Transistor as a Switch

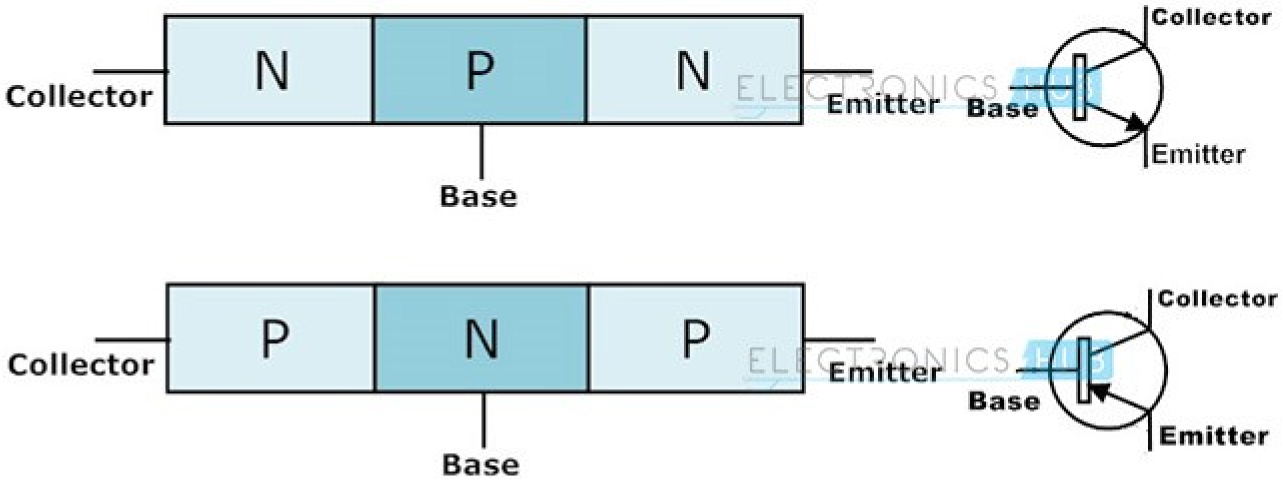
- Switching and Amplification are the two areas of applications of Transistors and Transistor as a Switch is the basis for many digital circuits.

Introduction

As one of the significant semiconductor devices, transistor has found use in enormous electronic applications such as embedded systems, digital circuits and control systems. In both digital and analog domains transistors are extensively used for different application usage like amplification, logic operations, switching and so on.

The Bipolar Junction Transistor or simply BJT is a three layer, three terminal and two junction semiconductor device. Almost in many of the applications these transistors are used for two basic functions such as switching and amplification

The name bipolar indicates that two types of charge carriers are involved in the working of a BJT. These two charge carriers are holes and electrons where holes are positive charge carriers and electrons are negative charge carriers.



Operating Modes of Transistors

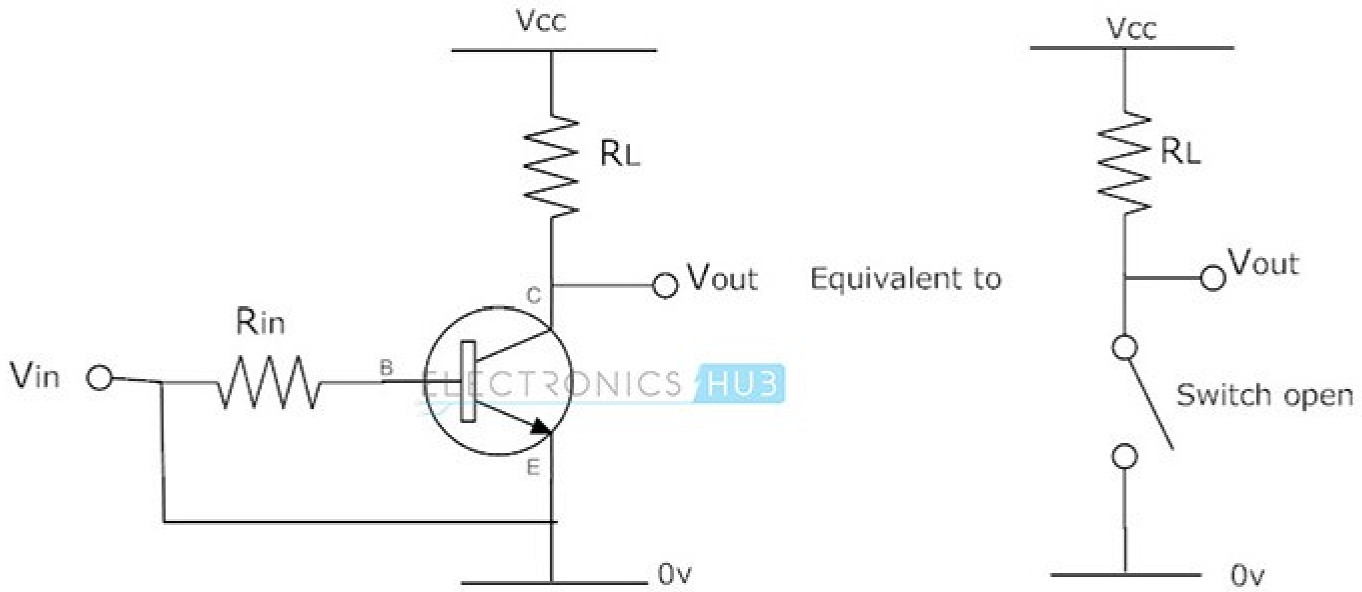
Depends on the biasing conditions like forward or reverse, transistors have three major modes of operation namely cutoff, active and saturation regions.

Active Mode

In this mode transistor is generally used as a current amplifier. In active mode, two junctions are differently biased that means emitter-base junction is forward biased whereas collector-base junction is reverse biased. In this mode current flows between emitter and collector and amount of current flow is proportional to the base current.

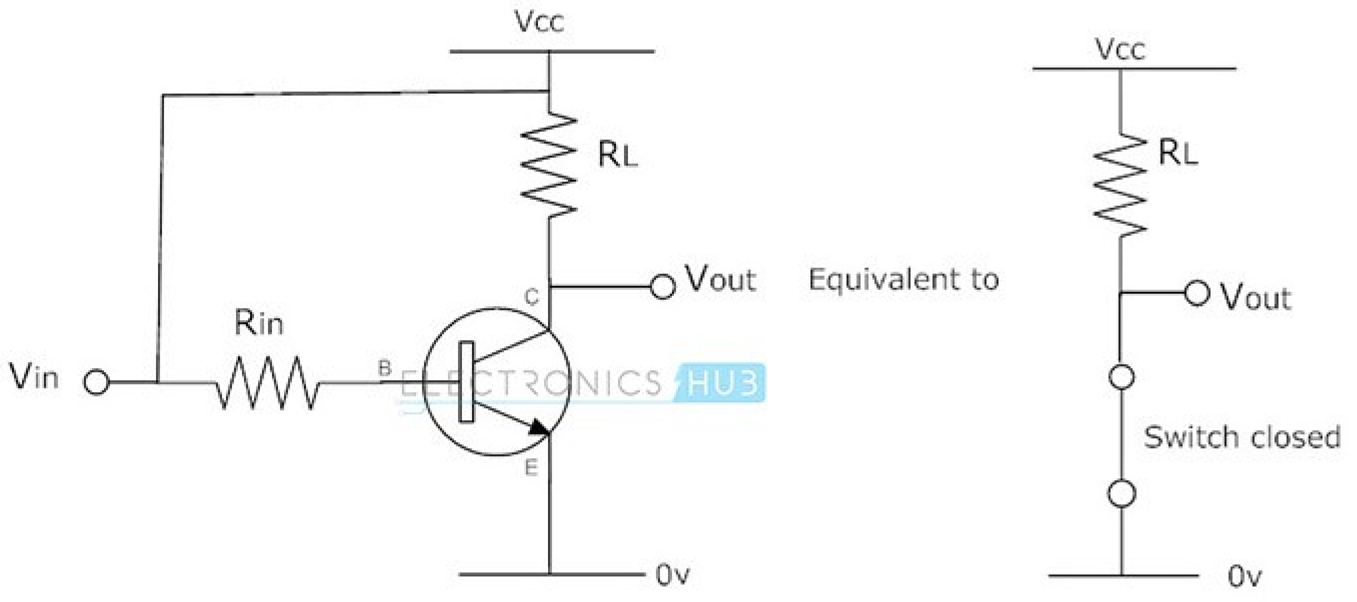
Cutoff Mode

In this mode, both collector base junction and emitter base junction are reverse biased. This in turn not allows the current to flow from collector to emitter when the base-emitter voltage is low. In this mode device is completely switched off as the result the current flowing through the device is zero.

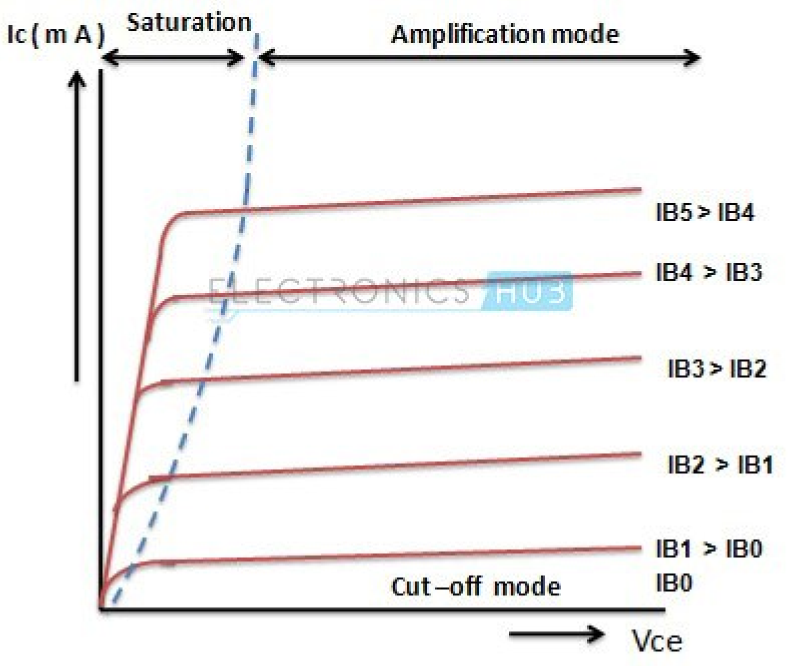


Saturation Mode

In this mode of operation, both the emitter base and collector base junctions are forward biased. Current flows freely from collector to emitter when the base-emitter voltage is high. In this mode device is fully switched ON.



The below figure shows the output characteristics of a BJT Transistor. In the below figure cutoff region has the operating conditions as zero collector output current, zero base input current and maximum collector voltage. These parameters causes a large depletion layer which further doesn't allow current to flow through the transistor. Therefore, the transistor is completely in OFF condition.



Similarly, in the saturation region, a transistor is biased in such a way that maximum base current is applied that results maximum collector current and minimum collector-emitter voltage. This causes the depletion layer to become small and to allow maximum current flow through the transistor. Therefore, the transistor is fully in ON condition.

Hence, from the above discussion, we can say that transistors can be made to work as ON/OFF solid state switch by operating transistor in cutoff and saturation regions. This type of switching application is used for controlling motors, lamp loads, solenoids, etc.

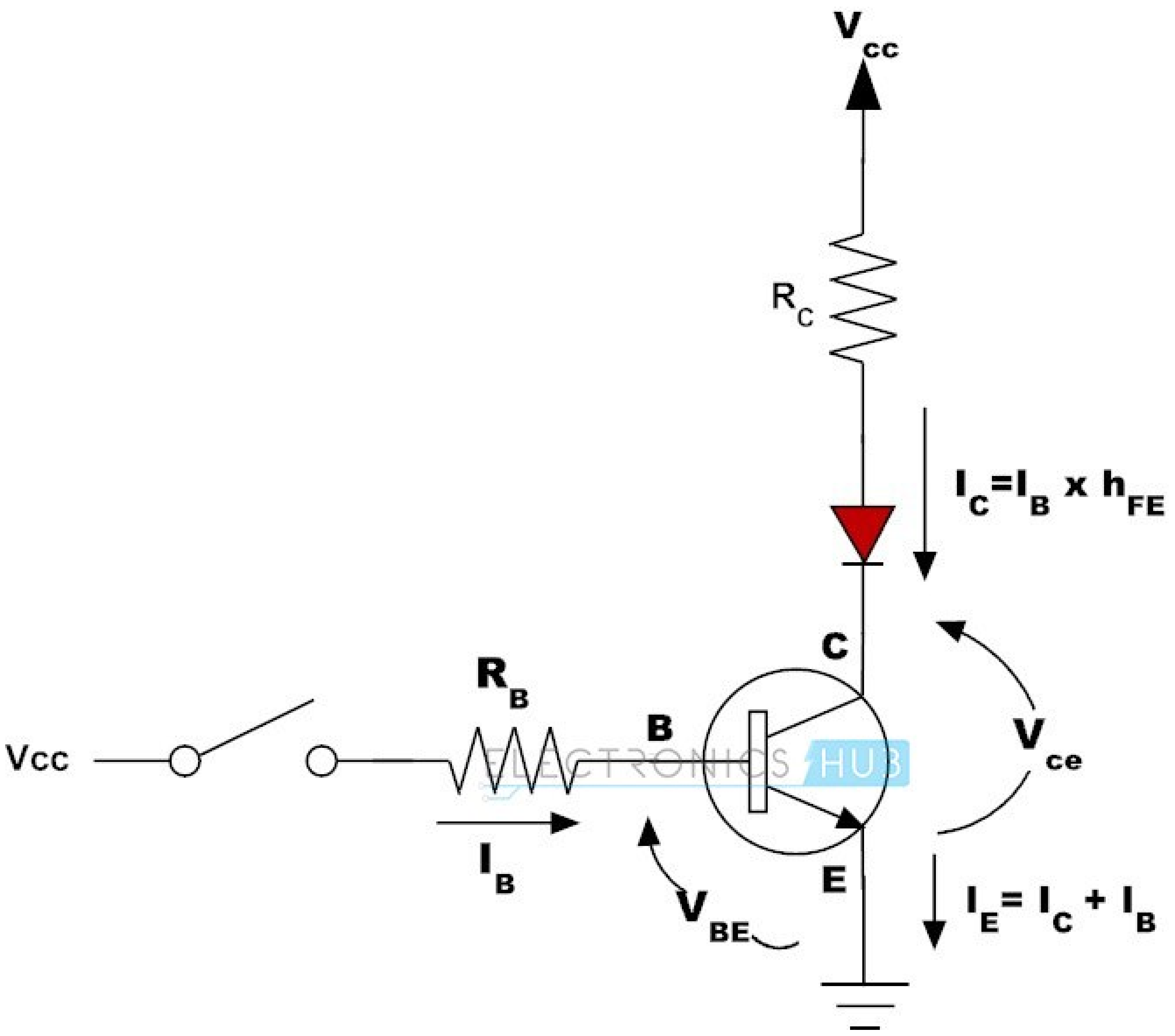
Transistor as a Switch

A transistor is used for switching operation for opening or closing of a circuit. This type solid state switching offers significant reliability and lower cost as compared with conventional relays. Both NPN and PNP transistors can be used as switches. Some of the applications use a power transistor as switching device, at that time it may necessary to use another signal level transistor to drive the high power transistor.

NPN Transistor as a Switch

Based on the voltage applied at the base terminal of a transistor switching operation is performed. When a sufficient voltage ($V_{in} > 0.7$ V) is applied between the base and emitter, collector to emitter voltage is approximately equal to 0. Therefore, the transistor acts as a short circuit. The collector current V_{cc}/R_c flows through the transistor.

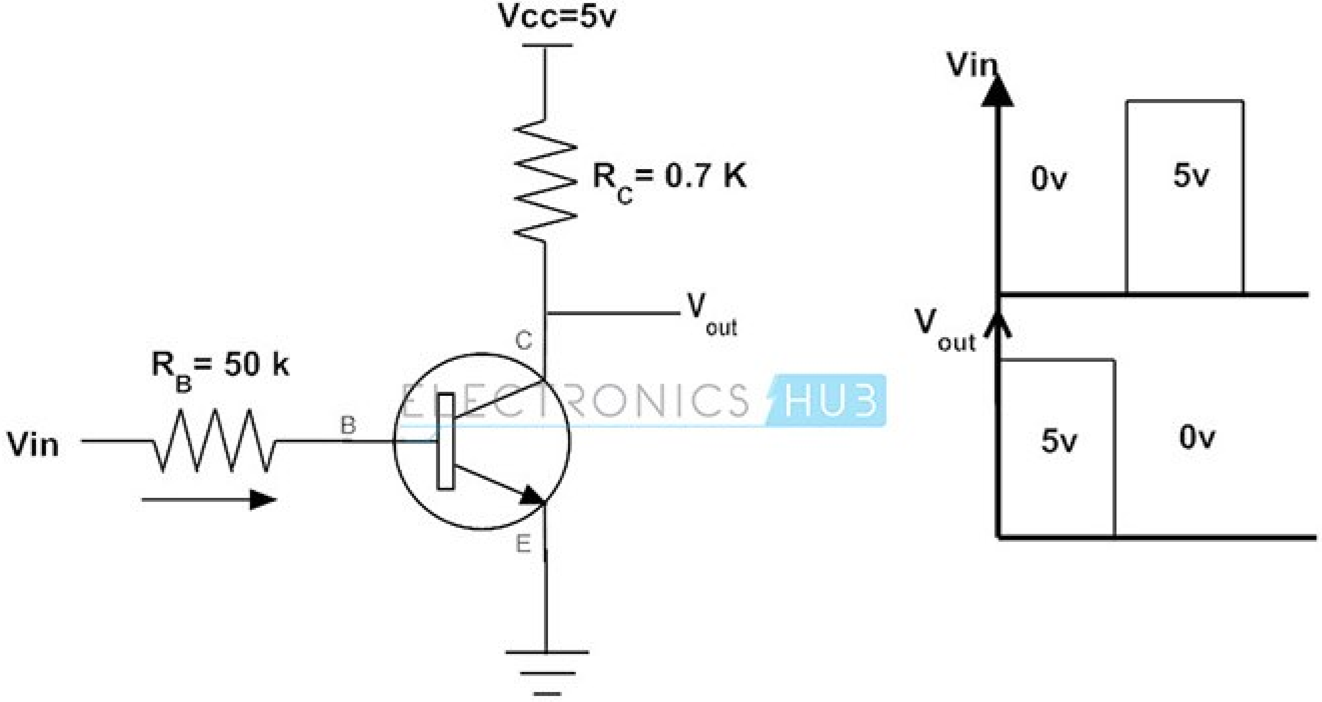
Similarly, when no voltage or zero voltage is applied at the input, transistor operates in cutoff region and acts as an open circuit. In this type of switching connection, load (here LED lamp) is connected to the switching output with a reference point. Thus, when the transistor is switched ON, current will flow from source to ground through the load.



Vcc
RC
IC=IB x hFE
C
RB
B
Vcc
Vce
ELECTRONICS HUB
IB
VBE
E
IE= IC + IB

Example of NPN Transistor as a Switch

Consider the below example where base resistance R_b = 50 k ohm, collector resistance R_c = 0.7k ohm, V_{cc} is 5V and the beta value is 125. At the base input a signal varying between 0 and 5V is given so we are going to see the output at the collector by varying the V_i at two states that is 0 and 5V as shown in figure.



$$I_c = V_{cc}/R_c \text{ when } V_{CE} = 0$$
$$I_c = 5V/0.7k \text{ ohm}$$
$$I_c = 7.1 \text{ mA}$$
$$\text{Base Current } I_b = I_c / \beta$$
$$I_b = 7.1 \text{ mA}/125$$
$$I_b = 56.8 \ \mu A$$

From the above calculations, the maximum or peak value of the collector current in the circuit is 7.1mA when Vce is equal to zero. And the correspond base current to which collector current flows is 56.8µA. So, it is clear that when the base current is increased beyond the 56.8 micro ampere then the transistor comes into the saturation mode.

Consider the case when zero volt is applied at the input. This causes the base current zero and as the emitter is grounded, emitter base junction is not forward biased. Therefore, the transistor is in OFF condition and the collector output voltage is equal to 5V.

When $V_i = 0V$, $I_b = 0$ and $I_c = 0$,

$$V_c = V_{cc} - (I_c R_c)$$
$$= 5V - 0$$
$$= 5V$$

Consider that input voltage applied is 5 volts, then the base current can be determined by applying Kirchhoff's voltage law.

When $V_i = 5V$

$$I_b = (V_i - V_{be}) / R_b$$

For silicon transistor $V_{be} = 0.7$ V

Thus, $I_b = (5V - 0.7V) / 50K$ ohm

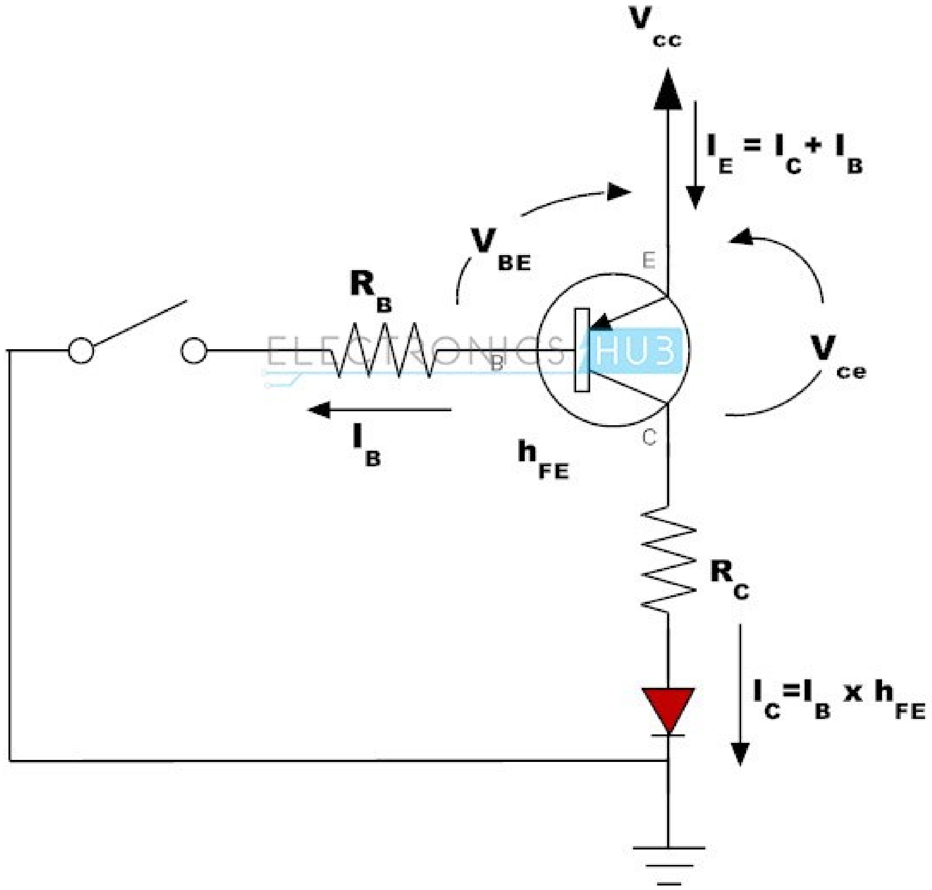
$= 86$ µA which is greater than 56.8 µA

Therefore the base current is greater than 56.8 micro ampere current, the transistor will be driven to saturation that is fully ON when 5V is applied at the input. Thus the output at the collector becomes approximately zero.

PNP Transistor as a Switch

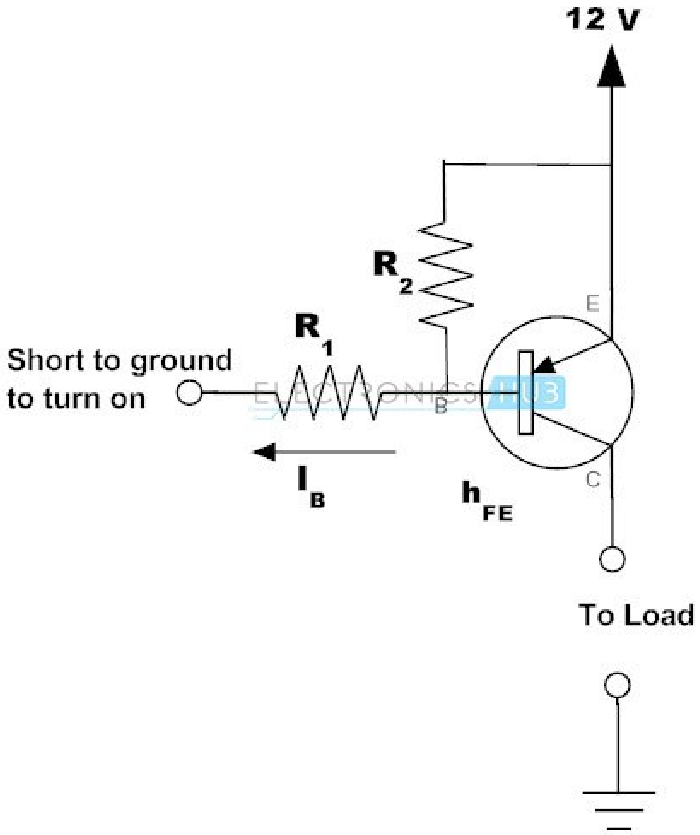
PNP transistor works same as NPN for a switching operation, but the current flows from the base. This type of switching is used for negative ground configurations. For the PNP transistor, the base terminal is always negatively biased with respect to the emitter. In this switching, base current flows when the base voltage is more negative. Simply a low voltage or more negative voltage makes transistor to short circuit otherwise it will be open circuited or high impedance state.

In this connection, load is connected to the transistor switching output with a reference point. When the transistor is turned ON, current flows from the source through transistor to the load and finally to the ground.



Example of PNP Transistor as a Switch

Similar to the NPN transistor switch circuit, PNP circuit input is also base, but the emitter is connected to constant voltage and the collector is connected to ground through the load as shown in figure.



In this configuration base is always biased negatively with respect to the emitter by connecting the base at negative side and the emitter at the positive side of the input supply. So the voltage V_{BE} is negative and the emitter supply voltage with respect to the Collector is positive (V_{CE} positive).

Therefore, for the conduction of transistor emitter must be more positive with respect to both collector and base. In other words base must be more negative with respect to the emitter.

For calculating the base and collector currents following expressions are used.

$$I_c = I_e - I_b$$

$$I_c = \beta . I_b$$

$$\mathbf{I_b = I_c / \beta}$$

Consider the above example, that the load requires 100 milli ampere current and the transistor has the beta value of 100. Then the current required for the saturation of the transistor is

$$\begin{aligned} \text{Minimum base current} &= \text{collector current} / \beta \\ &= 100 \text{ mA} / 100 \\ &= 1\text{mA} \end{aligned}$$

Therefore, when the base current is 1 mA, the transistor will be fully ON. But practically 30 percent of more current is required for guaranteed saturation of transistor. So, in this example the base current required is 1.3mA.

Introduction to Junction Field Effect Transistor (JFET)

Introduction

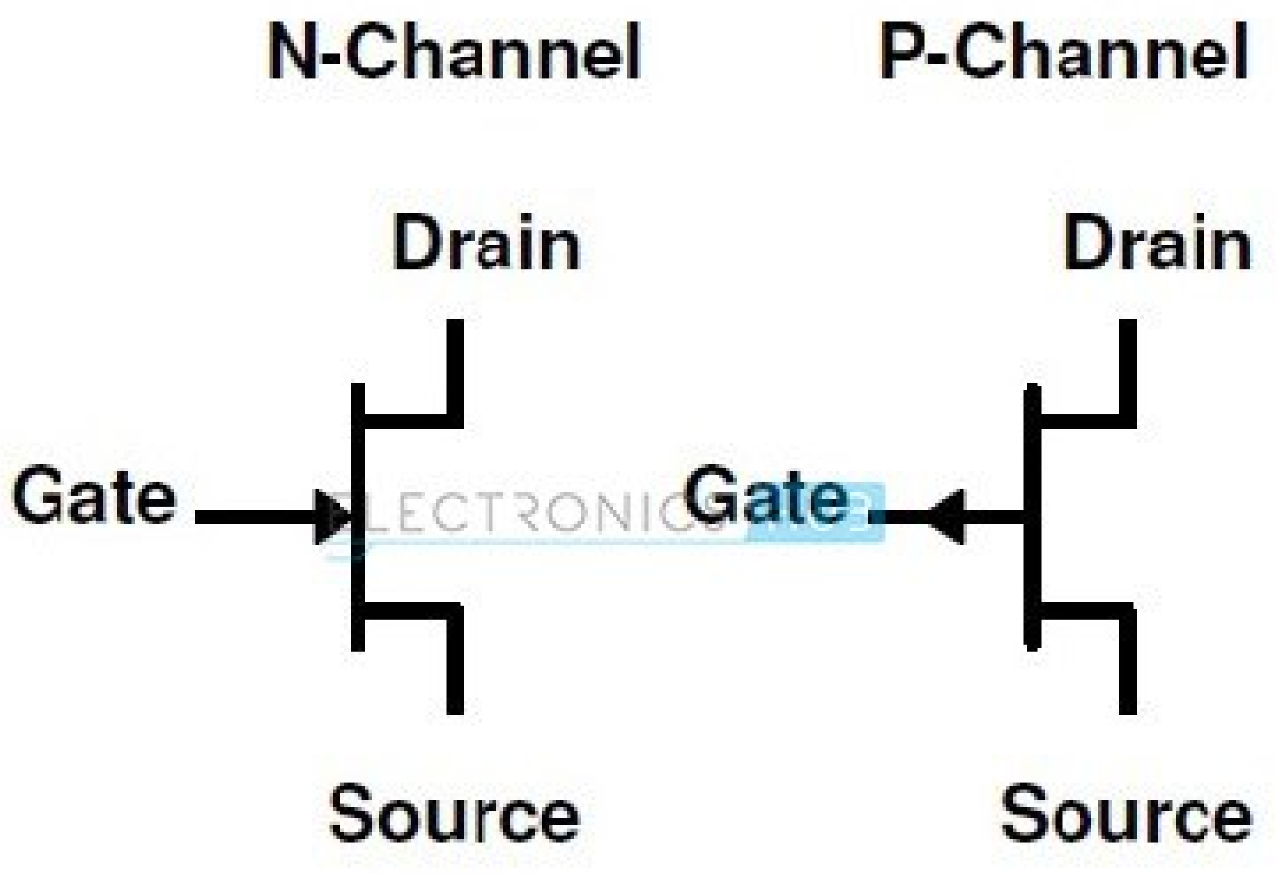
The FET transistors are voltage controlled devices, where as the BJT transistors are current controlled devices. The FET transistors have basically three terminals, such as Drain (D), Source (S) and Gate (G) which are equivalent to the collector, emitter and base terminals in the corresponding BJT transistor.

In BJT transistors the output current is controlled by the input current which is applied to the base, but in the FET transistors the output current is controlled by the input voltage applied to the gate terminal.

In the FET transistors the output current passes between the drain and source terminals and this path is called channel and this channel may be made of either P-type or N-type semiconductor materials. In BJT transistor a small input current operates the large load, but in FET a small input voltage operates the large load at the output.
The BJT transistors are ‘bipolar’ devices because they operates with both types of charge carriers, such as electrons and holes but the FET transistors are ‘unipolar’ devices because they operate with the charge carriers of either electrons (for N-channel) or holes (for P-channel).

The FET transistors can be made smaller in size compared to BJT transistor and also they have less power dissipation. Due to this high efficiency the FET transistors are used in many electronic circuit applications by replacing the corresponding BJT transistors. These FET transistors are very useful in the chip designing due to their low power consumption behaviour. Like BJT the FET transistors are also available in both P-channel and N-channel.

The FET transistors have high input impedance where as BJT has relatively low. Due to this high impedance values the FET transistors are very sensitive to small input voltages. The FET transistors are mainly classified into two types; they are Junction Field Effect Transistor (JFET) and Insulated Gate FET (IG-FET) or Metal Oxide Semiconductor FET (MOSFET).

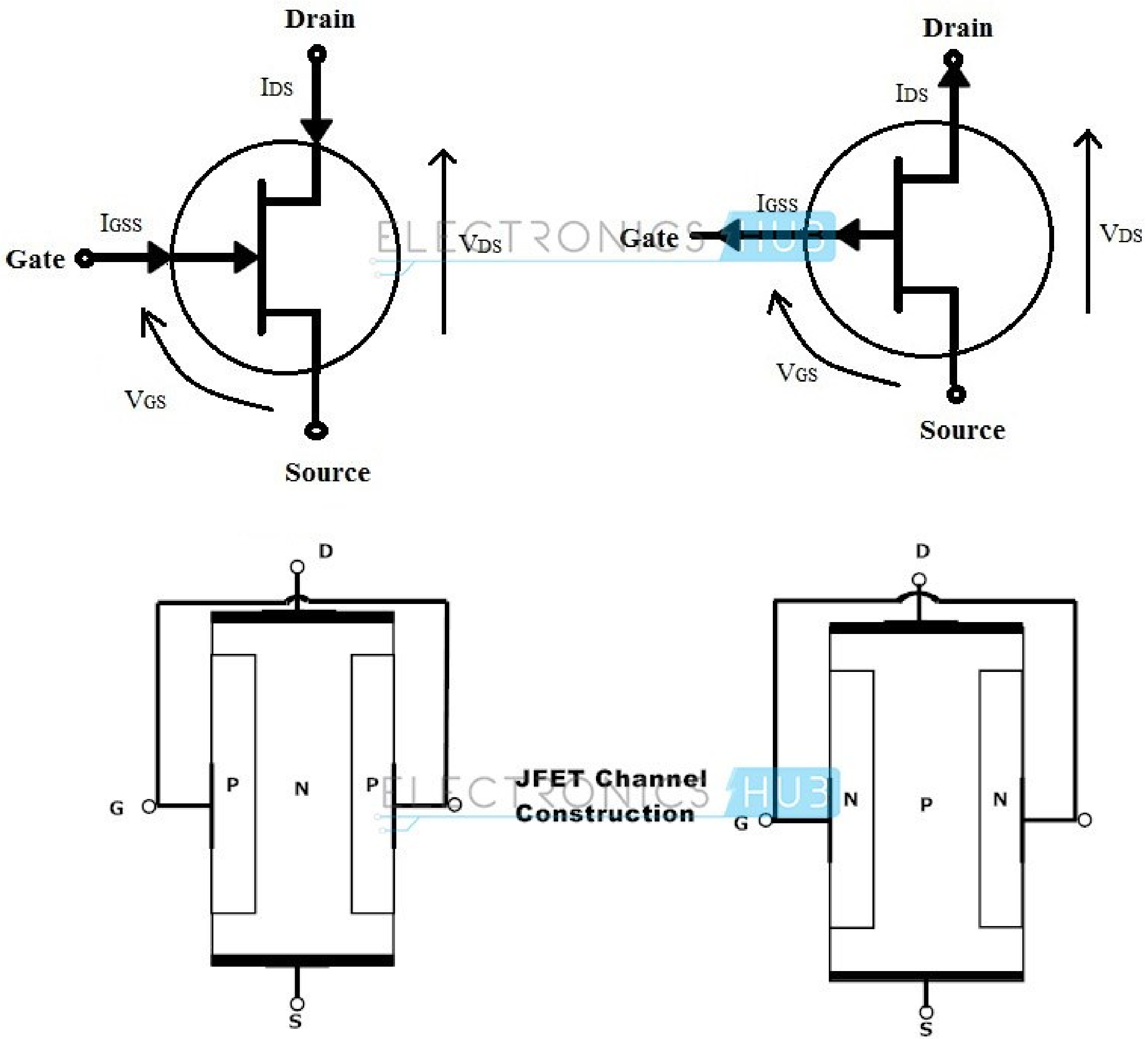


FET Transistor Symbols

Junction Field Effect Transistor (JFET)

The Junction Field Effect transistor (JFET) is one of the types of FET transistors. JFET is a simplest form of FET transistors and it has three terminals. The JFET transistors are used as electronically controlled switches, Voltage controlled resistors and as amplifiers.

BJT transistors are constructed with the PN-junctions but the JFET transistors have a channel instead of the PN-junctions. This channel is formed due to the either of P-type or N-type semiconductor materials.

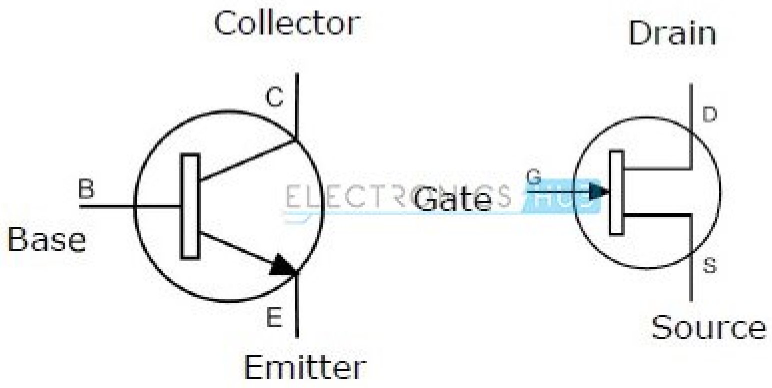


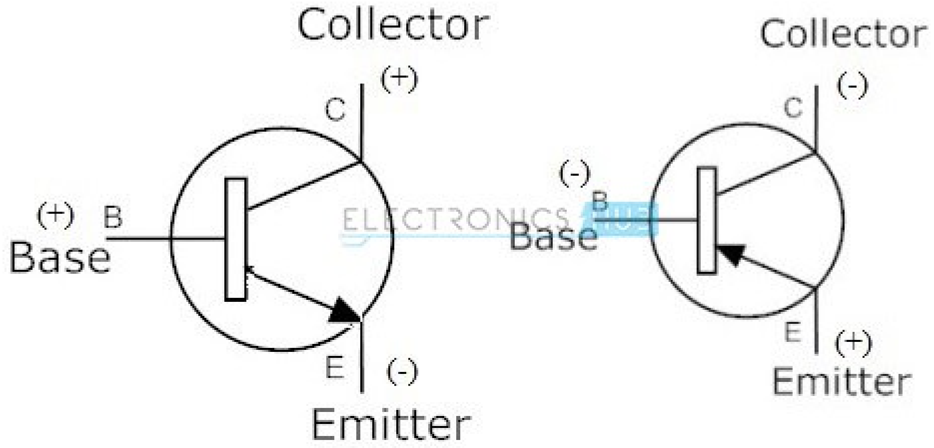
JFET symbols and channel construction

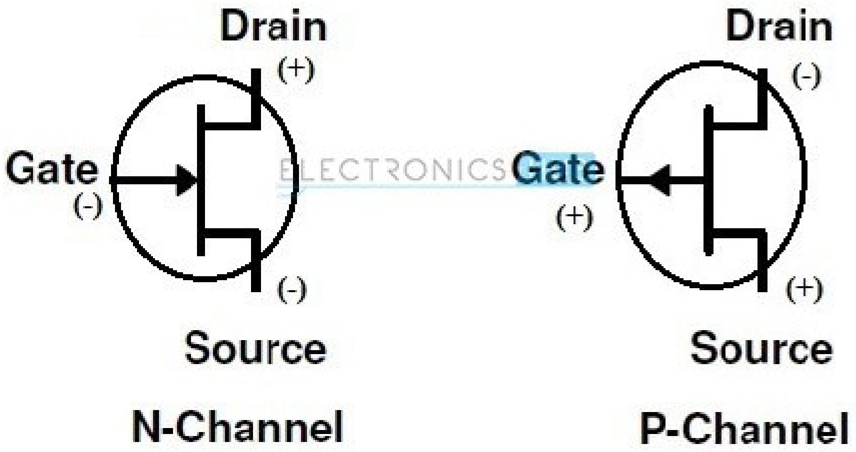
The JFET transistors are classified into two types; they are N-channel JFET and P-channel JFET. In the N-channel JFET the channel is doped with the donor impurities due to this the current passing through the channel is negative (i.e. due to electrons) but in the P-channel JFETs the channel is doped with the acceptor impurities due to this the current flowing through this channel is positive (i.e. due to holes).
The N-channel JFET has more current conduction than P-channel JFET because the mobility of electrons is greater than the mobility of holes. So the N-channel JFETs are widely used than P-channel JFETs.
The small voltage at the gate (G) terminal controls the current flow in the channel (between drain and source) of the JFET.

The emitter and collector terminals are connected using PN-junctions in BJT but in JFET the Drain and Source terminals are connected with the channel. The small voltage applied at the gate terminal controls the current flow in the channel between the drain and source of the JFET. This gate voltage is negative in N-channel JFET and it is positive in P-channel JFET.

One of the main differences between the BJT and JFET transistors is that when the JFET has reverse-biased junction, then the gate current may be zero, but in the BJT the base current always must be greater than zero. The comparison of symbols between BJT and JFET is shown in the below figures.



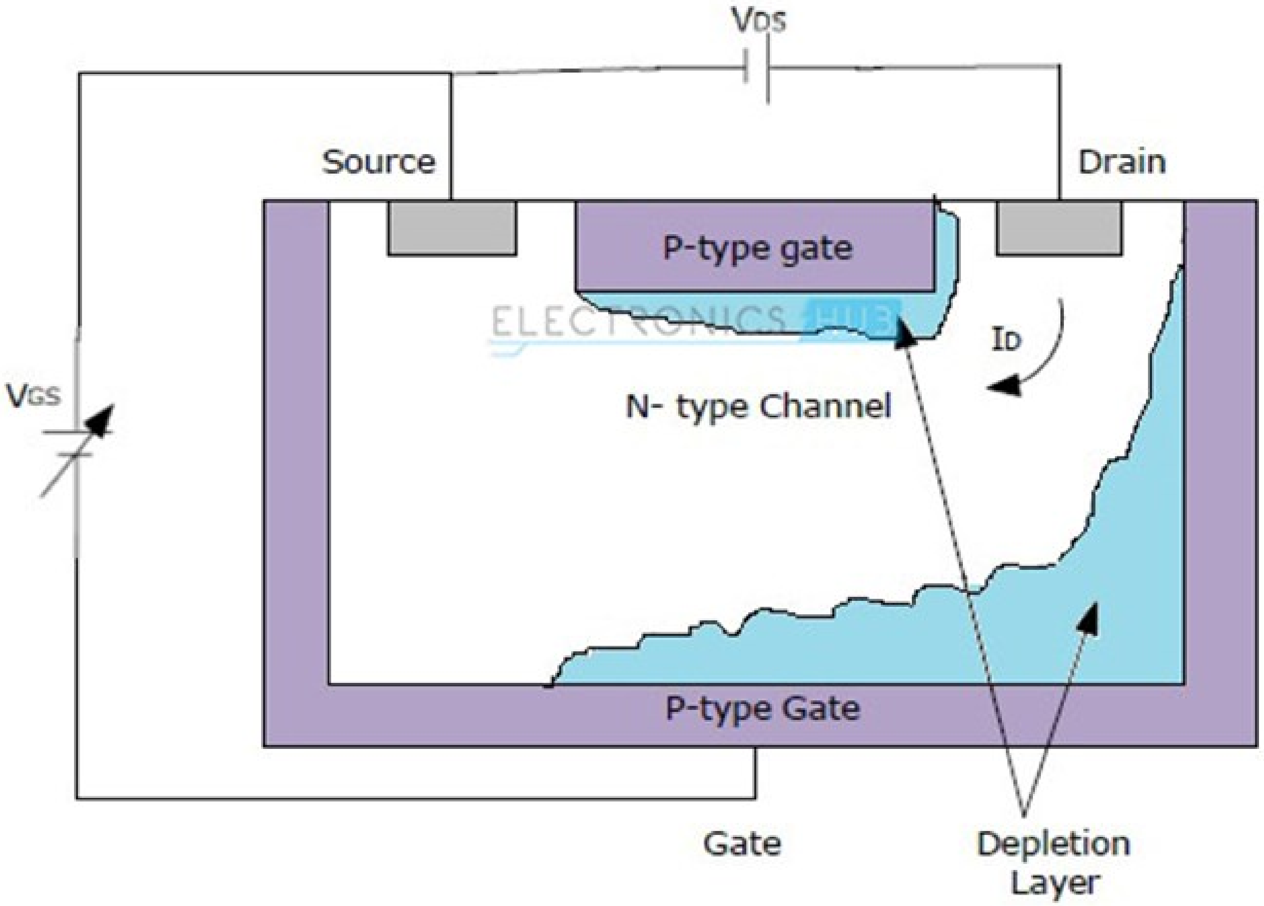




Comparison symbols between JFET and BJT

N-channel JFET Biasing

The internal diagram for N-channel JFET transistor is shown below. This is a transistor with N-type of channel and with P-type materials of the region. If the gate is diffused into the N-type channel, then a reverse biased PN-junction is formed which results a depletion region around the gate terminal when no external supply is applied to the transistor. Generally the JFETs are called as depletion mode devices.



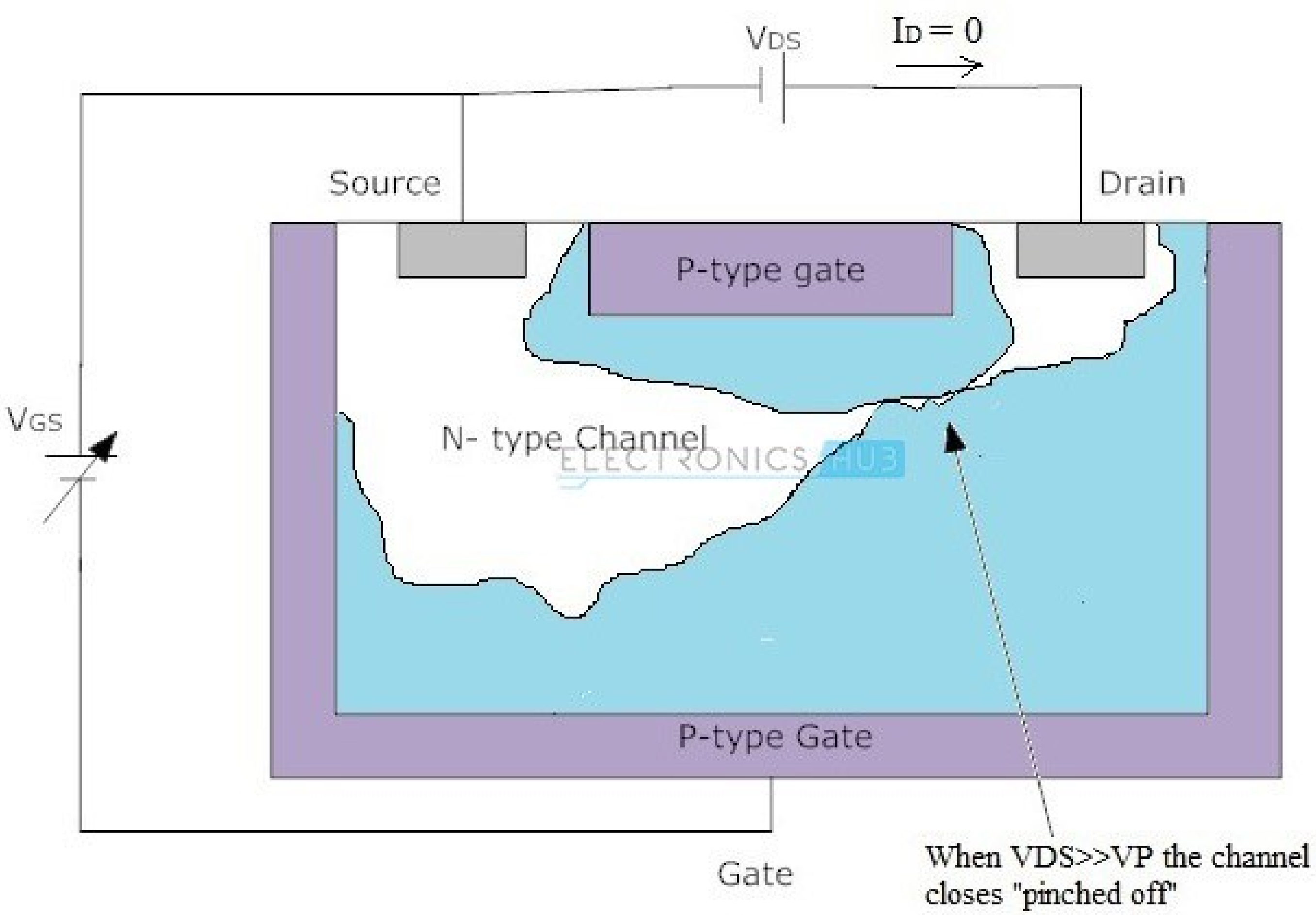
VDS
Source
Drain
P-type gate
ID
VGS
N- type Channel
P-type Gate
Gate
Depletion
Layer

This depletion region produces a potential gradient with the variation of thickness around the PN-junction. This PN-junction opposes the current flow through the channel by reducing the channel width and by increasing the channel resistance.

Now the channel of JFET conducts with zero bias voltage applied as input. Because of the large portion of the depletion region formed between the gate-drain and the small portion of the depletion region between gate and source.

If small voltage (V_{DS}) applied between the drain-source with zero gate voltage (V_G) then current (I_{DS}) will flow through this channel. Now if we apply a small amount of negative voltage ($-V_{GS}$) (i.e. reverse biased condition) then the depletion region width increases, which results in decreasing the portion of the channel length and reduces the conduction of the channel.
This process is called “squeezing effect”. If we will increase more negative voltage at the gate terminal then it reduces the channel width until no current flows through the channel. Now at this condition the JFET is said to be “pinched-off”. The applied voltage at which the channel of FET closes is called as “pinched-off voltage (V_P)”.

Pinch-off Effect



The JFET with N-channel structure is shown above. At primarily if the gate voltage is zero, then the channel resistance is also zero and the conduction of the channel is high. If the gate voltage (i.e. negative voltage) increases to above zero, then the resistance of the channel also increases and the small amount of current will flows through the channel.

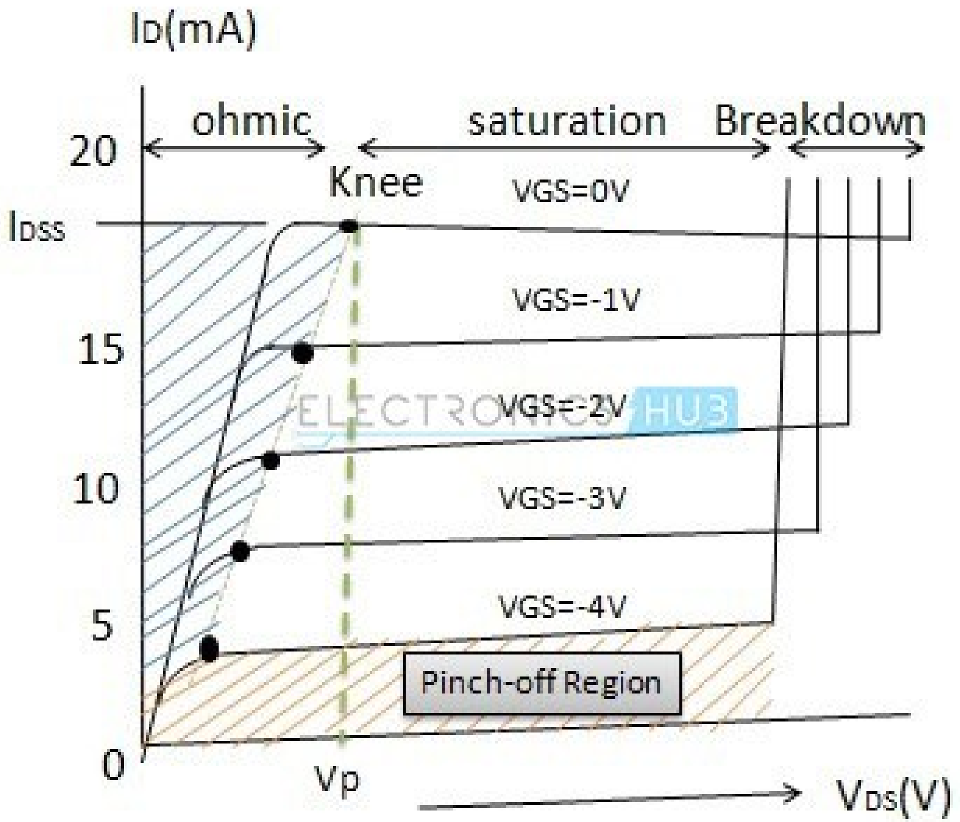
If we apply a large amount of negative voltage at the gate terminal, then the channel totally blocks the flow of current through it. In this condition, there is no current flow through the channel and now the JFET acts as a perfect resistor.

The state of JFET in which the channel closes is called “pinched-off” and the voltage applied at gate in that situation is called “pinched-off voltage (V_P)”. At the pinched-off condition the gate voltage (V_{GS}) controls the channel current. The P-channel JFET operation is same as the N-channel JFET with some variations, such as the channel current is positive because of the conduction due to holes and it is needed the reverse polarity to apply gate voltage.

JFET V-I Characteristics

The V-I characteristics of N-channel JFET are shown below. In this N-channel JFET structure the gate voltage (V_{GS}) controls the current flow between the source drain. The JFET is a voltage controlled device so no current flows through the gate, then the source current (I_S) is equal to the drain current (I_D) i.e. $I_D = I_S$.

In this V-I characteristic the voltage V_{GS} represents the voltage applied between the gate and the source and the voltage V_{DS} represents the voltage applied between the drain and source.



V-I characteristics of JFET transistor

The JFET has different characteristics at different stages of operation depending on the input voltages and the characteristics of JFET at different regions are explained below. Mainly the JFET operates in ohmic, saturation, cut-off and break-down regions.

Ohmic Region: If $V_{GS} = 0$ then the depletion region of the channel is very small and in this region the JFET acts as a voltage controlled resistor.

Pinched-off Region: This is also called as cut-off region. The JFET enters into this region when the gate voltage is large negative, then the channel closes i.e.no current flows through the channel.

Saturation or Active Region: In this region the channel acts as a good conductor which is controlled by the gate voltage (V_{GS}).

Breakdown Region: If the drain to source voltage (V_{DS}) is high enough, then the channel of the JFET breaks down and in this region uncontrolled maximum current passes through the device.

The V-I characteristic curves of P-channel JFET transistor are also same as the N-channel JFET with some exceptions, such as if the gate to source voltage (V_{GS}) increases positively then the drain current decreases.

The drain current I_D flowing through the channel is zero when applied voltage V_{GS} is equal to pinch-off voltage V_P. In normal operation of JFET the applied gate voltage V_{GS} is in between 0 and V_P, In this case the drain current I_D flowing through the channel can be calculated as follows

$I_D = I_{DSS} (1-(V_{GS}/V_P))^2$

Where

I_D = Drain current

I_{DSS} = maximum saturation current

V_{GS} = gate to source voltage

V_P = pinched-off voltage

The drain-source resistance is equal to the ratio of the rate of change in drain-source voltage and rate of change in drain current.

$R_{DS} = \Delta V_{DS} / \Delta I_D = 1/g_m$

Where

R_{DS} = drain-source resistance

V_{DS} = drain to source voltage

I_D = drain current

G_m= Trans-conductance gain