.
- Gate voltage is negative, hence there are electrons on the gate as shown in fig. 4.26 (b).
- Since the gate voltage is negative, it induces positive charges (free holes) in the channel by the capacitor action as shown in fig. 4.26 (b).
- When gate voltage is changed, the electric field of the capacitor changes which in turn changes the resistance of the n-channel.