Pearson BTEC Level 5 Higher Nationals in Engineering (RQF)

Unit 52: Further Electrical, Electronic and Digital Principles

Unit Workbook 4

in a series of 4 for this unit

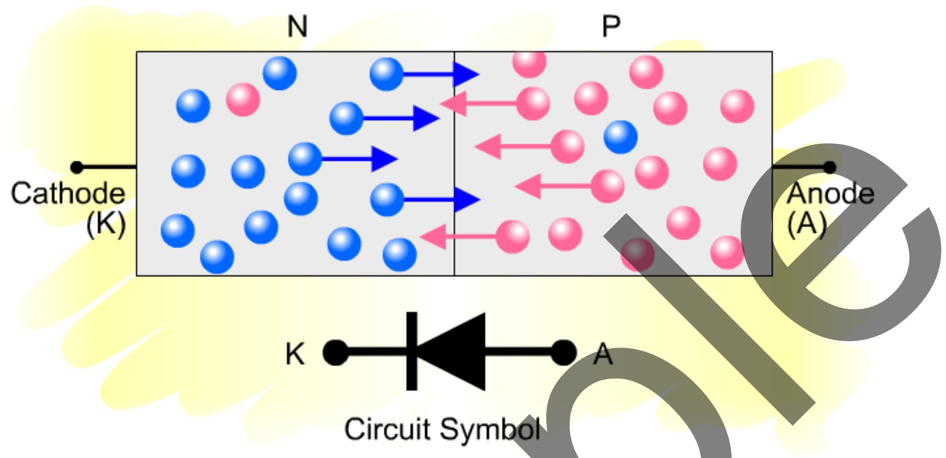
Learning Outcome 4

Non-linear Circuits

Diode Theory

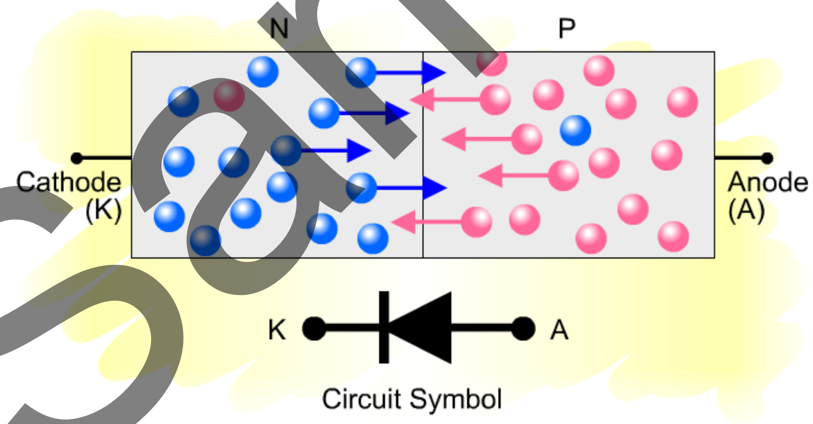
P-N Junction Diode

A simple semiconductor device is the diode. This consists of a region of p-type semiconductor alongside a region of n-type semiconductor. A silicon diode is formed from one complete crystal of silicon with the impurities infused into it to make it part n-type and part p-type. A junction exists at the boundary between the n-type and p-type silicon.

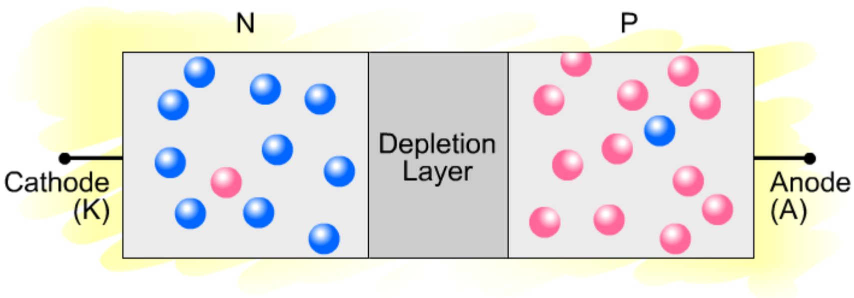


Depletion Layer

When the p-n junction is manufactured some of the free electrons in the n-type material will cross the junction and fill the holes in the p-type material.



Where these electrons fill the holes, a region will be created containing no free electrons. With no free electrons this region becomes an insulator. This region is called the **depletion layer** as it is depleted of free electrons.

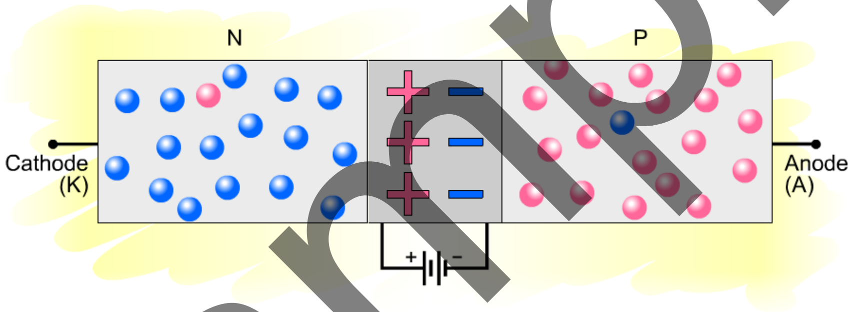


Barrier Potential

In the p-type region the increase in the number of electrons will cause a negative charge to build up as there will be more electrons than protons. This negative charge will repel electrons, so preventing more electrons crossing the junction.

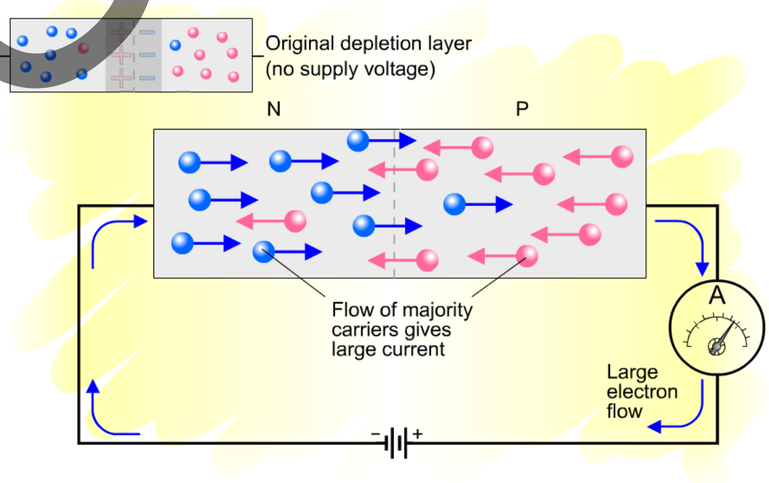
Where electrons have moved from the n-type region, the atoms will have an overall positive charge since these atoms will have fewer negative electrons than positive protons. This will cause a positive charge to build up in the n-type region.

The charge that builds up to stop electrons from crossing the junction is called the **barrier potential**.



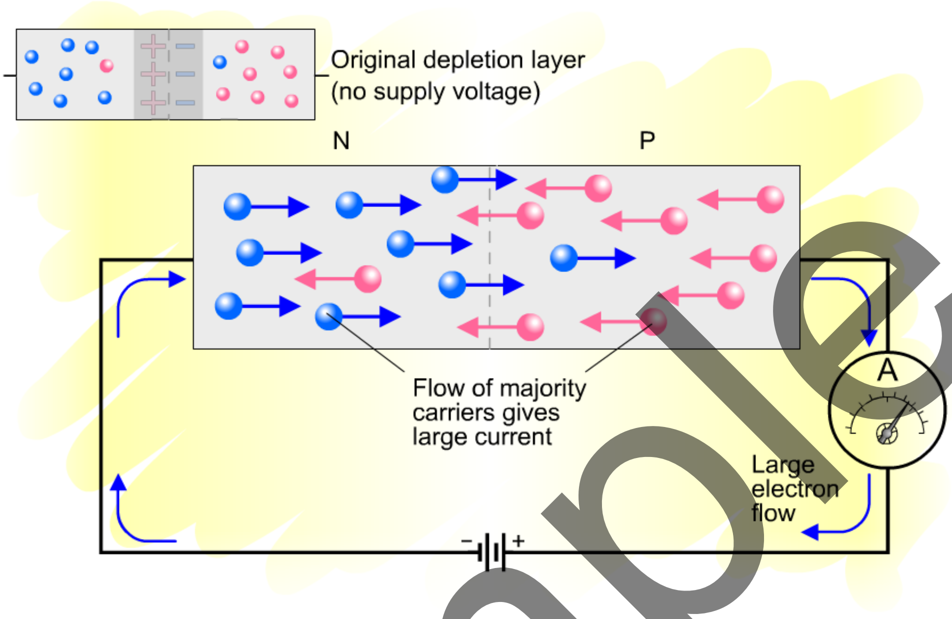
Connecting a Voltage to a Diode

Consider a voltage connected across the diode such that the positive voltage is applied to the p-type region and the negative voltage is applied to the n-type region. The positive voltage will repel the holes in the p-type material pushing them towards the junction. The negative voltage will repel the electrons in the n-type material also pushing them towards the junction.



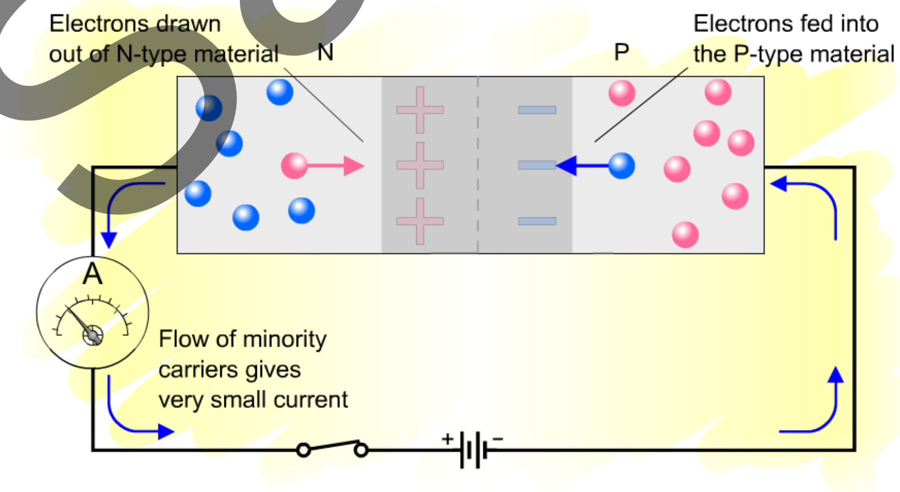
Forward Bias

If the applied voltage is large enough the depletion layer will totally collapse. Electrons from the negative terminal of the power supply will now be able to enter the diode, cross the junction, and continue round the circuit to the positive terminal. A current will therefore be flowing in the circuit. When voltage is applied to a diode so that a current will flow, the diode is said to be **forward biased**.



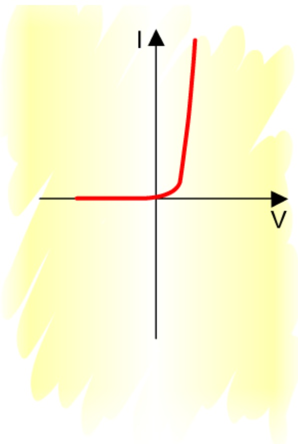
Reverse Bias

When voltage is applied to a diode so that a current does not flow the diode is said to be **reverse biased**. A very small current will actually flow when the diode is reverse biased caused by a small number of electrons that will still be found in the depletion layer, being pushed across the junction. This small current is called the **leakage current** and often is so small it cannot be measured with ordinary meters.



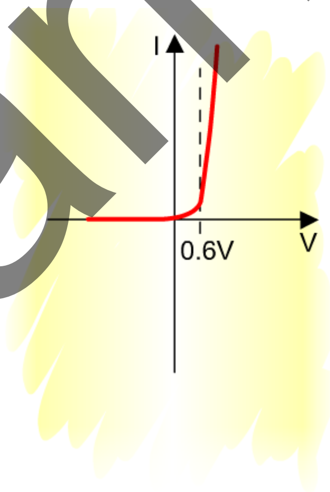
Diode Characteristics

A diode is a semiconductor device that will conduct well in one direction, but stop current flow in the other. The I-V characteristic curve for a diode shows how the current flowing in a diode is dependent upon the voltage that is applied across it.

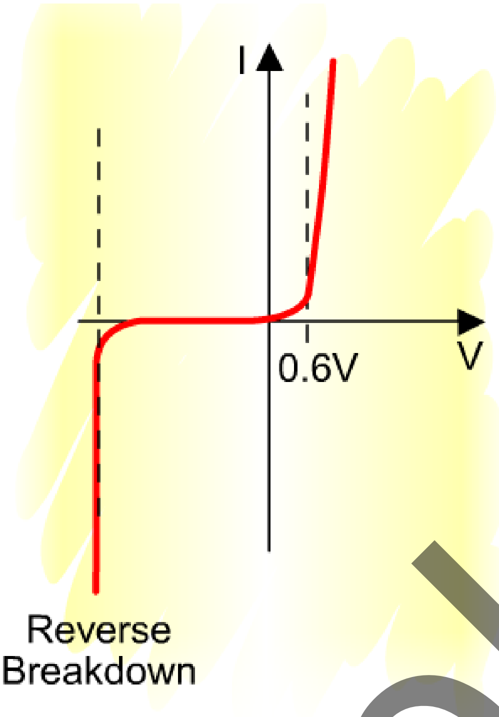


When forward biased, the diode will conduct well and allow a current to pass. When reverse biased, the diode does not conduct and will stop current flowing.

By examining the I-V characteristic curve, it can be seen that the diode doesn't fully conduct straight away when a forward biased voltage is applied across it. Before a diode can fully conduct, the depletion layer must be removed by applying a voltage across the diode. For a silicon diode, typically 0.6V must be applied across the diode before it will conduct.



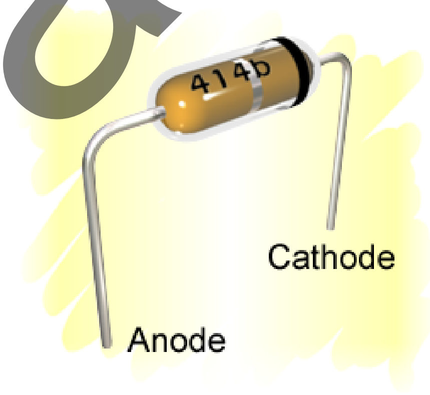
When a diode is reverse biased, a very small current will flow, typically only a few microamps. However, if the reverse bias voltage is sufficiently large, the current will suddenly rapidly increase. At this point, a large number of the outer electrons that were strongly bonded together, gain enough energy to break free. This point is called the **reverse breakdown point**. It is also called the **avalanche voltage**. The value of the avalanche voltage depends on how the diode was manufactured. To prevent damage, a diode must be selected so that the reverse voltage never exceeds this value.



Diode Symbol

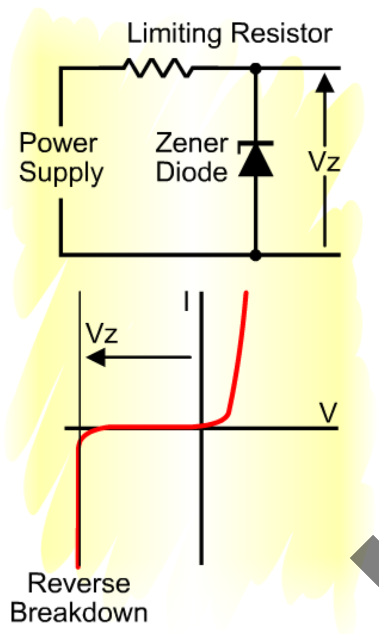
A diode is represented by the following symbol.

The diode will be forward biased when the anode is more positive in respect to the cathode. The cathode on a diode is often marked as shown.



Zener Diode

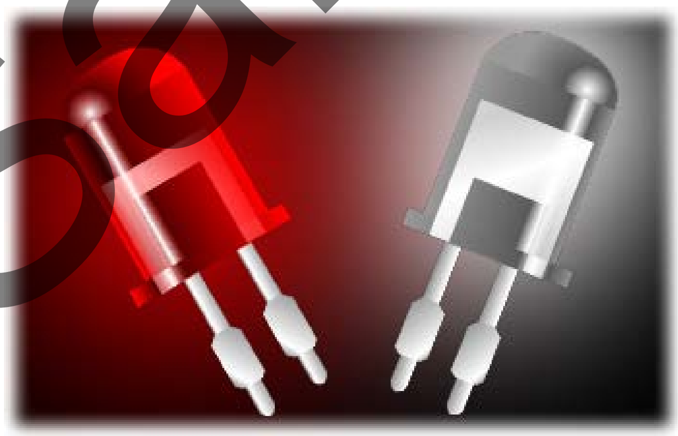
A **zener diode** is a special type of diode that can be used to regulate a voltage. The symbol for a zener diode has a bent bar to indicate the cathode.

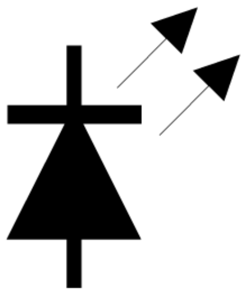


Unlike a standard diode, a zener diode is operated in reverse breakdown mode, with current flowing from cathode to anode.

Light Emitting Diode - LED

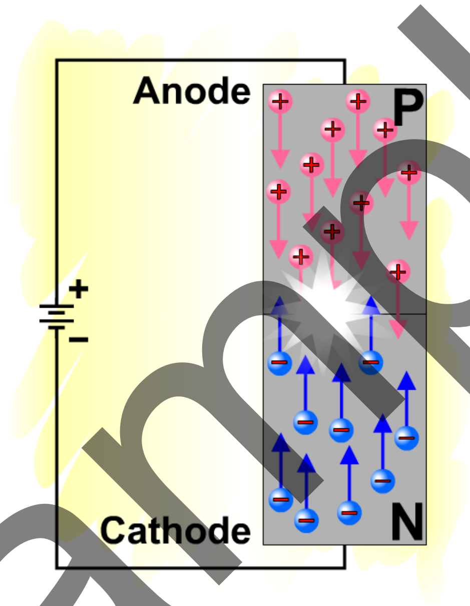
A special type of diode is the Light Emitting Diode (LED). This diode will emit light when it is forward biased. When reverse biased no current will flow, therefore no light will be emitted. The symbol for an LED is a diode symbol with arrows coming off it to indicate that it emits light.



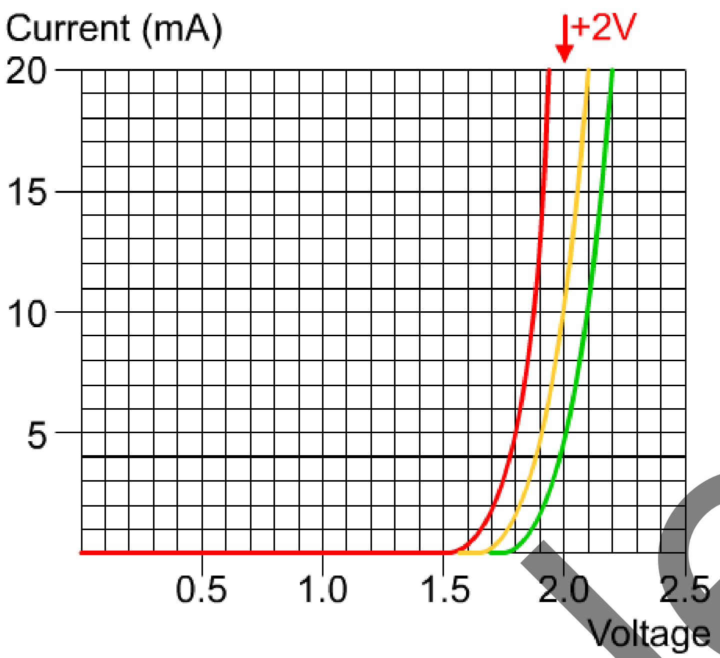


Symbol

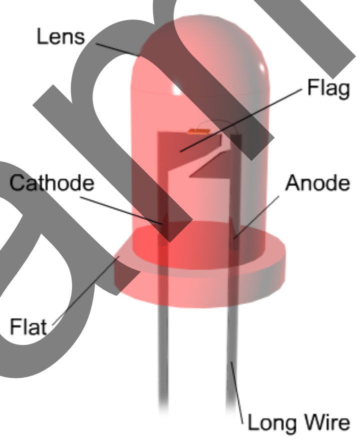
When electrons jump across the junction between the n-type and p-type material to combine with a hole, their energy level changes. In a silicon diode, this energy is converted to heat, but some materials, such as Gallium Arsenide (GaAs), will convert this energy to heat and also to light. Depending on the material used, LEDs that emit red, green, yellow and blue light can be manufactured.



The I-V characteristic for an LED is similar to a standard diode. It can be seen that LEDs require a higher switch-on voltage than ordinary silicon diodes. From the I-V characteristic curve shown, it can be seen that red LEDs are the most efficient, requiring the lowest switch-on voltage. Typically the forward bias voltage required to switch on an LED is about 2V. This compares with about 0.6V for an ordinary silicon diode.



The semiconductor material for an LED is encapsulated in a plastic case which also helps to colour the emitted light. Like a diode an LED has two connections - anode and cathode. The cathode is identified by a flat edge in the base of the LED and the connection wire for the anode is generally the longer wire, unless someone has cut it!



Mathematical Modelling of a Diode

The detailed physics of how diodes are constructed and function are covered in other units. However, we know that an ideal diode will only pass conventional current one way – from anode to cathode. If a diode is connected so that it is reverse-biased then there will be a small leakage current, but that will not be considered here.

We also know that there is some resistance within a diode, due to the physical block of semiconductor material used to construct it, and other physical factors.

One other consideration for a diode is the **turn-on voltage**, V_{on}. This can be thought of as the voltage required to be applied across the p-n junction of the diode before the inherent potential barrier caused during its manufacture can be overcome.

With these three factors in mind, we are now in a position to provide a mathematical model for a diode …

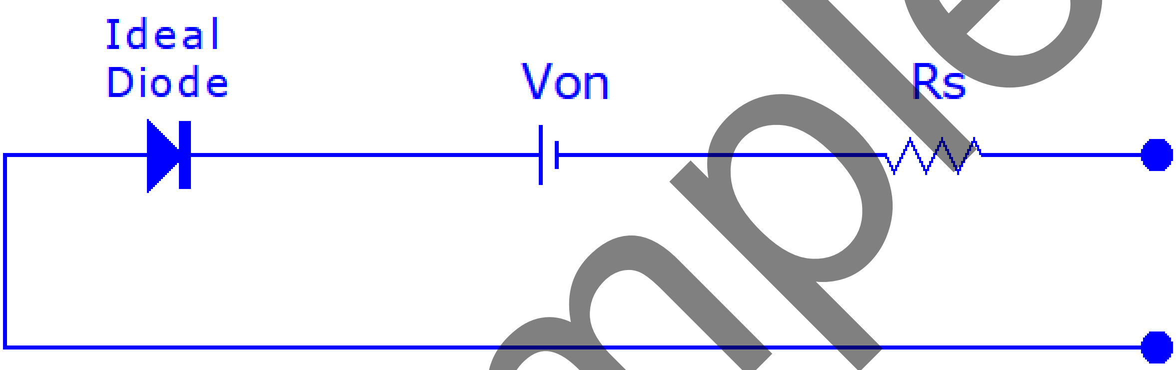


Figure 1: *General mathematical model of a diode*

A typical value for R_s would be 10 Ω, and V_{on} is around 0.7 V for a diode fabricated with silicon. Let us now specify the diode model to be used in our circuit calculations …

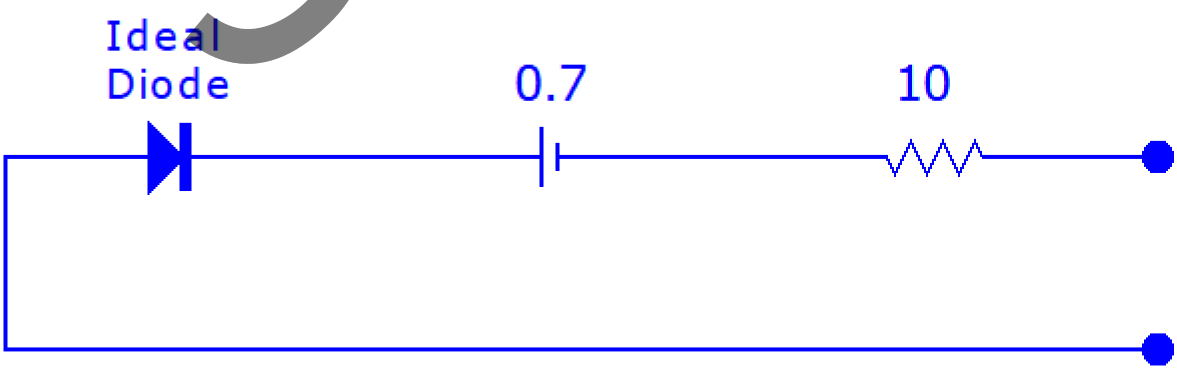
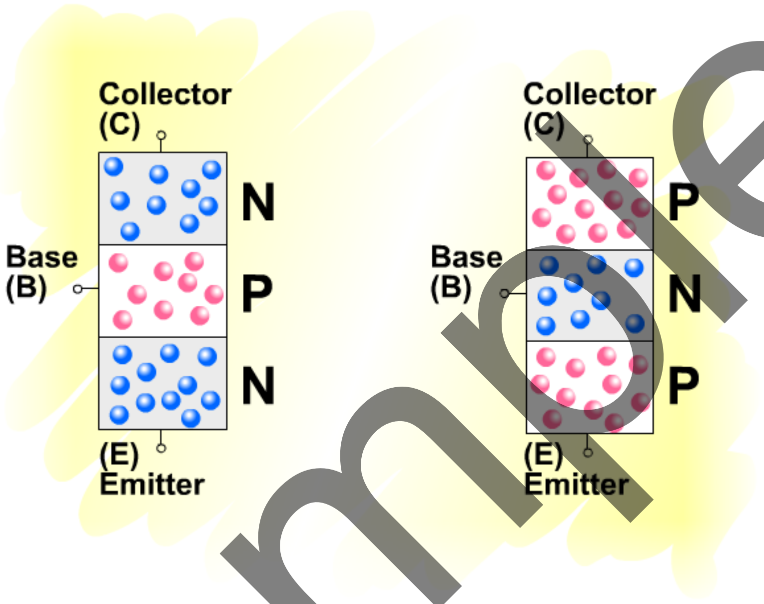


Figure 2: *Useful mathematical model of a diode*

Bipolar Junction Transistor (BJT) Theory

Bipolar Junction Transistor

The bipolar junction transistor is a semiconductor device containing two p-n junctions. To form the two junctions, the semiconductor material is arranged in three layers. This allows two different types of transistor to be created, depending on the order of the n-type and p-type semiconductor layers. The two types of bipolar junction transistors are NPN and PNP, although only the NPN transistor will be considered in this module.

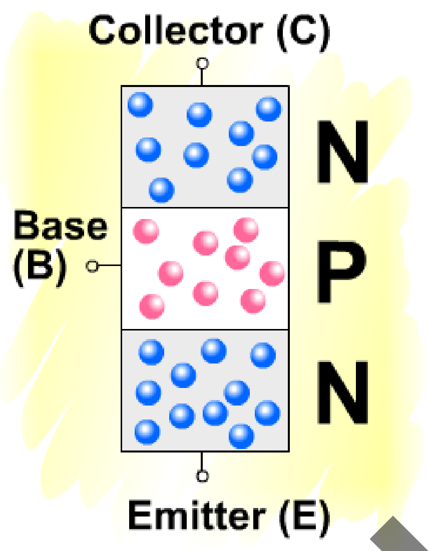


The three layers are called the **base**, **emitter**, and **collector**.

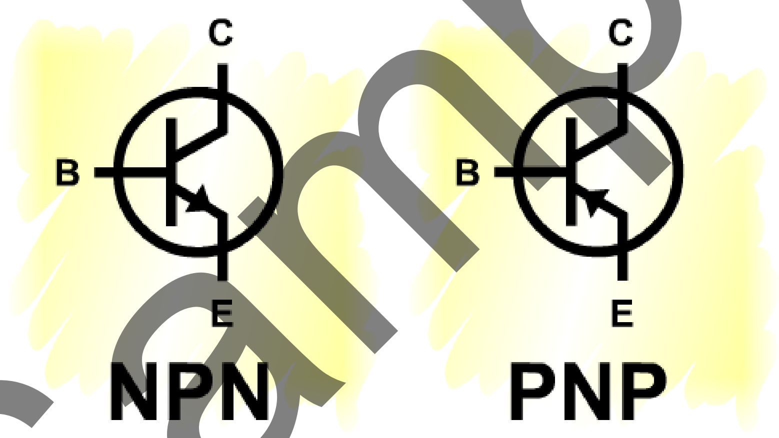
Base (B) - The base is the middle layer of semiconductor material and controls the flow of charge carriers between the emitter and the collector.

Emitter (E) - The emitter region is heavily doped with charge carriers that can be emitted into the base.

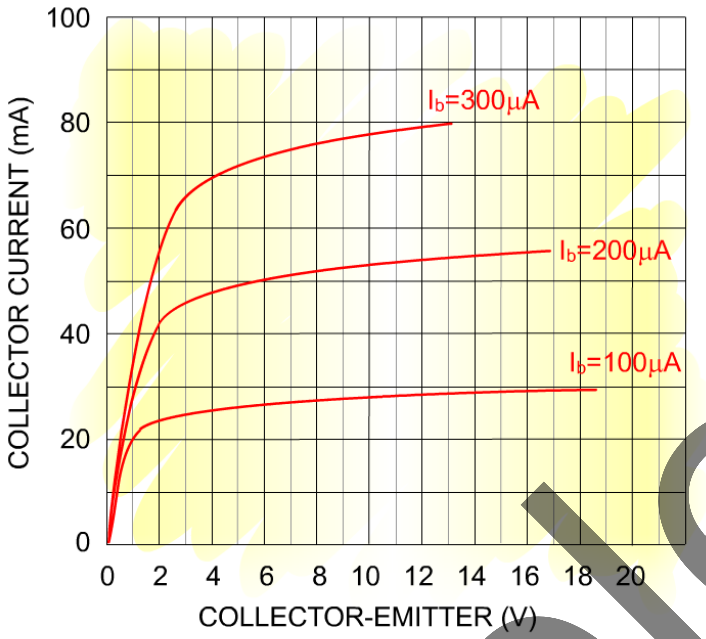
Collector (C) - The collector is lightly doped so that it can collect charge carriers from the base region.



Each type of bipolar junction transistor has its own circuit symbol showing the base, emitter and collector. The arrow on the symbol always appears on the emitter terminal and points from P to N. For an NPN transistor, the arrow on the emitter will point outwards.



The bipolar junction transistor contains two p-n junctions that behave exactly like a diode. Each junction must be correctly biased to allow electrons to flow between the emitter and collector. For this reason, an NPN transistor cannot be replaced by a PNP transistor.



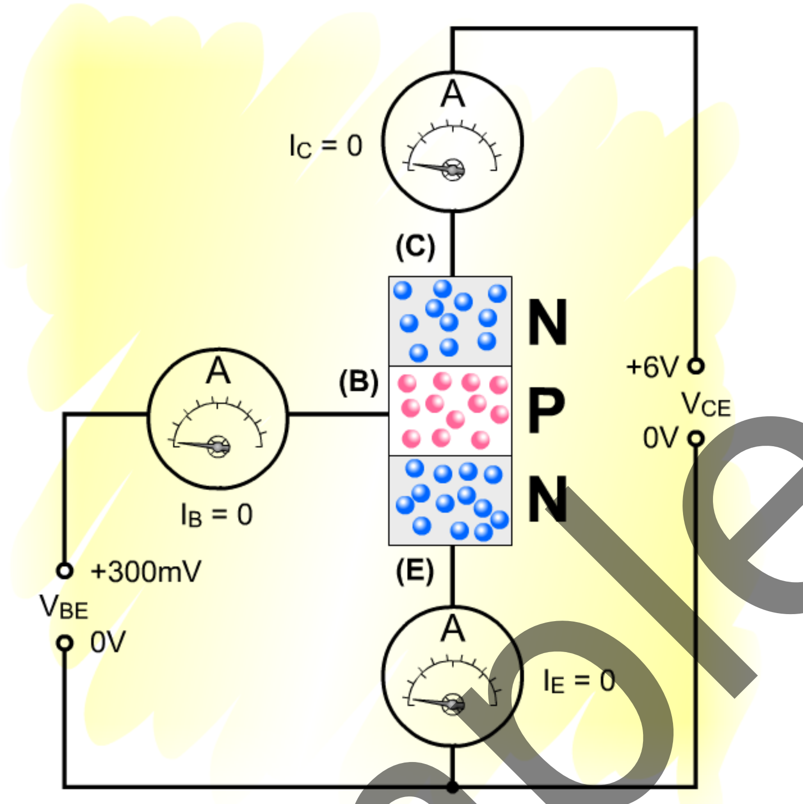
However, above a certain value the collector-emitter voltage has little effect on the collector current (for a given base current) and the transistor becomes more stable. The transistor is generally operated in this stable region, and the output characteristic graph shows what minimum value of collector-emitter voltage must be applied to keep it operating in the stable region.

Transfer Characteristic

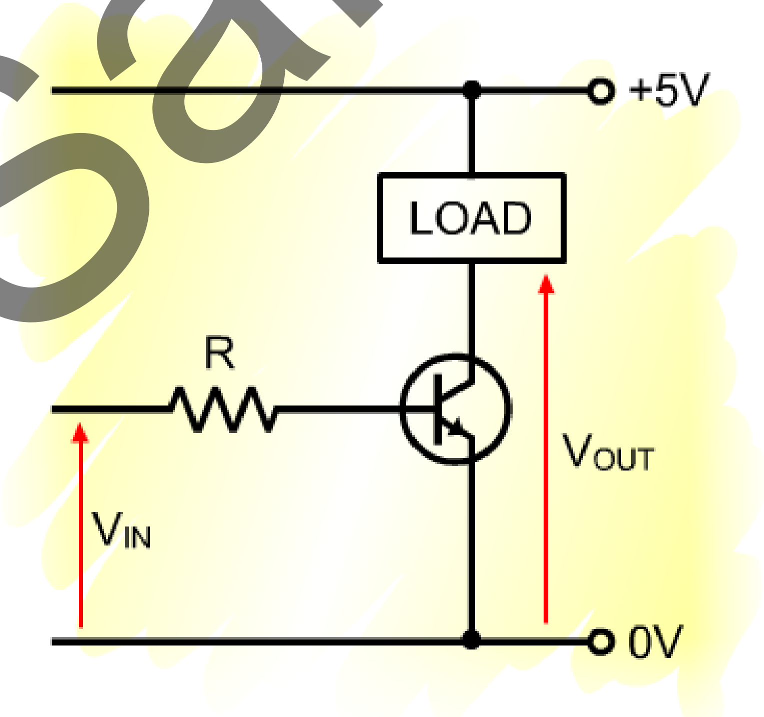
The transfer characteristic shows the collector current against base current at a fixed value of collector-emitter voltage. For a given collector-emitter voltage the graph will be approximately linear, which shows that the base current is almost a constant fraction of the collector current. The transistor acts as a current amplifier. The ratio of collector current to base current is called the DC current gain (h_{FE}).

$$DC\ current\ gain, h_{FE} = \frac{Collector\ current, I_C}{Base\ current, I_B}$$

The value of DC current gain varies between transistors - even between transistors of the same type.

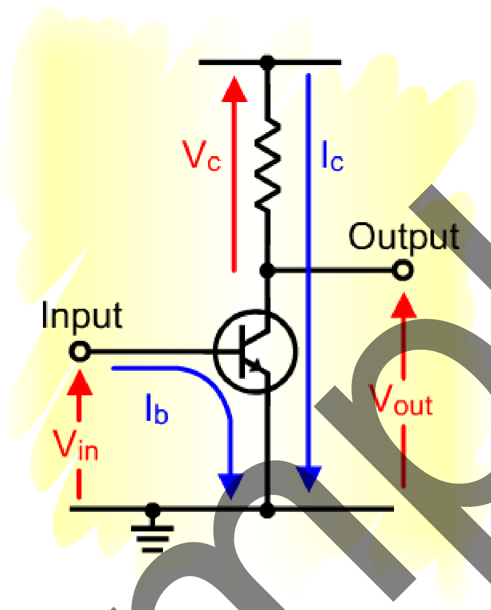


In a practical transistor switch circuit the load is connected between the collector and the positive supply rail. A resistor is connected between the base and the power supply. This is to ensure that the current through the base-emitter junction is kept to a safe level, in order to prevent damage to the transistor.



Voltage Amplifier

In a voltage amplifier, the output voltage is greater than the input voltage. There may or may not be a gain in current. An input voltage (Vin) sets up a small base current (I_b), which in turn causes a much larger collector current (I_c) to flow. The relatively large collector current causes a significant voltage (Vc) across the collector resistor. A small change in the input voltage (Vin) will result in a relatively large change in the output voltage (Vout). The emitter is common to both input and output circuits, so this is called a **Common Emitter Amplifier**.



Mathematical Modelling of a Bipolar Junction Transistor

We shall begin with our model of small-signal bipolar junction transistor …

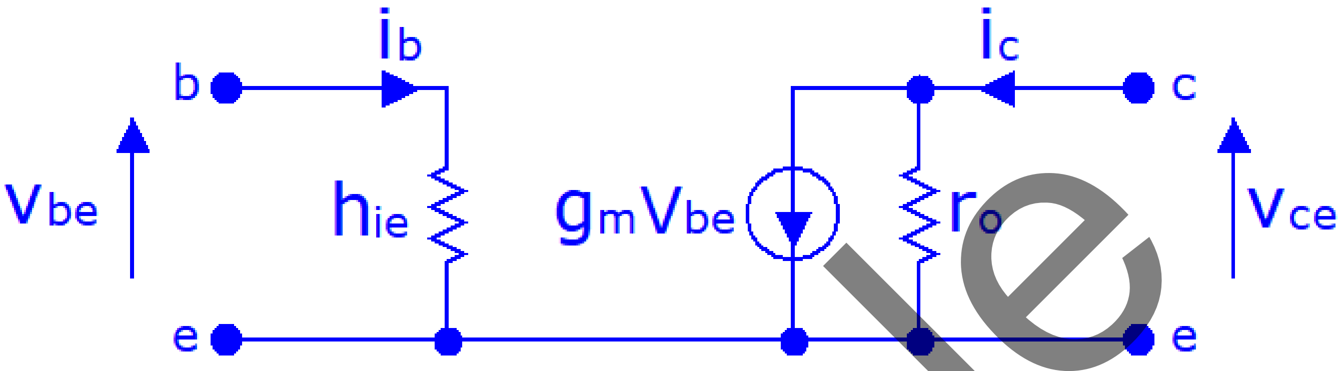


Figure 5: *Small-signal model of a bipolar junction transistor*

Let's start with a key to the terminology used in Figure 5 …

b – base terminal of the BJT

e – emitter terminal of the BJT

c – collector terminal of the BJT

v_{be} – base to emitter voltage

v_{ce} – collector to emitter voltage

i_b – base current

i_c – collector current

h_{ie} – input resistance (between base and emitter for small signals)

g_m – transconductance (change in quiescent collector current/change in quiescent base=emitter voltage)

i.e. $g_m = \frac{dI_C}{dV_{BE}}$

r_o – output resistance (between base and emitter). Sometimes referred to as $1/h_{oe}$

Let's look at an an example amplifier and see how we may calculate various parameters for it …

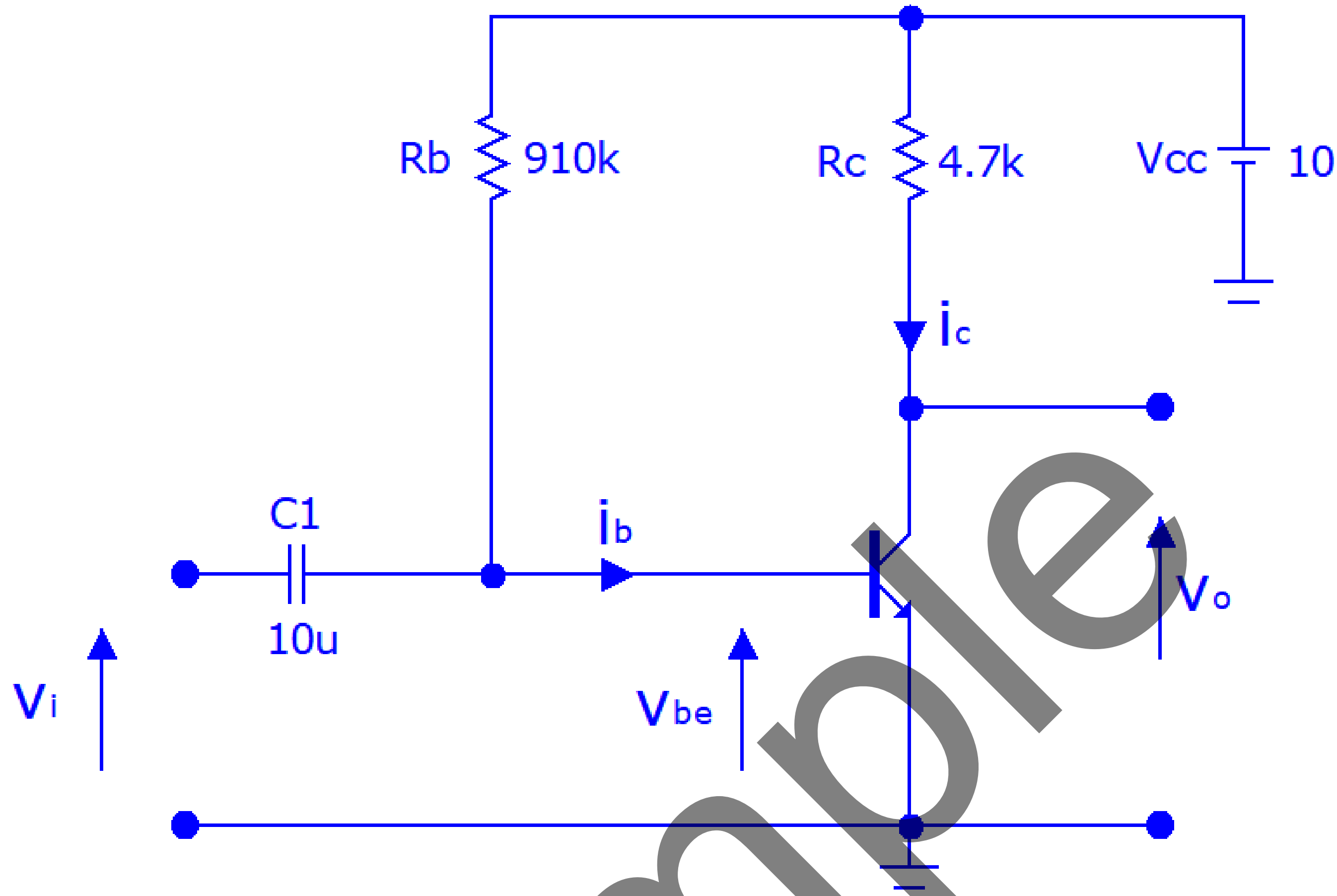


Figure 6: *Amplifier using a bipolar junction transistor*

We are given some data …

$h_{fe} = h_{FE} = 100$

$h_{oe} = 10\ \mu S \quad \therefore \quad r_o = 1/h_{oe} = 1/0.00001 = 100\ k\Omega$

We are required to find the small-signal voltage gain, input resistance and output resistance for this amplifier using a h-parameter model. A silicon npn transistor is used.

NOTE: - when subscripts are in lower case they represent AC parameters. When they are in upper-case they represent quiescent DC parameters (i.e. no signal applied to the input).

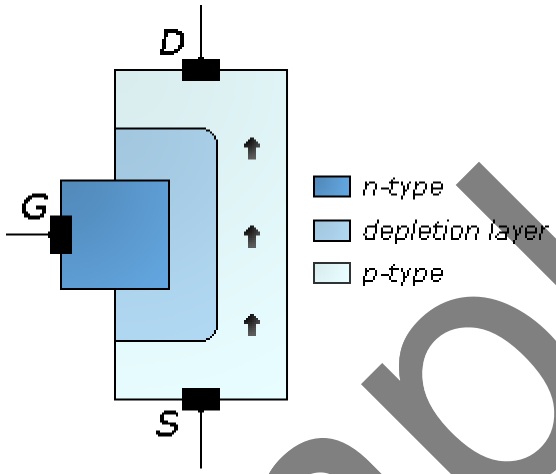
The first step here is to determine the base current. We assume that $v_{BE} = 0.7\ V$ for silicon, so R_b will develop 10 – 0.7 volts i.e. 9.3 volts. Therefore, the quiescent base current i_B is $9.3/910{,}000 = 10.2\ \mu A$.

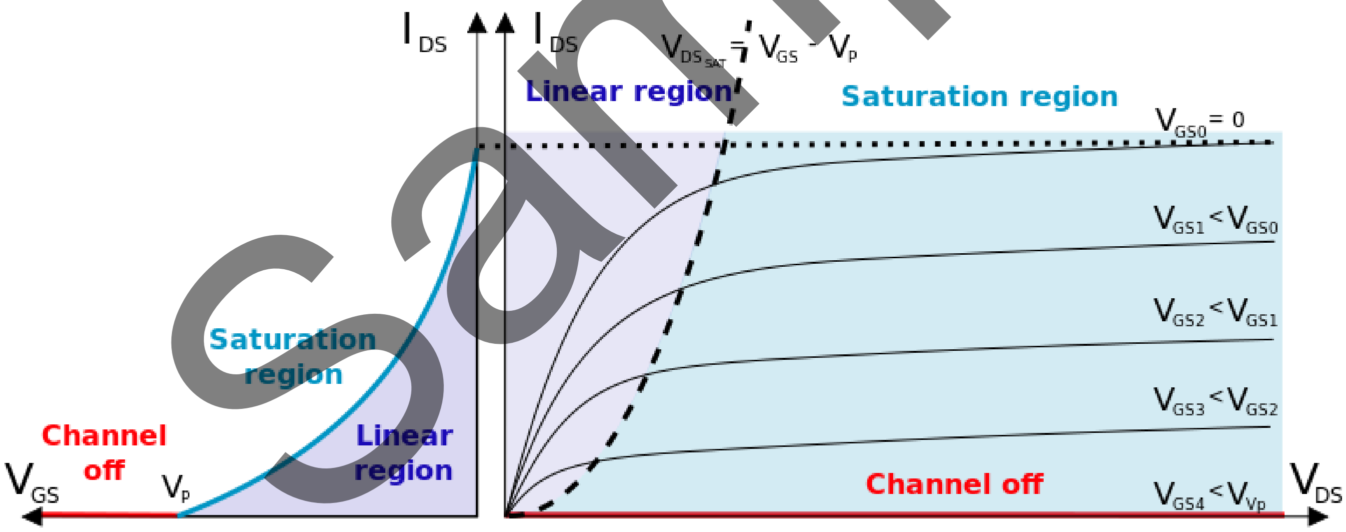
Since we have calculated the base current, and are given the value of h_{FE} we may calculate the quiescent collector current…

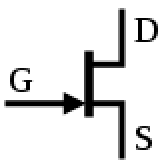
Field Effect Transistor (FET) Theory

Junction Field Effect Transistor (JFET)

This is a three-terminal device which is controlled totally by voltage – it does not require any biasing current. The device has a source, gate and drain. Electric charge flows from source to drain through a semiconducting channel. This channel can be 'pinched' by applying a reverse biasing voltage between the gate and source, thereby narrowing the conducting channel between source and drain and lowering the current.







MOSFETs

The **M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor (MOSFET) can be used in many applications where a bipolar junction transistor, (BJT), is used, plus several where a conventional BJT cannot be used. There are two main types of MOSFET: **Depletion** and **Enhancement**.

The main difference between the two types of MOSFET, is that with no voltage on the Gate terminal (equivalent to the base on a BJT), the Depletion type device conducts, and the Enhancement type device does not.

The Enhancement MOSFET device is the most similar, in operation, to a conventional bipolar junction transistor.

The main reasons for using a MOSFET instead of a bipolar junction transistor are its:

- Very high input impedance
- Lack of susceptibility to thermal-runaway (thermal runaway is when the current in the device causes a temperature increase, which in turn causes the current to increase further causing even more heating)
- Low noise characteristics, allowing very small signals to be handled (noise is an unwanted element introduced onto the required signal)

Compared to a BJT amplifier, MOSFET amplifiers have a low gain so their use is limited to low gain applications. Early MOSFETs were susceptible to damage from electrostatic discharge and so had to be handled carefully, although modern MOSFETs have diode protection to prevent damage.

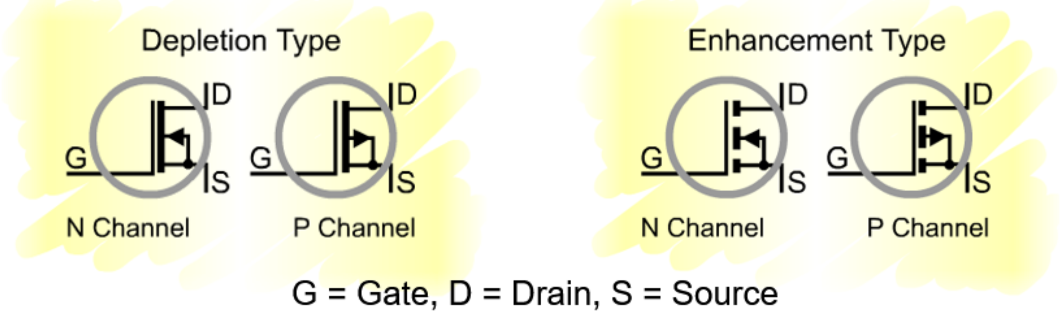
Some applications of MOSFETs are:

Driver - used to interface low current output circuits to relatively high current devices.

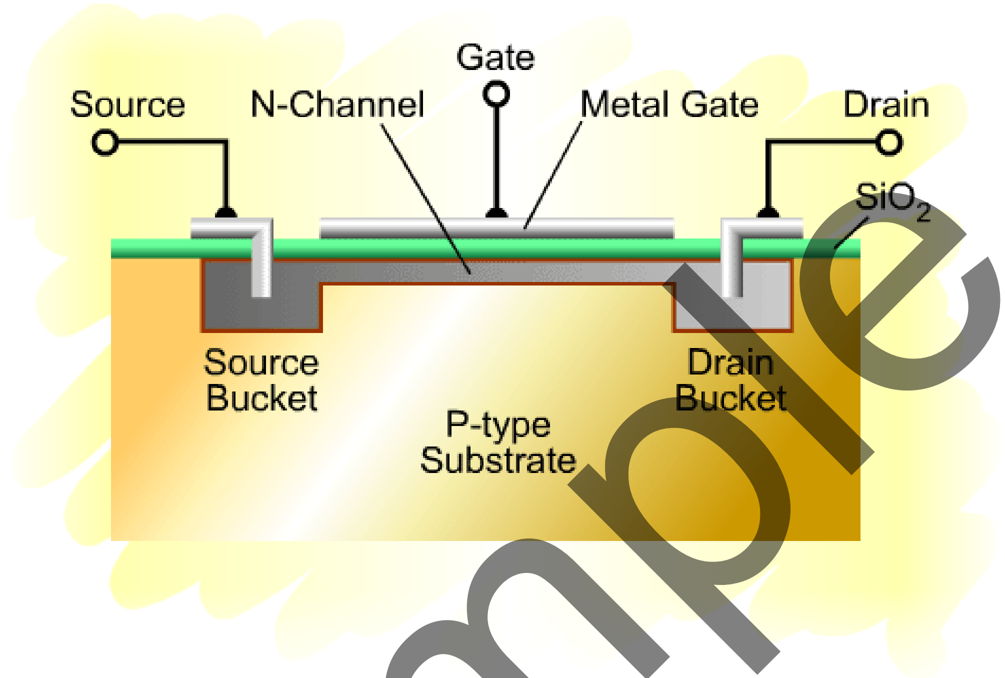
Buffer/Voltage Follower - Their high input impedance and low noise characteristics make them ideal for applications such as first stages of measurement instruments, radio receivers and amplifiers.

Voltage Controlled Resistor - Used as voltage controlled resistors in applications such as Automatic Gain Control, and Voltage Controlled Filters/Attenuators.

Power Amplifier and Switching Applications - MOSFETs have very low ON resistances (typically < 2Ω), meaning low power dissipation in the device.



The n-channel MOSFET is made on a p-type substrate with an n-type channel diffused into the top surface layer. An insulating layer of silicon dioxide (SiO_2) is laid on top. Three connections are made to the device, **Source**, **Drain** and **Gate**, which are the MOSFET equivalent of the Emitter, Collector and Base on a bipolar junction transistor.



The channel exists between the source and drain and allows a current to flow even when there is no signal connected to the gate. No current will flow into the gate due to the insulating layer of silicon dioxide.

The characteristic curves for depletion and enhancement MOSFETs are similar except that the curves for the enhancement type are shifted by an amount equal to the threshold voltage. This is because, before it can conduct, the enhancement type MOSFET has to have a gate voltage greater than the threshold voltage.