Field Effect Transistor

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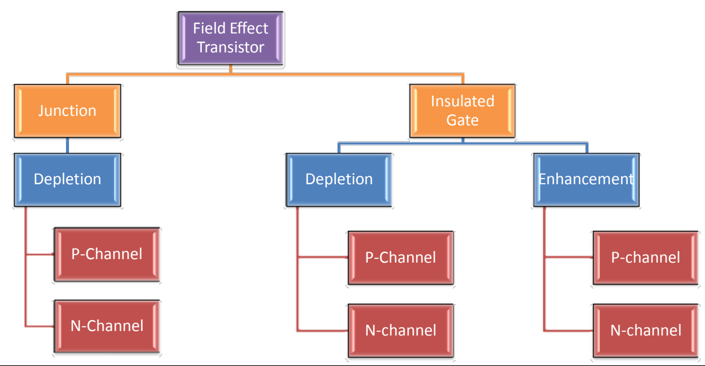
Field Effect Transistor

- In the **Bipolar Junction Transistor (BJT),** the output Collector current of the transistor is proportional to input current flowing into the base terminal of the device, thereby making the bipolar transistor a current operated device as a smaller current can be used to switch a larger load current.
- The **Field Effect Transistor**, or simply **FET** however, uses the voltage that is applied to their input terminal, called the Gate to control the current flowing through them resulting in the output current being proportional to the input voltage.

Field Effect Transistor

- As their operation relies on an electric field (hence the name field effect) generated by the input Gate voltage, this then makes the **Field Effect Transistor** a voltage operated device.
- There are two main types of field effect transistor, the **Junction Field Effect Transistor** or **JFET** and the **Insulated-Gate Field Effect Transistor** or **IGFET**, which is more commonly known as the standard **Metal Oxide Semiconductor Field Effect Transistor** or **MOSFET**.

Field Effect Transistor



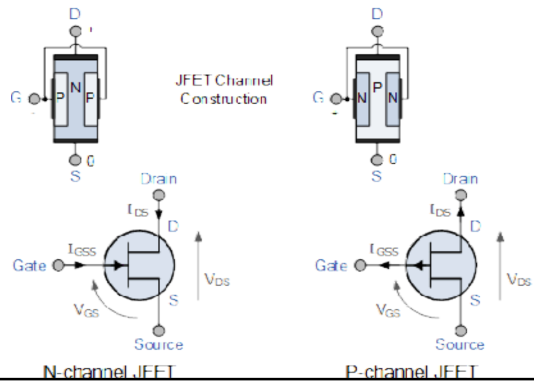
Junction Field Effect Transistor

- The functioning of Junction Field Effect Transistor depends upon the flow of majority carriers (electrons or holes) only.
- Based on majority carriers, there are two types of JFETs commonly used in the field semiconductor devices:
  - **N-Channel JFET** and
  - **P-Channel JFET**.

N-Channel JFET

- It has a thin layer of N type material formed on P type substrate. Then the gate is formed on top of the N channel with P type material.
- At the end of the channel and the gate, lead wires are attached and the substrate has no connection.
- Following figure shows the crystal structure and schematic symbol of an N-channel JFET.

N- & P-Channel JFET



P-Channel JFET

- It has a thin layer of P type material formed on N type substrate.
- The gate is formed on top of the P channel with N type material.
- At the end of the channel and the gate, lead wires are attached. Rest of the construction details are similar to that of N- channel JFET.
- The preceding figure shows the crystal structure and schematic symbol of an N-channel JFET.

Junction Field Effect Transistor

- Basically, JFETs consist of an **N** type or **P** type silicon bar containing PN junctions at the sides.
  - **Gate** – By using diffusion or alloying technique, both sides of N type bar are heavily doped to create PN junction. These doped regions are called gate (G).
  - **Source** – It is the entry point for majority carriers through which they enter into the semiconductor bar.
  - **Drain** – It is the exit point for majority carriers through which they leave the semiconductor bar.
  - **Channel** – It is the area of N type material through which majority carriers pass from the source to drain.

Parameters of JFET

- The main parameters of JFET are –
  - AC drain resistance (r_d)
  - Trans-conductance (g_m)
  - Amplification factor (μ)

Parameters of JFET

AC drain resistance (r_d) –

- It is the ratio of change in the drain source voltage (ΔV_{DS}) to the change in drain current (ΔI_D) at constant gate-source voltage (V_{GS}).
- It can be expressed as,

$$r_d = \frac{\Delta V_{DS}}{\Delta I_D}\bigg|_{V_{GS}}$$

Parameters of JFET

Transconductance (g_m) –

- It is the ratio of change in drain current (ΔI_D) to the change in gate source voltage (ΔV_{GS}) at constant drain-source voltage (V_{DS}).
- It can be expressed as,

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}}\bigg|_{V_{DS}}$$

Parameters of JFET

Amplification Factor (μ) –

- It is the ratio of change in drain-source voltage (ΔV_{DS}) to the change in gate source voltage (ΔV_{GS}) constant drain current (I_D).
- It can be expressed as,

$$\mu = \left.\frac{\Delta V_{DS}}{\Delta V_{GS}}\right|_{I_D}$$

Relation between JFET parameters

- Since I_D depends on V_{DS} and V_{GS},

$$I_D = f(V_{DS}, V_{GS})$$

$$dI_D = \left(\frac{\partial I_D}{\partial V_{DS}}\right)_{V_{GS}} dV_{DS} + \left(\frac{\partial I_D}{\partial V_{GS}}\right)_{V_{DS}} dV_{GS}$$

- Differentiating *wrt* V_{GS},

$$\frac{dI_D}{dV_{GS}} = \left(\frac{\partial I_D}{\partial V_{DS}}\right)_{V_{GS}} \left(\frac{dV_{DS}}{dV_{GS}}\right) + \left(\frac{\partial I_D}{\partial V_{GS}}\right)_{V_{DS}}$$

Relation between JFET parameters

- If I_D is constant,

$$0 = \left(\frac{\partial I_D}{\partial V_{DS}}\right)_{V_{GS}} \left(\frac{\partial V_{DS}}{\partial V_{GS}}\right)_{I_D} + \left(\frac{\partial I_D}{\partial V_{GS}}\right)_{V_{DS}}$$

$$0 = \left(\frac{1}{r_D}\right)(-\mu) + g_m$$

- Therefore,

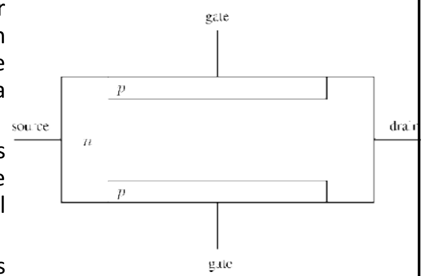
$$\mu = g_m \times r_D$$

JFET Construction and Operation

- In an *n* channel JFET an *n*-type channel is formed between two *p*-type layers which are connected to the gate.
- Majority carrier electrons flow from the source and exit the drain, forming the drain current.
- The *pn* junction is reverse biased during normal operation, and this widens the depletion layers which extend into the *n* channel only (since the doping of the *p* regions is much larger than that of the *n* channel).
- As the depletion layers widen, the channel narrows, restricting current flow.

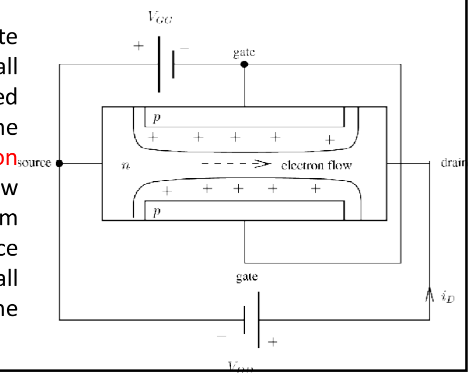
JFET Construction and Operation

- The cross sectional diagram shows an N-type semiconductor channel with a *n*-type region called the Gate diffused into the N-type channel forming a reverse biased PN-junction.
- It is this junction which forms the *depletion region* around the Gate area when no external voltages are applied.
- JFETs are therefore known as depletion mode devices.



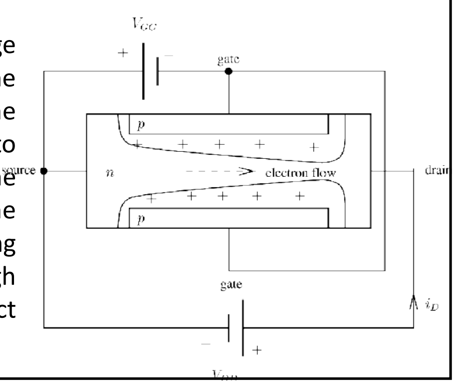
JFET Construction and Operation

- With no external Gate voltage (V_G = 0), and a small voltage (V_{DS}) applied between the Drain and the Source, maximum saturation current (I_{DSS}) will flow through the channel from the Drain to the Source restricted only by the small depletion region around the junctions.



JFET Construction and Operation

- If a small negative voltage ($-V_{GS}$) is now applied to the Gate the size of the depletion region begins to increase reducing the overall effective area of the channel and thus reducing the current flowing through it, a sort of squeezing effect takes place.



JFET Construction and Operation

- So by applying a reverse bias voltage increases the width of the depletion region which in turn reduces the conduction of the channel.
- As the Gate voltage ($-V_{GS}$) is made more negative, the width of the channel decreases until no more current flows between the Drain and the Source and the FET is said to be pinched-off (similar to the cut-off region for a BJT).
- The voltage at which the channel closes is called the pinch-off voltage, (V_P).

JFET Construction and Operation

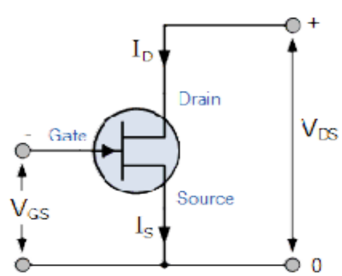
- In this pinch-off region the Gate voltage, V_{GS} controls the channel current and V_{DS} has little or no effect.
- The result is that the FET acts more like a voltage controlled resistor which has zero resistance when $V_{GS} = 0$ and maximum ON resistance (r_{DS}) when the Gate voltage is very negative.
- Under normal operating conditions, the JFET gate is always negatively biased relative to the source.

JFET Construction and Operation

- It is essential that the Gate voltage is never positive since if it is all the channel current will flow to the Gate and not to the Source, the result is damage to the JFET.
- The P-channel **JFET** operates exactly the same as the N-channel above, with the following exceptions:
  - Channel current is positive due to holes,
  - The polarity of the biasing voltage needs to be reversed.

V-I curves of a JFET

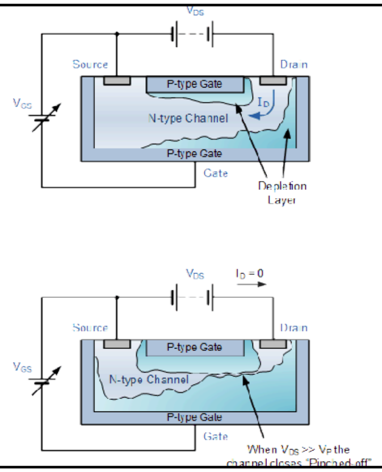
- The voltage V_{GS} applied to the Gate controls the current flowing between the Drain and the Source terminals.
- V_{GS} refers to the voltage applied between the Gate and the Source while V_{DS} refers to the voltage applied between the Drain and the Source.

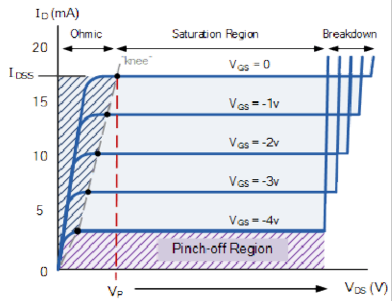


V-I curves of a JFET

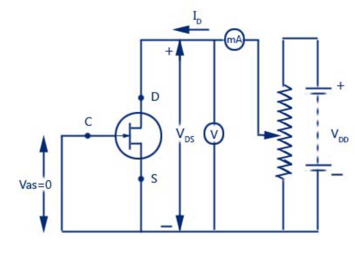
- Because a **JFET** is a voltage controlled device, No current flows into the gate! then the Source current (I_S) flowing out of the device equals the Drain current flowing into it and therefore ($I_D = I_S$).
- The characteristics curves example shown above, shows the four different regions of operation for a JFET and these are given as:

V-I curves of a JFET

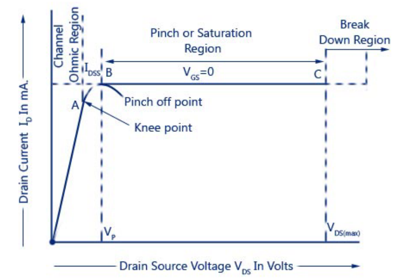




Drain Characteristics – with Shorted Gate

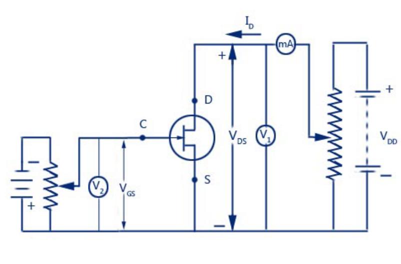


Circuit Diagram for Determining Drain Characteristic with Shorted Gate for An N-Channel JFET

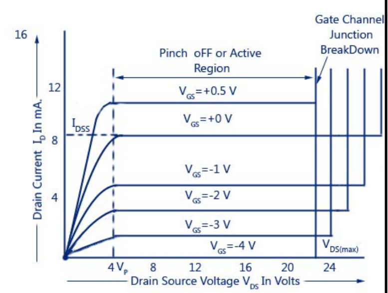


jFET Drain Characteristic With Shorted Gate

Drain Characteristics – with Shorted Gate



Circuit Diagram for Determining Drain Characteristic with External-Bias for An N-Channel JFET



Drain Characteristic with External-Bias

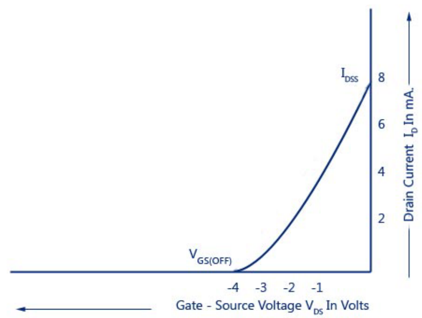
V-I curves of a JFET

- The Drain current is zero when $V_{GS} = V_P$. For normal operation, V_{GS} is biased to be somewhere between V_P and 0.
- Then we can calculate the Drain current, I_D for any given bias point in the saturation or active region.

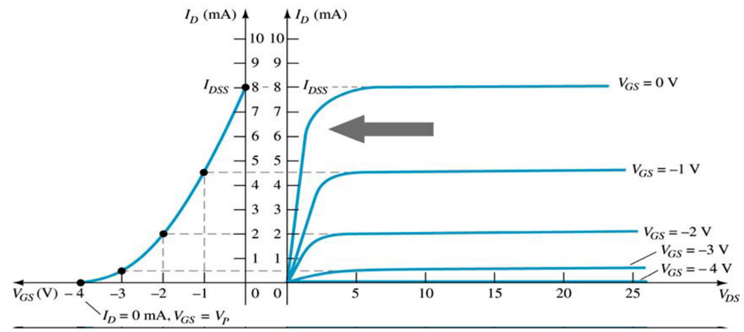
$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

- Note that the value of the Drain current will be between zero (pinch-off) and I_{DSS}(maximum current).

Transfer Characteristics



Transfer & Drain Characteristics



V-I curves of a JFET

- **Ohmic Region** – When V_{GS} = 0 the depletion layer of the channel is very small and the JFET acts like a voltage controlled resistor.
- **Cut-off Region** – This is also known as the pinch-off region were the Gate voltage, V_{GS} is sufficient to cause the JFET to act as an open circuit as the channel resistance is at maximum.
- **Saturation or Active Region** – The JFET becomes a good conductor and is controlled by the Gate-Source voltage, (V_{GS}) while the Drain-Source voltage, (V_{DS}) has little or no effect.
- **Breakdown Region** – The voltage between the Drain and the Source, (V_{DS}) is high enough to causes the JFET's resistive channel to break down and pass uncontrolled maximum current.

Difference between BJT and FET

BJT

- It is a bipolar devices, in this transistor there is a flow of both majority & minority charge carriers.
- BJTs are current controlled.
- It consist of three terminals namely emitter, base and collector.

JFET

- It is a unipolar devices, in this transistor there are only the majority charge carriers flows.
- JFETs are voltage controlled.
- It consist of three terminals namely source, drain and gate.

Difference between BJT and FET

BJT

- BJTs are applicable for low current applications.
- They are overheated due to a negative temperature co-efficient.
- BJTs have a higher maximum frequency and a higher cutoff frequency.

JFET

- JFETs are applicable for low voltage applications.
- It has positive temperature coefficient, hence over heating prevented.
- JFETs have low to medium gain.

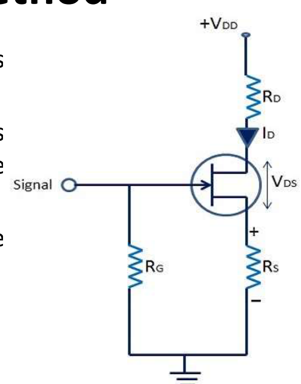
JFET Biasing

- There are two methods in use for biasing the JFET:
  - Self-Bias Method and
  - Potential Divider Method.

Self-Bias Method

- The figure shows the self-bias method of n-channel JFET.
- The drain current flows through R_s and produces the required bias voltage.
- Hence, R_s is the bias resistor. The voltage across bias resistor,

$$V_S = I_D R_S$$

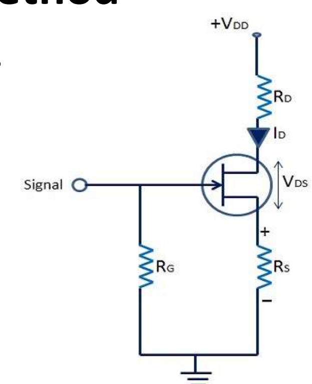


Self-Bias Method

- As we know, gate current is negligibly small, the gate terminal is at DC ground, $V_G = 0$,

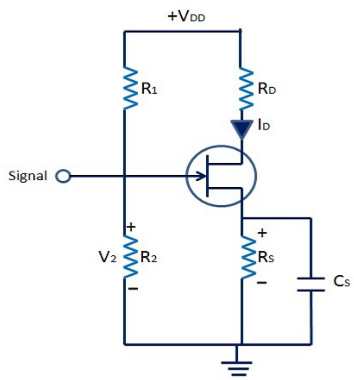
$$V_{GS} = V_G - V_S = 0 - I_D R_S$$

- or $V_{GS} = -I_D R_S$
- The V_{GS} keeps gate negative with respect to the source.



Voltage Divider Method

- The figure shows voltage divider method of biasing the JFETs.
- Here, resistor R_1 and R_2 form a voltage divider circuit across drain supply voltage (V_{DD}), and it is more or less identical to the one used in transistor biasing.



Voltage Divider Method

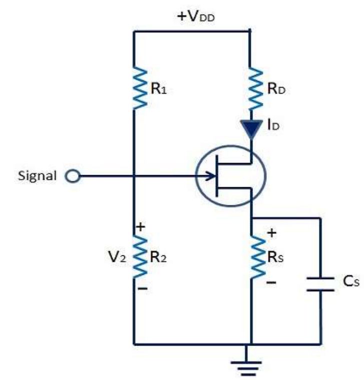
- The voltage across R_2 provides necessary bias.

$$V_2 = V_G = \frac{V_{DD}}{R_1 + R_2} \times R_2$$

$$V_2 = V_{GS} + I_D R_S$$

$$V_{GS} = V_2 - I_D R_S$$

- The circuit is so designed that V_{GS} is always negative.



Voltage Divider Method

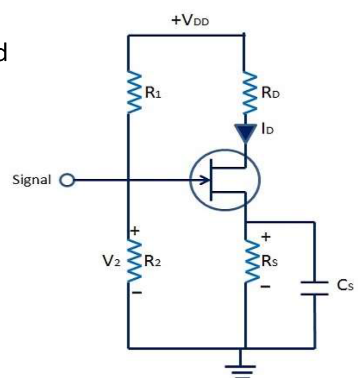
- The operating point can be found using the following formula.

$$V_{GS} = V_2 - I_D R_S$$

$$I_D = \frac{V_2 - V_{GS}}{R_S}$$

- and

$$V_{DS} = V_{DD} - I_D(R_D + R_S)$$



IGFET or MOSFET

- As well as the Junction Field Effect Transistor (JFET), there is another type of Field Effect Transistor available whose Gate input is electrically insulated from the main current carrying channel and is therefore called an **Insulated Gate Field Effect Transistor (IGFET)**.
- The most common type of IGFET which is used in many different types of electronic circuits is called the **Metal Oxide Semiconductor Field Effect Transistor** or **MOSFET** for short.

IGFET or MOSFET

- The **IGFET** or **MOSFET** is a voltage controlled field effect transistor that differs from a JFET in that it has a Metal Oxide Gate electrode which is electrically insulated from the main semiconductor n-channel or p-channel by a very thin layer of insulating material usually silicon dioxide.
- This ultra thin insulated metal gate electrode can be thought of as one plate of a capacitor. The isolation of the controlling Gate makes the input resistance of the **MOSFET** extremely high way up in the Mega-ohms (MΩ) region.

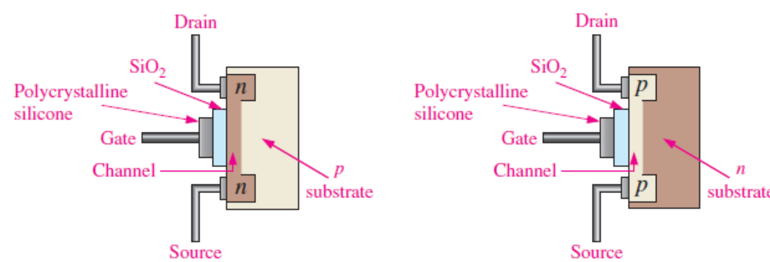
MOSFET

- As the Gate terminal is electrically isolated from the main current carrying channel between the drain and source, NO current flows into the gate.
- Just like the JFET, the MOSFET also acts like a voltage controlled transistor where the current flowing through the main channel between the Drain and Source is proportional to the input voltage.

MOSFET

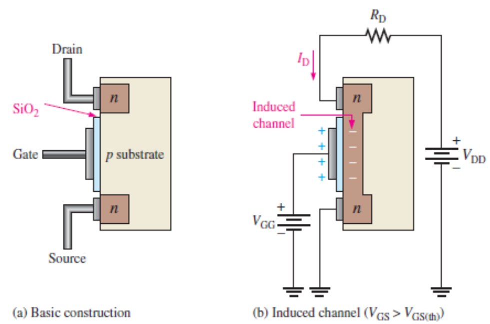
- Like the JFET, MOSFETs are three terminal devices with a Gate, Drain and Source and both P-channel (PMOS) and N-channel (NMOS) MOSFETs are available.
- The main difference this time is that MOSFETs are available in two basic forms:
  - **Depletion Type:** the transistor requires the Gate-Source voltage, (V_{GS}) to switch the device OFF. The depletion mode MOSFET is equivalent to a Normally Closed/On switch.
  - **Enhancement Type:** the transistor requires a Gate-Source voltage, (V_{GS}) to switch the device ON. The enhancement mode MOSFET is equivalent to a Normally Open/Off switch.

Depletion-mode MOSFET



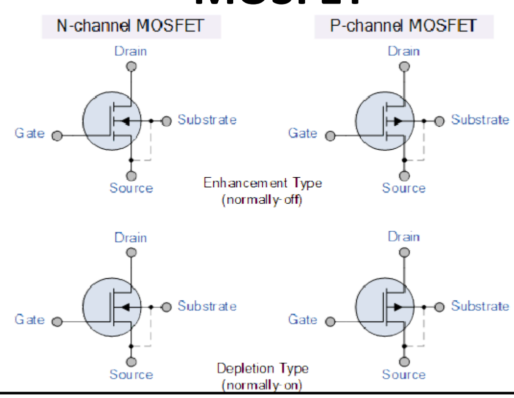
(a) *n* channel (b) *p* channel

Enhancement-mode MOSFET



E-MOSFET

MOSFET



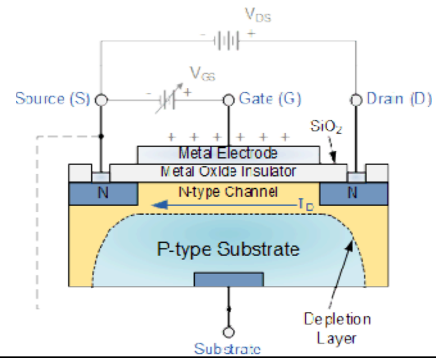
MOSFET

- The four MOSFET symbols have an additional terminal called the **Substrate** and is not normally used as either an input or an output connection but instead it is used for grounding the substrate.
- It connects to the main semiconductor channel through a diode junction to the body or metal tab of the MOSFET.
- Usually in discrete type MOSFETs, this substrate lead is connected internally to the source terminal.
- When this is the case, it is omitted from the symbol.

MOSFET

- The line in the MOSFET symbol between the drain (D) and source (S) connections represents the transistors semiconductor channel.
- If this channel line is a solid unbroken line then it represents a **Depletion** (normally-ON) type MOSFET as drain current can flow with zero gate biasing potential.
- If the channel line is shown as a dotted or broken line, then it represents an **Enhancement** (normally-OFF) type MOSFET as zero drain current flows with zero gate potential.
- The direction of the arrow pointing to this channel line indicates whether the conductive channel is a P-type or an N-type semiconductor device.

MOSFET - Construction



MOSFET - Construction

- The construction of the Metal Oxide Semiconductor FET is very different to that of the Junction FET.
- Both the Depletion and Enhancement type MOSFETs use an electrical field produced by a gate voltage to alter the flow of charge carriers, electrons for n-channel or holes for P-channel, through the semiconductive drain-source channel.
- The gate electrode is placed on top of a very thin insulating layer and there are a pair of small n-type regions just under the drain and source electrodes.

MOSFET - Construction

- With a insulated gate MOSFET device it is possible to bias the gate of a MOSFET in either polarity, positive (+ve) or negative (-ve).
- Both the p-channel and the n-channel MOSFETs are available in two basic forms, the **Enhancement** type and the **Depletion** type.

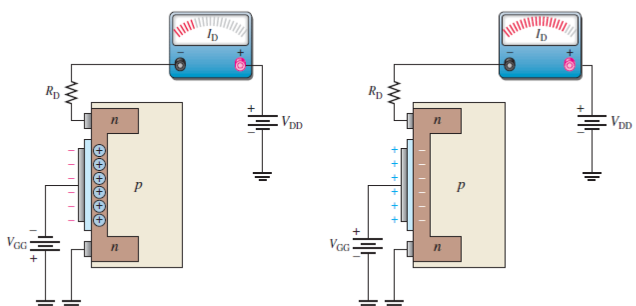
Depletion-mode MOSFET

- The **Depletion-mode MOSFET**, is normally switched ON (conducting) without the application of a gate bias voltage.
- For the n-channel depletion MOS transistor, a negative gate-source voltage, $-V_{GS}$ will deplete (hence its name) the conductive channel of its free electrons switching the transistor OFF.
- Likewise for a p-channel depletion MOS transistor a positive gate-source voltage, $+V_{GS}$ will deplete the channel of its free holes turning it OFF.

Depletion-mode MOSFET

- In other words, for an n-channel depletion mode MOSFET: $+V_{GS}$ means more electrons and more current. While a $-V_{GS}$ means less electrons and less current.
- The opposite is also true for the p-channel types. Then the depletion mode MOSFET is equivalent to a normally-closed switch.
- The circuit symbol shown above for a depletion MOSFET uses a solid channel line to signify a normally closed conductive channel.

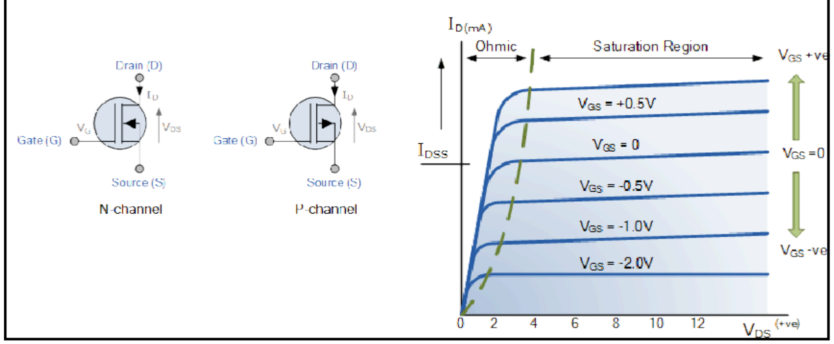
Depletion-mode MOSFET



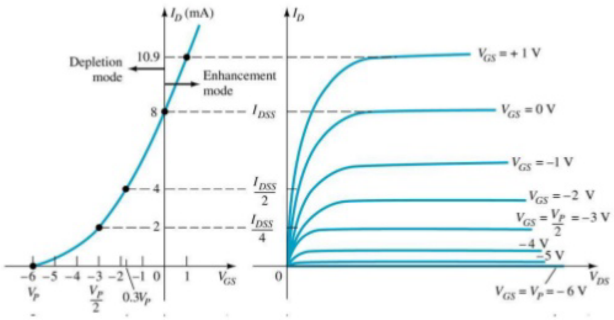
(a) Depletion mode: V_{GS} negative and less than $V_{GS(off)}$

(b) Enhancement mode: V_{GS} positive

Depletion-mode MOSFET



Depletion-mode MOSFET



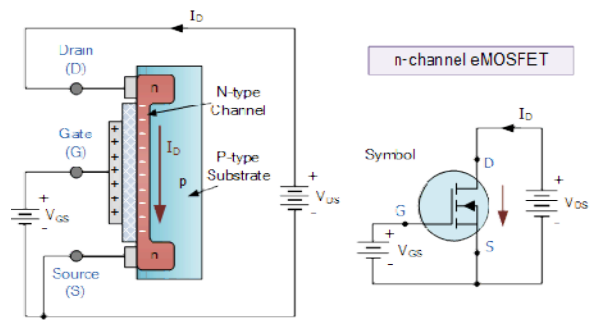
Depletion-mode MOSFET

- The depletion-mode MOSFET is constructed in a similar way to their JFET transistor counterparts were the drain-source channel is inherently conductive with the electrons and holes already present within the n-type or p-type channel.
- This doping of the channel produces a conducting path of low resistance between the Drain and Source with zero Gate bias.

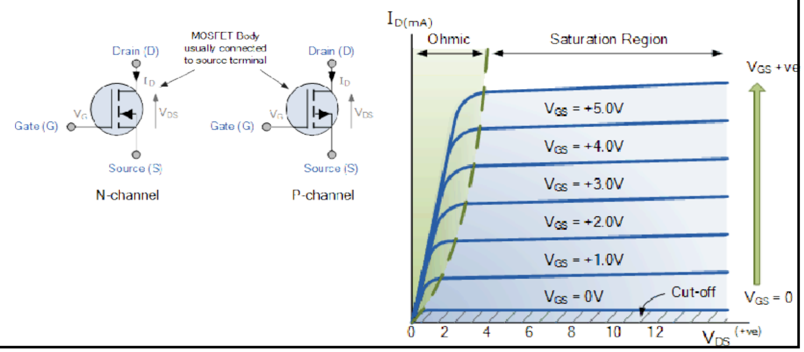
Enhancement-mode MOSFET

- The more common **Enhancement-mode MOSFET** or eMOSFET, is the reverse of the depletion-mode type.
- Here the conducting channel is lightly doped or even undoped making it non-conductive. This results in the device being normally OFF (non-conducting) when the gate bias voltage, V_{GS} is equal to zero.
- The circuit symbol shown above for an enhancement MOS transistor uses a broken channel line to signify a normally open non-conducting channel.

Enhancement-mode MOSFET



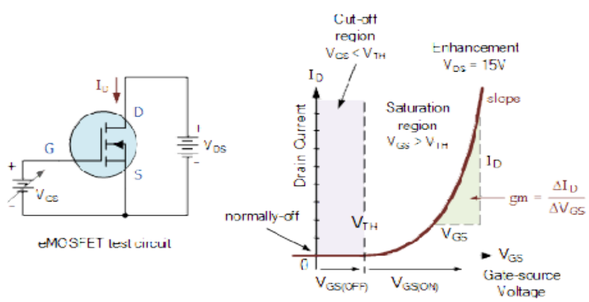
Enhancement-mode MOSFET



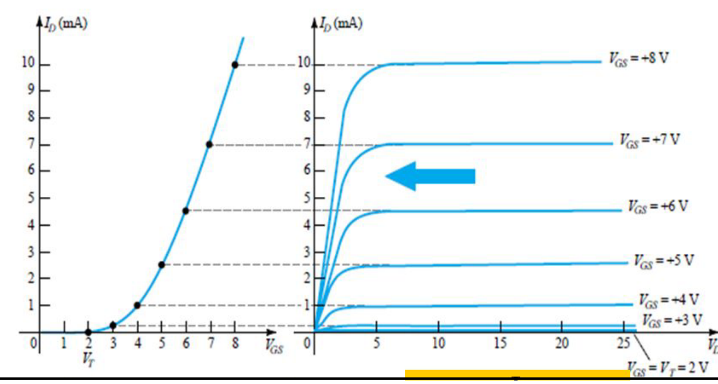
Enhancement-mode MOSFET

- For the n-channel eMOSFET, a drain current will only flow when a gate voltage (V_{GS}) is applied to the gate terminal greater than the threshold voltage (V_{TH}) level in which conductance takes place making it a transconductance device.
- The application of a positive (+ve) gate voltage to a n-type eMOSFET attracts more electrons towards the oxide layer around the gate thereby increasing or enhancing the thickness of the channel allowing more current to flow.
- This is why this kind of transistor is called an enhancement mode device as the application of a gate voltage enhances the channel.

Enhancement-mode MOSFET



Enhancement-mode MOSFET



Enhancement-mode MOSFET

- Increasing this positive gate voltage will cause the channel resistance to decrease further causing an increase in the drain current, I_D through the channel.
- In other words, for an n-channel eMOSFET: $+V_{GS}$ turns the transistor ON, while a zero or $-V_{GS}$ turns the transistor OFF. Thus the enhancement-mode MOSFET is equivalent to a normally-open switch.
- The reverse is true for the p-channel eMOSFET. When $V_{GS} = 0$ the device is OFF and the channel is open. The application of a negative (-ve) gate voltage to the p-type eMOSFET enhances the channels conductivity turning it ON.
- Then for an p-channel enhancement mode MOSFET: $+V_{GS}$ turns the transistor OFF, while $-V_{GS}$ turns the transistor ON.

Application of MOSFET

- There are some important applications of MOSFET, as given below:
  - It is used for switching and amplifying electronics signals in the electronic devices.
  - It is used as an inverter.
  - It can be used in digital circuit.
  - It can be used as a high frequency amplifier.
  - It can be used as a passive element e.g. resistor, capacitor and inductor.
  - It can be used in brushless DC motor drive.
  - It can be used in electronic DC relay.
  - It is used in switch mode power supply (SMPS).

Difference between JFET & MOSFET

- JFETs can only be operated in the depletion mode whereas MOSFETs can be operated either in depletion and enhancement mode or only in enhancement mode.
- MOSFETs have input impedance much higher than that of JFETs. The input resistance of JFET is in the range of around a $10^8\Omega$. For MOSFET, the input resistance will be in the range of 10^{10} to $10^{15}\Omega$.
- The output characteristics of JFET is flatter than that of the MOSFET, because the drain resistance in the JFET (1 MΩ) is higher than the MOSFET (50kΩ)
- The MOSFET devices are more useful in electrometer applications than are the JFETs.

Difference between JFET & MOSFET

- Compared to the JFET, MOSFETs are easier to fabricate.
- MOSFETs are widely used in VLSI circuits than JFETs. The MOSFET is susceptible to overload voltages.
- The source and drain terminals can be interchanged (so it is called as symmetrical device). Because of these two characteristics the MOSFET is widely used in analog signal switching.
- In a JFET, the electric field across the reverse biased PN junction controls the conductivity of the channel. In a MOSFET, the electric field induced across an insulating layer deposited on the semiconductor material controls the conductivity of the channel.

Field Effect Transistor

END