Course Code - 21EC1203 **Course Name: Design of Basic Electronic Circuits**
L-T-P-S: 3-0-0-0 **Credits: 3** **Prerequisite: NIL**

CO#	Course Outcome (CO)	PO	PSO	BTL
CO1	Understand the basic electronic components.	1,5	1	2
CO2	Understand the basic circuit analysis techniques	1,5	1	2
CO3	Understand the active circuit elements and working.	1,5	1	2
CO4	Analyze the applications of semiconductor devices	1,5	1	4

DESIGN OF BASIC ELECTRONIC CIRCUIT

Lecture Notes

CO3

DIODE

Introduction:

- When one side of a single-crystal semiconductor is doped with acceptors and the other side is doped with donors, a p-n junction is produced and is referred to as a junction diode.

- A **diode** refers to a two-terminal solid-state semiconductor device that presents low impedance to current flow in forward direction and high impedance to current flow in the opposite direction. This property makes the diode to be used for unidirectional current applications in electronic circuits.

- It offers a low resistance on the order of milliohms in one direction and a high resistance on the order of giga ohms in the other direction.

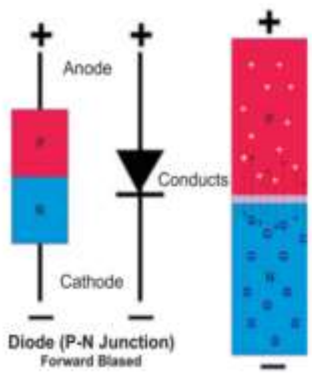
- A diode exhibits a nonlinear relation between the voltage across its terminals and the current through it.

- Indirect semiconductor materials like 'Si' and 'Ge' are used for construction of general purpose diodes.

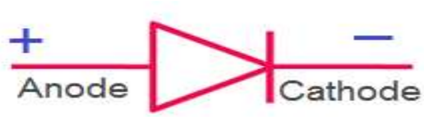
- Small signal diodes can be used as rectifiers in low-power, low current (less than 1-amp) applications. But for larger forward bias currents or higher reverse bias blocking voltages due to overheat involved with PN junction, small signal diode would melt so **Power Diodes** will be replacing their small signal counter parts.

- Used in various applications for switching purpose, rectification and harmonic generation.

- **A pn junction is known as a semiconductor diode.**



- **Circuit symbol**

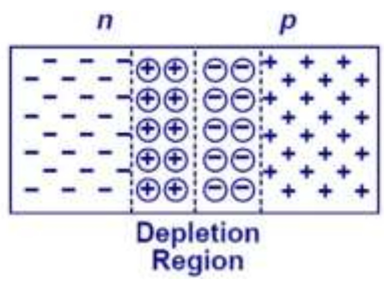


Anode terminal is represented by the arrow head, which also indicates the direction of conventional current flow through the device, and cathode by a vertical line.

JUNCTION THEORY

UNBIASED JUNCTION OR OPEN CIRCUITED JUNCTION

The semiconductor junction is formed by simply bringing P and N Type semiconductor materials together. At junction electrons and holes from either sides of the junction will diffuse and combine, which results in a lack of mobile carriers in the region near the junction called as ***depletion or space charge or transition region*** and establishes a **contact potential** near the junction equal to $\Delta V = V_T \ln\left(\frac{N_D N_A}{n_i^2}\right) = V_T \ln\left(\frac{N_D N_A}{A_0 T^3 e^{-E_g/kT}}\right)$



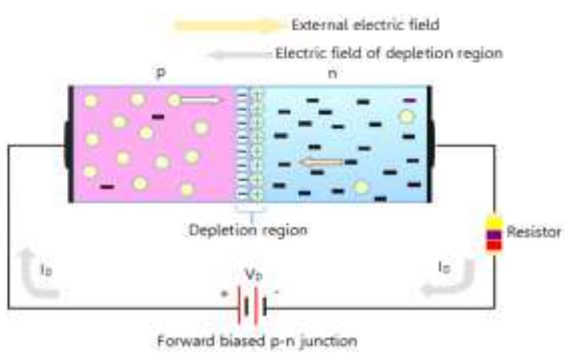
In the absence of an applied bias voltage, the net flow of charge in any one direction for a semiconductor diode is zero.

BIASED JUNCTION:

Act of providing necessary external voltage to the junction to establish sufficient current passage through the device is called as biasing the junction. It is categorized as

a. Forward Bias ($V_d > 0$)

1. A forward-bias or "on" condition is established by applying the positive potential to the p-type material and the negative potential to the n-type material as shown in Fig.



2. **Decreases** depletion region width and barrier potential depending on applied voltage which subsequently increases the current flow due to the majority carriers.

3. Applied voltage more than barrier potential (Cut in voltage /knee voltage) contributes for charge flow (current) across junction.

4. Current contribution is due to majority charge carriers and **diffusion/forward** current exponentially increases with applied voltage as given *diode equation* by

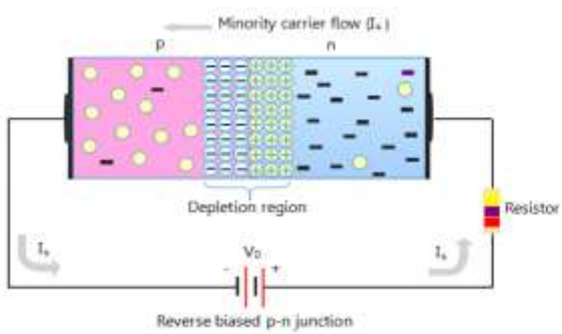
$$I = I_0\left(e^{\frac{v_d}{\eta V_T}} - 1\right) \approx I_0 e^{\frac{v_d}{\eta V_T}}.$$

I	Current through the diode, in A
v_d	Diode voltage with the anode positive with respect to the cathode, in V
I_0	Leakage (or reverse saturation) current.
η	empirical constant known as the *emission coefficient* or the *ideality factor*.
V_T	Voltage equivalent of temperature ($=\frac{kT}{q}$)

5. Diode resistance decreases and **small** (closely in **ohms**).
6. Treated as a switch in **on** condition during its operation.

b. Reverse Bias ($V_d < 0$)

1. A reverse bias is established by applying external potential across the p-n junction such that the positive terminal is connected to the n-type material and the negative terminal is connected to the p-type material as shown in Fig.



2. Depletion region width increases depending on applied voltage.
3. Applied voltage more than breakdown voltage contributes for large amount of charge flow (current) across junction.
4. Current contribution is due to minority charge carriers and leakage or **reverse** current.
5. Diode resistance is very **large** (nearly in *Mega ohms*).
6. Treated as a switch in **off** condition during its operation.

c) Zero External Voltage: ($V_d = 0$)

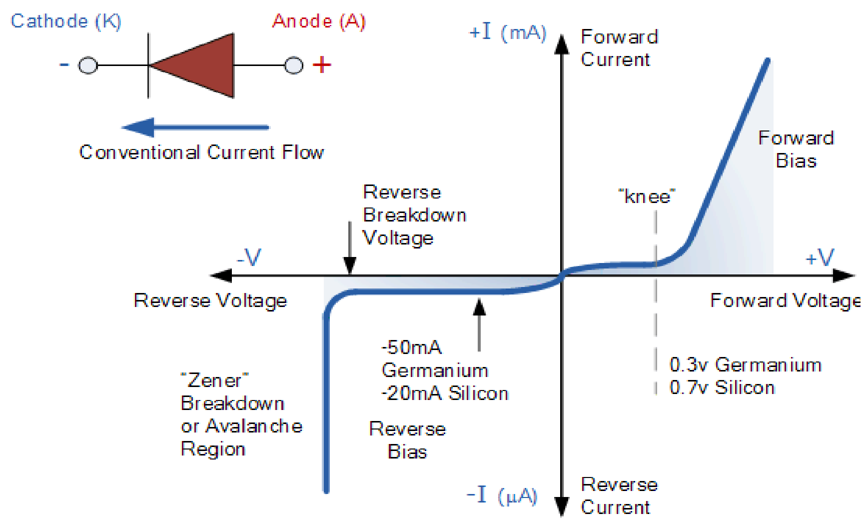
When no external voltage is applied i.e circuit is open and no current flow through the circuit.

V-I CHARACTERISTICS

1. For positive values of V_d ($V_d > 0$) , from Diode Equation $I = I_0(e^{\frac{V_d}{\eta V_T}} - 1) \approx I_0 e^{\frac{V_d}{\eta V_T}}$, the first term of the equation above will grow very quickly and effect of the second term will be neglected. Hence it appears as an exponential function for forward bias.

   a. The diode current will be very small for $V_d < V_{TD}$, known as the *threshold voltage or the cut-in voltage or the turn-on voltage* (typically 0.7 V for 'Si' and0.3V for 'Ge').

   b. The diode conducts fully if '$V_d > V_{TD}$'. Thus, the threshold voltage is the voltage at which a forward-biased diode begins to conduct fully.



2. From Diode equation, in the reverse bias ($V_d < 0$),

   a. For diode voltage $V_d < 0$, $I = I_0$ and practically a small current in micro ampere will flowfor voltages below reverse break down voltage.

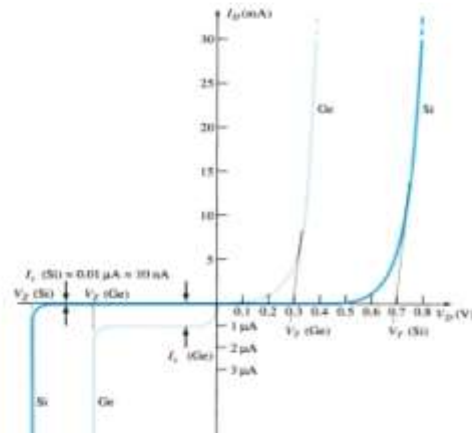
   b. For diode voltage $V_d > V_{\text{break down}}$, large current appears due to the junction break down which damages diode in case of ordinary P-N junction diodes.

3. **Effect of material:**

   a. Silicon diodes have, in general, higher PIV and current rating and wider temperature ranges than germanium diodes.

   b. From contact potential of the junction $\Delta V = V_T \ln\left(\frac{N_D N_A}{n_i^2}\right) = V_T \ln\left(\frac{N_D N_A}{A_0 T^3 e^{-E_g/kT}}\right)$,

   'Ge'with relatively smaller energy gap of 0.7 ev than 'Si'of 1.4ev is exhibiting a lower cut in and break down potentials and large currents for even small values of voltages.

c. 

4. Effect of temperature

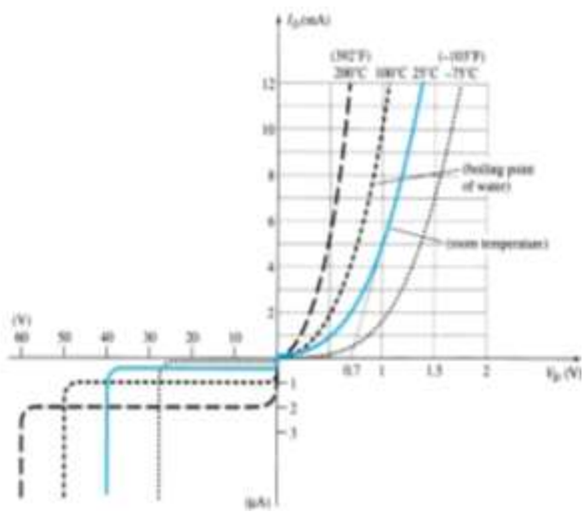
a. Reverse saturation current doubles for every 10^0c raise in temperature as given by $I_s = K\,T^m e^{-V_{g0}/\eta V_t}$ *i.e* $\dfrac{I_{s2}}{I_{s1}} = 2^{\frac{T_2 - T_1}{10}}$.

b. Cut in potential reduces by 2mv/^{0}c, as given by

$$V_{T2} = V_{T1} + K_{TC}(\mathrm{T}_2 - \mathrm{T}_1)$$

where K_{TC} is the temperature coefficient

c. Resultant effect is as shown in Fig



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Problems to be solved

1.1 The measured values of a diode at a junction temperature of 25°C are given by V_D=0.5V when I_D=5μA and V_D=0.6Vwhen I_D=100μA Determine (a) the emission coefficient (b) the leakage current.

1.2 Determine the diode current at 20 c for a silicon diode with Is=50nA with an applied forward voltage 0.6V.

1.3 The measured values of a diode at a junction temperature of 25°C are given by $V_d = 0.5V$ at $I_d = 5\mu A$ and $V_d = 0.6V$ at $I_d = 100\mu A$. Find η and I_s.

Review Questions:

1.4 What is a *pn* junction?

1.5 Explain diffusion.

1.6 Describe the depletion region.

1.7 Explain what the barrier potential is and how it is created.

1.8 What is the typical value of the barrier potential for a silicon diode?

1.9 What is the typical value of the barrier potential for a germanium diode?

DIODE RESISTANCE

Diode will exhibit resistance for current flow due to its materialistic properties. This resistance will be considered depending upon the type of input signal. Three types of resistance levels s are defined for a diode as given below

1. **DC or Static Resistance:** The application of a dc voltage to a circuit containing a semiconductor diode will result in an operating point. The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D given by

$$R_s = \frac{V_D}{I_D}$$

Note: The lower the current through a diode the higher the dc resistance level. The dc resistance levels at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics.

2. **AC or Dynamic Resistance:** Any varying input applied to input will move the instantaneous operating point up and down a region of the characteristics and thus defines a specific change in current and voltage. A tangent line drawn to the curve through the Q-point will define a particular change in voltage and current that can be used to determine dynamic resistance for that region of the diode characteristics given by $r_d = \frac{\Delta V_d}{\Delta I_d}$

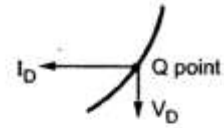
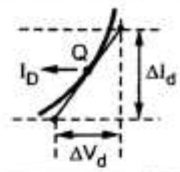
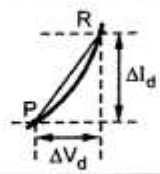
Note: More accuracy will be achieved with small segment of variations.

For small signal variations $r_d = \frac{26mV}{I_D}$ *,where* I_D *is quiescent point current.*

3. **Average AC Resistance**

If the input signal is sufficiently large to produce a broad swing such as the resistance associated with the device for this region is called the **average ac resistance.** The average ac resistance is the resistance determined by a straight line drawn between the points corresponding to the maximum and minimum values of input voltage given by

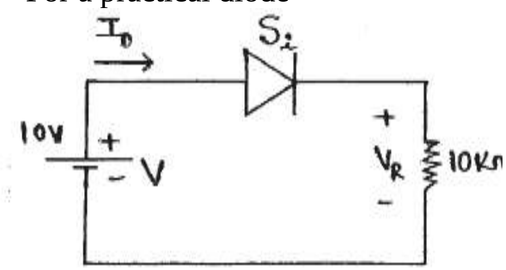
$$r_{av} = \frac{V_B - V_A}{I_B - I_A}$$

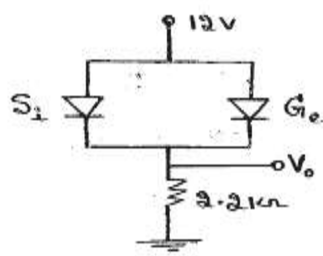
Resistance level type	Mathematical Equation	Construction required	Graphical representation
D.C. or Static	$R_D = \frac{V_D}{I_D}$ at Q point	Obtain Q point on the characteristics	
A.C or Dynamic	$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{26 \text{ mV}}{I_D}$	Draw a tangent line at Q point, to the characteristics.	
Average a.c. resistance	$r_d = \left.\frac{\Delta V_d}{\Delta I_d}\right\|_{\text{pt. to pt.}}$	Draw a straight line joining two points corresponding to maximum and minimum values of voltage	

Problems to be solved

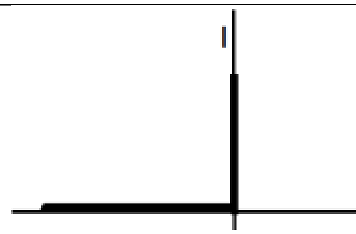
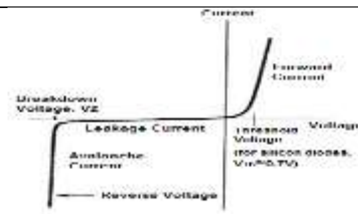
Estimate the static diode resistances for the diodes from the given circuits

a. For an ideal diode
b. For a practical diode





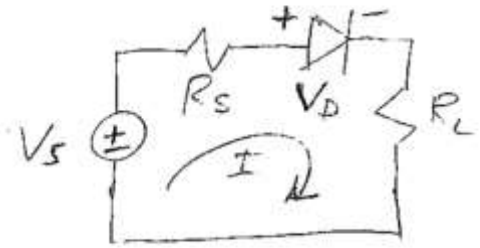
IDEAL Vs PRACTICAL DIODES

Characteristic	**Ideal**	**Practical**
Threshold Voltage	No Threshold Voltage	Depends on material used
Forward current	Infinite if Vin > 0V	Finite
Forward Resistance	Zero	Finite
Reverse Resistance	Infinite	Large but finite
Breakdown Voltage	No Breakdown	Finite and depends on
Equivalent Ckt		
Forward bias		
Reverse bias		
V-I Characteristic		

Load line analysis for a diode circuit

A load line is used in graphical analysis of nonlinear electronic circuits, representing the constraint other parts of the circuit place on a non-linear device, like a diode or transistor. It is usually drawn on a graph of the current vs the voltage in the nonlinear device, called the device's characteristic curve. A load line, usually a straight line, represents the response of the linear part of the circuit, connected to the nonlinear device in question.

The example below shows how a load line is used to determine the current and voltage in a simple diode circuit. The diode, a nonlinear device, is in series with a linear circuit consisting of a resistor, R and a voltage source, V_{DD}. The characteristic curve *(curved line)*, representing the current *I* through the diode for any given voltage across the diode V_D, is an exponential curve. The load line *(diagonal line)* represents the relationship between current and voltage due to Kirchhoff's voltage law applied to the resistor and voltage source

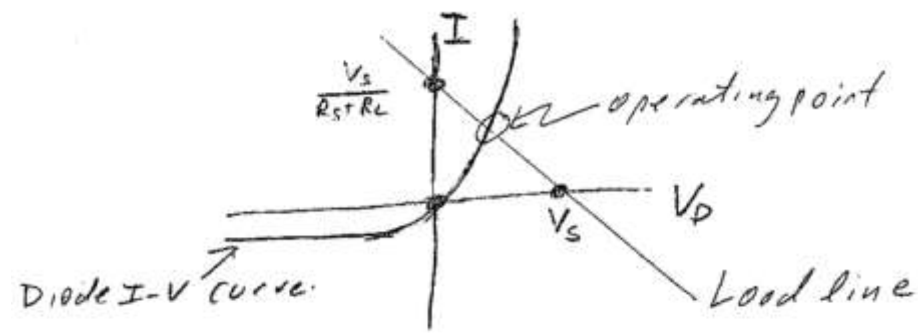


$$-V_S + IR_S + V_D + IR_L = 0$$

$$\therefore\ I = \frac{V_S - V_D}{R_S + R_L}$$

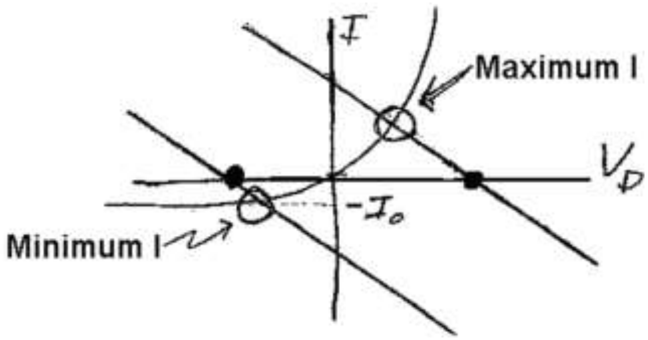
A plot of the current, I, versus the voltage drop across the diode, V_D, will yield a straight line, called the "Load Line", of possible values of current flow in the circuit. Since the current going through the three elements in series must be the same, and the voltage at the terminals of the diode must be the same, the operating point of the circuit will be at the intersection of the curve with the load line.

We form the line by noting that I = 0 at $V_D = V_S$ and that $I = V_D/(R_S + R_L)$ at $V_S = 0$, as shown below:



The so called "Operating Point" is found through the second equation that relates I and V_D, namely the diode equation $I = I_0[\exp(V_D/K_BT) - 1]$. The I-V relation for the diode will cross the Load Line at the Operation Point (open circle above). This provides a graphical solution for the currents and voltages in a circuit with a diode.

What happens when the source voltage changes with time, i.e., $V_S = V_S(t)$? Here the Load Line varies with time; the slope is constant at $dI/dV = -1/(R_S + R_L)$ while the intercept shifts, as shown below. When $V_S(t)$ varies symmetrically around zero, as with the AC line, we see that the maximum positive value of $V_S(t)$ leads to the maximum current flow, while the maximum negative value of $V_S(t)$ leads to a minimal current, so that asymptotically $I(V_S \rightarrow -\infty) \rightarrow -I_0$. The rhythmic change in Operating Point (open circles below) is the basis of the half-wave rectifier that you constructed.



Breakdown in Junction Diode

The breakdown of the pn junction can be of two types, these are

(i) Avalanche Breakdown

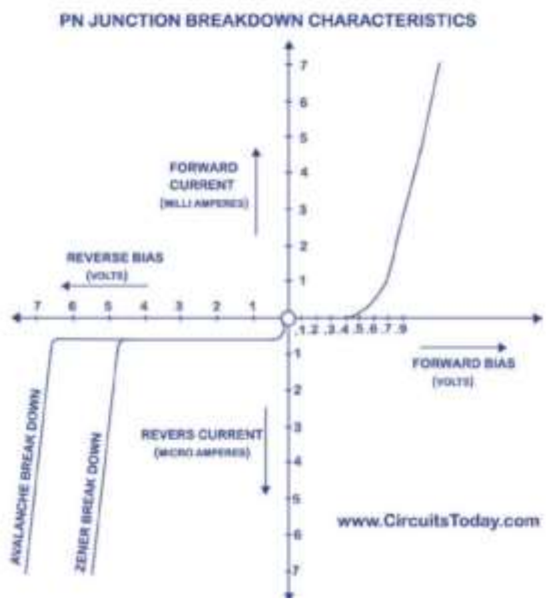
For thicker junctions the breakdown mechanism is by the process of avalanche breakdown. In this mechanism when the electric field existing in the depletion layer is sufficiently high, the velocity of the carriers (minority carriers) crossing the depletion layer increases. These carriers collide with the crystal atoms. Some collisions are so violent that electrons are knocked off the crystal atoms, thus creating electron hole pairs as the pair of electron hole is created in the midst of the high field, they quickly separate and attain high velocities to cause further pair generation through more collisions. This is cumulative process and as we approach the breakdown voltage, the field becomes so large that the chain of collisions can give rise to an almost infinite current with very slight additional increase in voltage. The process is known as avalanche breakdown. Once this breakdown occurs, the junction cannot regain its original position. Thus the diode is said to be burnt off.

In a Simple Explanation: Avalanche breakdown occurs in normal P N junctions. Since the doping level is normal there is large depletion layer when the diode is rev. biased. Increased rev. bias imparts more energy to minority carriers. Further increase in rev. bias gives higher momentum to carriers. They collide with crystal ions and break covalent bonds. Generated carries after getting enough energy produce more carries. Reverse current increases rapidly giving rise to **avalanche breakdown**

Zener Breakdown

This breakdown takes place in a very thin junction i.e. when both sides of the junction are very heavily doped and consequently the depletion layer is narrow. In the zener breakdown mechanism, the electric field becomes as high as 10^7 v/m in the depletion layer with only a small applied reverse bias voltage. In this process it becomes possible for some electrons to jump across the barrier from the valence band in p- type material to some of the unfilled conduction band in n-material. This process is known as zener breakdown. In this process the junction is not damaged.

In a Simple Explanation: When PN Junction is heavily doped the depletion layer is thin. When Reverse bias is increased there is high electric field due to thin depletion layer. This high field ruptures covalent bonds and generates large no. of carriers, so large current-**Zener breakdown** occurs



Special Diodes

A number of specific types of diodes are manufactured for specific applications in this fast developing world. Some of the more common special-purpose diodes are

(i) Zener diode
(ii) Light-emitting diode (LED)
(iii) Photo-diode
(iv) Tunnel diode
(v) Varactor diode and
(vi) Shockley diode

Zener Diode :

A zener diode is a special type of diode that is designed to operate in the reverse breakdown region. An ordinary diode operated in this region will usually be destroyed due to excessive current. This is not the case for the zener diode. A zener diode is heavily doped to reduce the reverse breakdown voltage. P and N regions are highly doped (1:105). Its symbol has Ƶ instead of bar in normal diode. These diodes operate in reverse breakdown called Zener breakdown. For most of the diodes zener breakdown occurs up to 6v of Rev. Bias. Forward characteristics similar to normal diode. At breakdown, diode maintains constant voltage. There is minimum value of breakover current to maintain diode in breakdown region. This causes a very thin depletion layer. As a result, a zener diode has a sharp reverse breakdown voltage VZ. This is clear from the reverse characteristic of zener diode shown in Fig. Note that the reverse characteristic drops in an almost vertical manner at reverse voltage VZ.

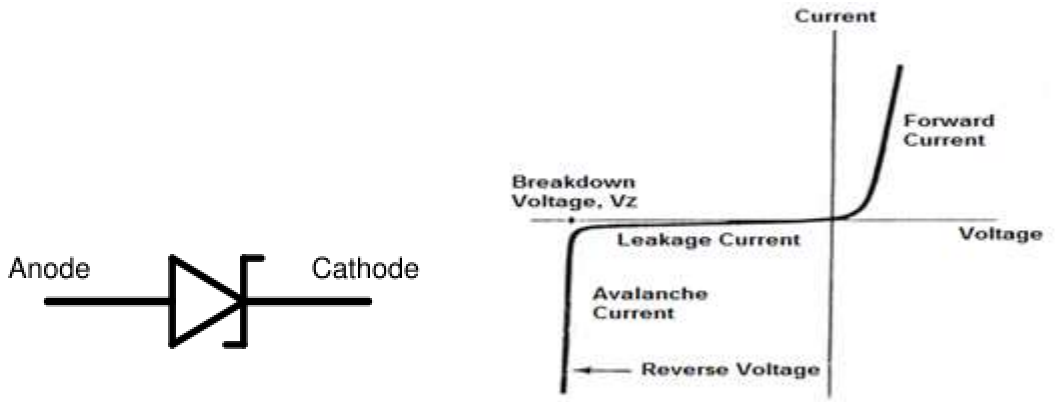


Fig: Zener diode symbol and characteristic curve

As the curve reveals, two things happen when VZ is reached : (i) The diode current increases rapidly. (ii) The reverse voltage VZ across the diode remains almost constant. In other words, the zener diode operated in this region will have a relatively constant voltage across it, regardless of the value of current through the device. This permits the zener diode to be used as a voltage regulator.

Apllications of zener diode

Used as voltage regulator, voltage reference, wave shaping etc

Zener Diode

A specially designed silicon diode which is optimised to operate in the breakdown region is known as as zener diode.

Characteristics of Zener Diode

(i) Its characteristics are similar to an ordinary diode with the exception that it has a sharp (or distinct) breakdown voltage called zener voltage v_z.

(ii) It can be operated in any of the three region i.e. forward, leakage or breakdown. But usually it is operated in the breakdown region as shown in above figure.

(iii) The voltage is almost constant (v_z) over the operating region.

(iv) Usually, the value of v_z at particular test current I_{zr} is specified in the data sheet.

(v) During operation it will not burn as long as the external circuit limits the current flowing through it below the burn out value i.eI_{zr} (the maximum rated zener current).

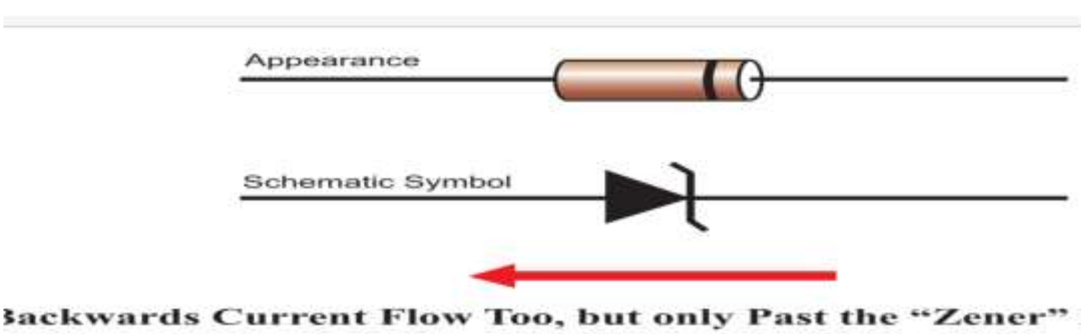


Figure-12

Application

(i) Meter Protection

(ii) Voltage Regulator

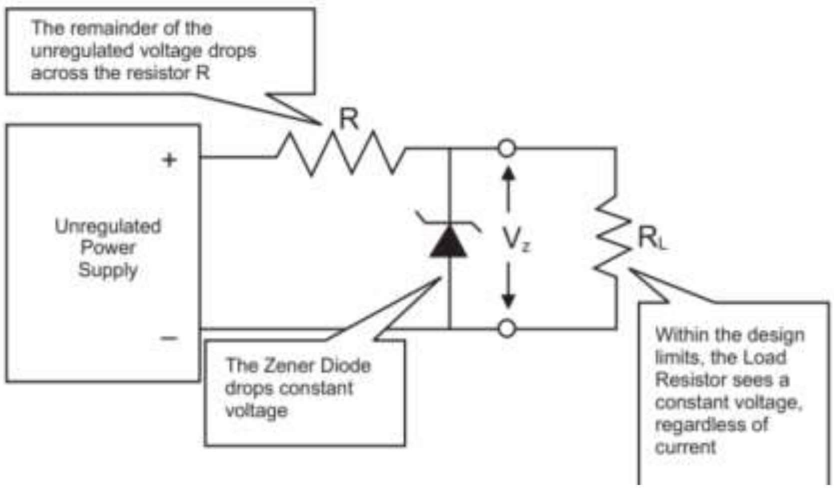
(iii) Wave Shaping Circuit

Zener Diode Regulator

The major application of zener diode in the electronic circuit is as a voltage regulator. It provides a constant voltage to the load from a source whose voltage may vary over sufficient range. The zener diode of zener voltage V_z is reverse connected across the load R_1 across which constant voltage is desired. A resistor R is connected in series with the circuit which absorbs the output voltage fluctuation so as to maintain constant voltage (V_0) across the load.

Let a variable voltage Vin be applied across the load R_1. When the value of Vin is less than zener voltage V_z of the zener diode. No current flows through it and the same voltage appears across the load. When the input voltage Vin is more than V_z this will cause the zener diode to conduct a large current I_z .

In the above discussion it has been seen that when a zener diode of zener voltage V_z is connected in reverse direction parallel to the load. It maintains a constant voltage across the load equal ypVz and hence stablises the output voltage.



Light-Emitting Diode (LED):

A light-emitting diode (LED) is a diode that gives off visible light when forward biased. Light-emitting diodes are not made from silicon or germanium but are made by using elements like gallium, phosphorus and arsenic. By varying the quantities of these elements, it is possible to produce light of different wavelengths with colours that include red, green, yellow and blue. For example, when a LED is manufactured using gallium arsenide, it will produce a red light. If the LED is made with gallium phosphide, it will produce a green light.

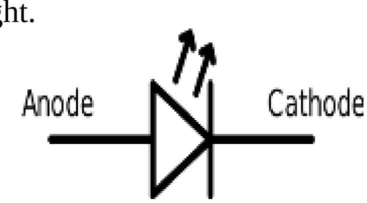


Fig: Light emitting diode

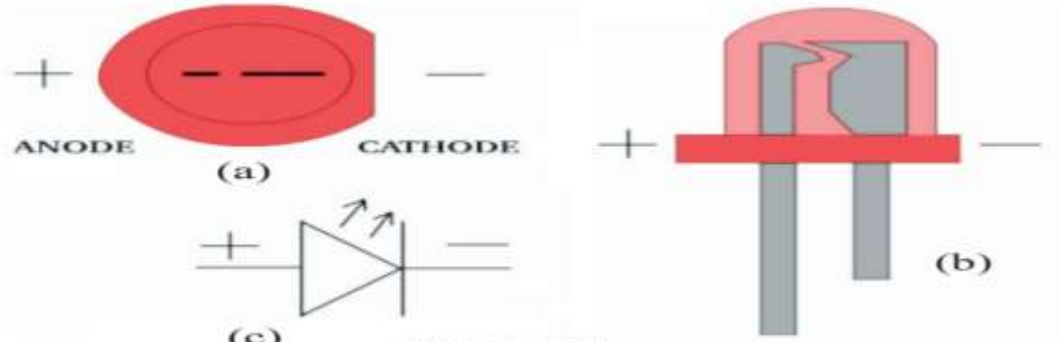


Figure-14

When light-emitting diode (LED) is forward biased the electrons from the n-type material cross the PN junction and recombine with holes in the p-type material. Recall that these free electrons are in the conduction band and at a higher energy level than the holes in the valence band. When recombination takes place, the recombining electrons release energy in the form of heat and light. In germanium and silicon diodes, Light-emitting diode almost the entire energy is given up in the form of heat and emitted light is insignificant. However, in materials like gallium arsenide, the number of photons of light energy is sufficient to produce quite intense visible light.

Advantages:The light-emitting diode (LED) is a solid-state light source. LEDs have replaced incandescent lamps in many applications because they have the following advantages :
(i) Low voltage (ii) Longer life (more than 20 years) (iii) Fast on-off switching

Applications of LEDs: The LED is a low-power device. The power rating of a LED is of the order of milliwatts. This means that it is useful as an indicator but not good for illumination. Probably the two most common applications for visible LEDs are
(i) as a power indicator (ii) seven-segment display iii) Instrument display iv) panel indicators, v) digital watches, vi) calculator etc

Photo-diode: A photo-diode is a reverse-biased silicon or germanium PN junction in which reverse current increases when the junction is exposed to light. The reverse current in a photo-diode is directly proportional to the intensity of light falling on its PN junction. This means that greater the intensity of light falling on the PN junction of photo-diode, the greater will be the reverse current. Principle. When a rectifier diode is reverse biased, it has a very small reverse leakage current. The same is true for a photo-diode. The reverse current is produced by thermally generated electron hole pairs which are swept across the junction by the electric field created by the reverse voltage. In a rectifier diode, the reverse current increases with temperature due to an increase in the number of electron-hole pairs. A photo-diode differs from a rectifier diode in that when its PN junction is exposed to light, the reverse current increases with the increase in light intensity and vice-versa. This is explained as follows.

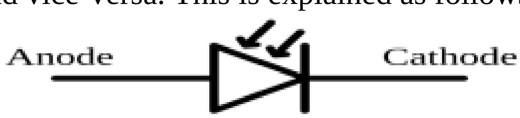
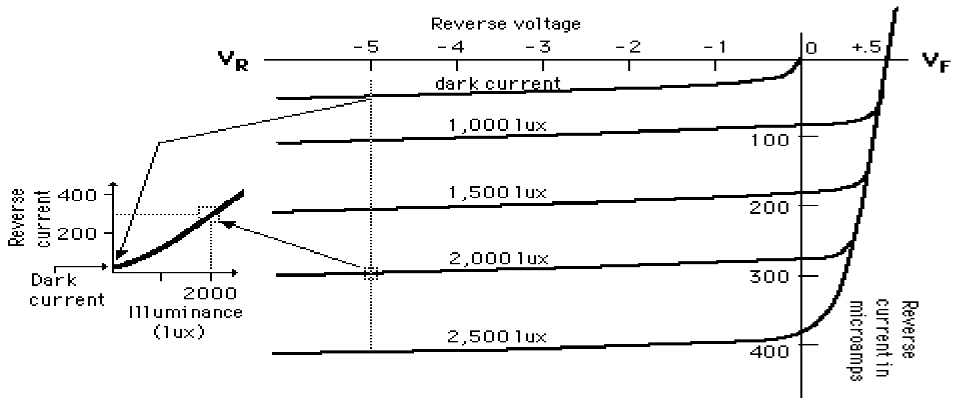


Fig: Photo diode

When light (photons) falls on the PN junction, the energy is imparted by the photons to the atoms in the junction. This will create more free electrons (and more holes). These additional free electrons will increase the reverse current. As the intensity of light incident on the PN junction increases, the reverse current also increases. In other words, as the incident light intensity increases, the resistance of the device (photo-diode)decreases



There are a large number of applications of photodiodes Alarm circuit using photo-diode, Counter circuit using photo-diode.

i. Photo Diode

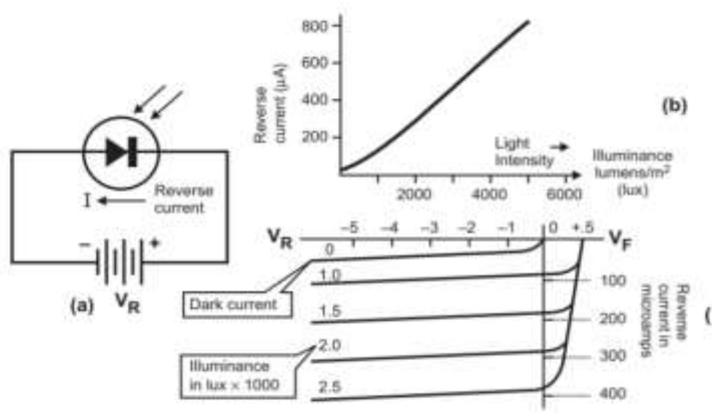


Figure-13

Tunnel Diode:

A tunnel diode is a PN junction that exhibits negative resistance between two values of forward voltage (i.e., between peak-point voltage and valley-point voltage). A conventional diode exhibits *positive resistance when it is forward biased or reverse biased. However, if a semiconductor junction diode is heavily doped with impurities, it exhibits negative resistance (i.e. current decreases as the voltage is increased) in certain regions in the forward direction. Such a diode is called tunnel diode. Theory. The tunnel diode is basically a PN junction with heavy doping of p-type and n-type semiconductor materials. In fact, a tunnel diode is doped approximately 1000 times as heavily as a conventional diode. This heavy doping results in a large number of majority carriers. Because of the large number of carriers, most are not used during the initial recombination that produces the depletion layer. As a result, the depletion layer is very narrow. In comparison with conventional diode, the depletion layer of a tunnel diode is 100 times narrower. The operation of a tunnel diode depends upon the tunneling effect and hence the name.

Tunneling effect.

The heavy doping provides a large number of majority carriers. Because of the large number of carriers, there is much drift activity in p and n sections. This causes many valence electrons to have their energy levels raised closer to the conduction region. Therefore, it takes only a very small applied forward voltage to cause conduction. The movement of valence electrons from the valence energy band to the conduction band with little or no applied forward voltage is called tunneling. Valence electrons seem to tunnel through the forbidden energy band. As the forward voltage is first increased, the diode current rises rapidly due to tunneling effect. Soon the tunneling effect is reduced and current flow starts to decrease as the forward voltage across the diode is increased. The tunnel diode is said to have entered the negative resistance region. As the voltage is further increased, the tunneling effect plays less and less part until a valley-point is reached. From now onwards, the tunnel diode behaves as ordinary diode i.e., diode current increases with the increase in forward voltage

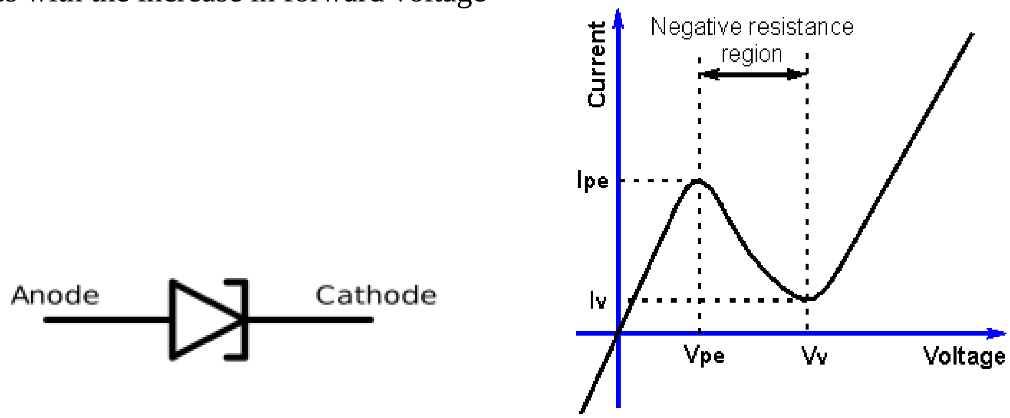


Fig: Tunnel diode symbol and characteristics

Varactor Diode:

` Also called as Vari-cap or voltage variable capacitor (VVC) or Tuning Diode A junction diode which acts as a variable capacitor under changing reverse bias is known as a varactor diode. When a PN junction is formed, depletion layer is created in the junction area. Since there are no charge carriers within the depletion zone, the zone acts as an insulator. The p-type material with holes (considered positive) as majority carriers and n-type material with electrons (−ve charge) as majority carriers act as charged plates. Thus the diode may be considered as a capacitor with n-region and pregion forming oppositely charged plates and with depletion zone between them acting as a dielectric. A varactor diode is specially constructed to have high capacitance under reverse bias. The values of capacitance of varactor diodes are in the picofarad (10−12 F) range.

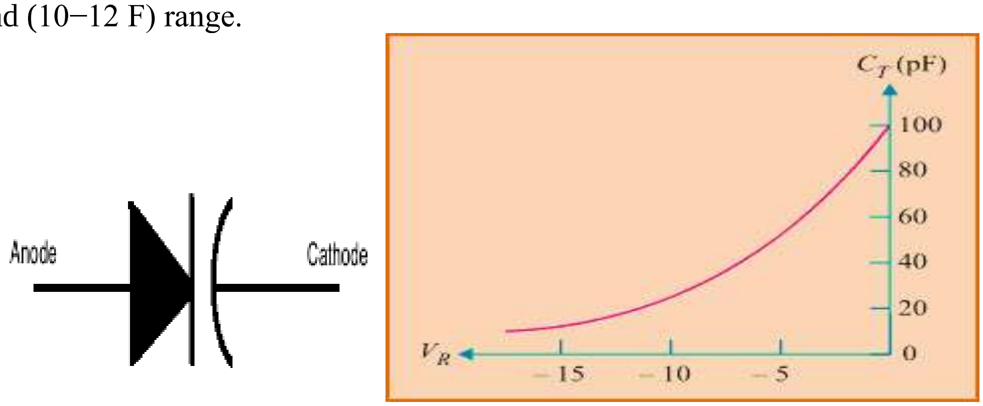


Fig: varactor diode symbol and characteristics

Theory.

For normal operation, a varactor diode is always *reverse biased. The capacitance of varactor diode is found as : CT = d A Wε where CT = Total capacitance of the junction ε = Permittivity of the semiconductor material A = Cross-sectional area of the junction Wd = Width of the depletion layer When reverse voltage across a varactor diode is increased, the width Wd of the depletion layer increases. Therefore, the total junction capacitance CT of the junction decreases. On the other hand, if the reverse voltage across the diode is lowered, the width Wd of the depletion layer decreases. Consequently, the total junction capacitance CT increases. * A forward biased varactor diode would serve no useful purpose.

It finds applications in low noise Microwaves devices (Parametric amplifier), Resonant circuits, Electronic tuning.

Shockley Diode

Named after its inventor, a Shockley diode is a PN device having two terminals This device acts as a switch and consists of four alternate P-type and N-type layers in a single crystal. The various layers are labelled as P1, N1, P2 and N2 for identification. Since a P-region adjacent to an N-region may be considered a junction diode, the Shockley diode is equivalent to three junction diodes connected in series, if we remove the gate terminal of an SCR, the resulting device is Shockley diode.

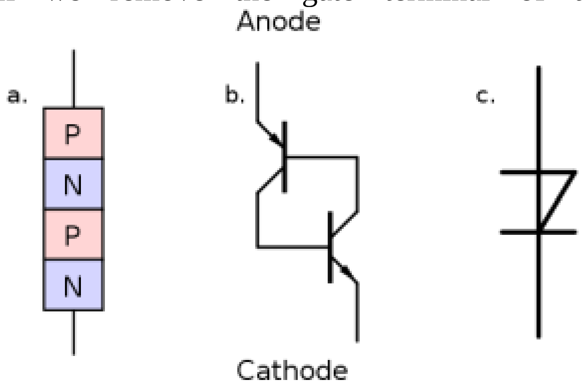


Fig: schokley diode

application in fast switching and low voltage rectification.

Bipolar Transistor Basics

In the **Diode** tutorials we saw that simple diodes are made up from two pieces of semiconductor material, either silicon or germanium to form a simple PN-junction and we also learnt about their properties and characteristics.

If we now join together two individual signal diodes back-to-back, this will give us two PN-junctions connected together in series that share a common P or N terminal.

The fusion of these two diodes produces a three layer, two junction, three terminal device forming the basis of a **Bipolar Transistor**, or **BJT** for short.

Transistors are three terminal active devices made from different semiconductor materials that can act as either an insulator or a conductor by the application of a small signal voltage.

The transistor's ability to change between these two states enables it to have two basic functions: "switching" (digital electronics) or "amplification" (analogue electronics).

Then bipolar transistors have the ability to operate within three different regions:

- 1. Active Region - the transistor operates as an amplifier and $I_c = \beta.I_b$
- 2. Saturation -the transistor is "fully-ON" operating as a switch and $I_c = I(saturation)$
- 3. Cut-off - the transistor is "fully-OFF" operating as a switch and $I_c = 0$

Typical Bipolar Transistor

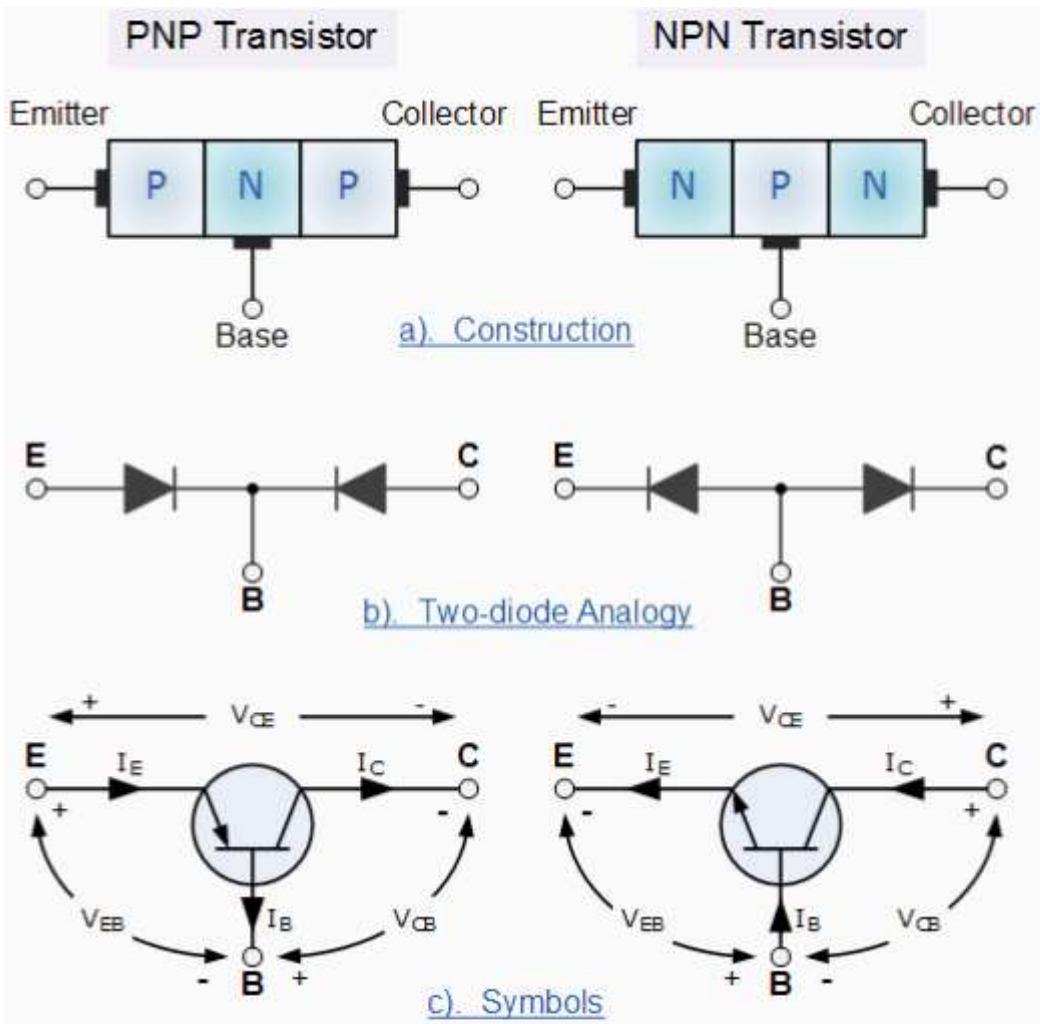
The word Transistor is an acronym, and is a combination of the words Transfer Varistor used to describe their mode of operation way back in their early days of development.

There are two basic types of bipolar transistor construction, NPN and PNP, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made.

The **Bipolar Transistor** basic construction consists of two PN-junctions producing three connecting terminals with each terminal being given a name to identify it from the other two. These three terminals are known and labelled as the Emitter (E), the Base (B) and the Collector (C) respectively.

Bipolar Transistors are current regulating devices that control the amount of current flowing through them in proportion to the amount of biasing voltage applied to their base terminal acting like a current-controlled switch. The principle of operation of the two transistor types NPN and PNP, is exactly the same the only difference being in their biasing and the polarity of the power supply for each type.

Bipolar Transistor Construction



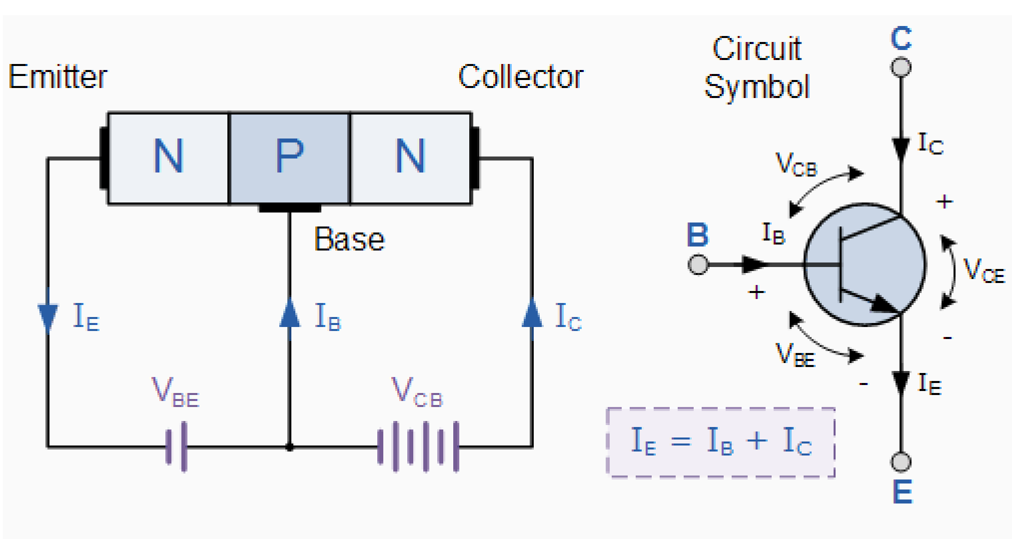
The construction and circuit symbols for both the NPN and PNP bipolar transistor are given above with the arrow in the circuit symbol always showing the direction of "conventional current flow" between the base terminal and its emitter terminal. The direction of the arrow always points from the positive P-type region to the negative N-type region for both transistor types, exactly the same as for the standard diode symbol.

The NPN Transistor

In the previous tutorial we saw that the standard **Bipolar Transistor** or BJT, comes in two basic forms. An NPN (Negative-Positive-Negative) type and a PNP (Positive-Negative-Positive) type, with the most commonly used transistor type being the **NPN Transistor**. We also learnt that the transistor junctions can be biased in one of three different ways - **Common Base**, **Common Emitter** and **Common Collector**. In this tutorial we will look more closely

at the "Common Emitter" configuration using **NPN Transistors** with an example of the construction of a NPN transistor along with the transistors current flow characteristics is given below.

An NPN Transistor Configuration



We know that the transistor is a **"current"** operated device (Beta model) and that a large current (Ic) flows freely through the device between the collector and the emitter terminals when the transistor is switched "fully-ON".

However, this only happens when a small biasing current (Ib) is flowing into the base terminal of the transistor at the same time thus allowing the Base to act as a sort of current control input. The transistor current in an NPN transistor is the ratio of these two currents (Ic/Ib), called the *DC Current Gain* of the device and is given the symbol of hfe or nowadays Beta, (β). The value of β can be large up to 200 for standard transistors, and it is this large ratio between Ic and Ib that makes the NPN transistor a useful amplifying device when used in its active region as Ib provides the input and Ic provides the output. Note that Beta has no units as it is a ratio.

Also, the current gain of the transistor from the Collector terminal to the Emitter terminal, Ic/Ie, is called Alpha, (α), and is a function of the transistor itself (electrons diffusing across the junction). As the emitter current Ie is the product of a very small base current plus a very large collector current, the value of alpha α, is very close to unity, and for a typical low-power signal transistor this value ranges from about 0.950 to 0.999

α and β Relationship in a NPN Transistor

$$\text{DC Current Gain} = \frac{\text{Output Current}}{\text{Input Current}} = \frac{I_C}{I_B}$$

$$I_E = I_B + I_C \;\ldots\ldots\; (\text{KCL}) \quad \text{and} \quad \frac{I_C}{I_E} = \alpha$$

$$\text{Thus:} \quad I_E = I_B + I_C = \frac{I_C}{\alpha}$$

$$\text{and} \quad I_B = I_C\left(1 - \frac{1}{\alpha}\right)$$

$$\therefore \quad \beta = \frac{I_C}{I_B} = \frac{1}{\left(1 - \frac{1}{\alpha}\right)} = \frac{\alpha}{1 - \alpha}$$

By combining the two parameters α and β we can produce two mathematical expressions that gives the relationship between the different currents flowing in the transistor.

$$\beta = \frac{\alpha}{1-\alpha} \quad \text{and} \quad \alpha = \frac{\beta}{\beta+1}$$

$$\text{If} \quad \alpha = 0.99 \quad \beta = \frac{0.99}{0.01} = 99$$

The values of Beta vary from about 20 for high current power transistors to well over 1000 for high frequency low power type bipolar transistors. The value of Beta for most standard NPN transistors can be found in the manufactures datasheets but generally range between 50 - 200.

The equation above for Beta can also be re-arranged to make I_c as the subject, and with a zero base current ($I_b = 0$) the resultant collector current I_c will also be zero, ($\beta \times 0$). Also when the base current is high the corresponding collector current will also be high resulting in the base current controlling the collector current. One of the most important properties of the **Bipolar Junction Transistor** is that a small base current can control a much larger collector current. Consider the following example.

Example No1

An NPN Transistor has a DC current gain, (Beta) value of 200. Calculate the base current Ib required to switch a resistive load of 4mA.

$$I_B = \frac{I_C}{\beta} = \frac{4 \times 10^{-3}}{200} = 20\mu A$$

Therefore, $\beta = 200$, $I_c = 4mA$ and $I_b = 20\mu A$.

One other point to remember about **NPN Transistors**. The collector voltage, (Vc) must be greater and positive with respect to the emitter voltage, (Ve) to allow current to flow through the transistor between the collector-emitter junctions. Also, there is a voltage drop between the Base and the Emitter terminal of about 0.7v (one diode volt drop) for silicon devices as the input characteristics of an NPN Transistor are of a forward biased diode. Then the base voltage, (Vbe) of a NPN transistor must be greater than this 0.7V otherwise the transistor will not conduct with the base current given as.

$$I_B = \frac{V_B - V_{BE}}{R_B}$$

Where: Ib is the base current, Vb is the base bias voltage, Vbe is the base-emitter volt drop (0.7v) and Rb is the base input resistor. Increasing Ib, Vbe slowly increases to 0.7V but Ic rises exponentially.

Example No2

An NPN Transistor has a DC base bias voltage, Vb of 10v and an input base resistor, Rb of 100kΩ. What will be the value of the base current into the transistor.

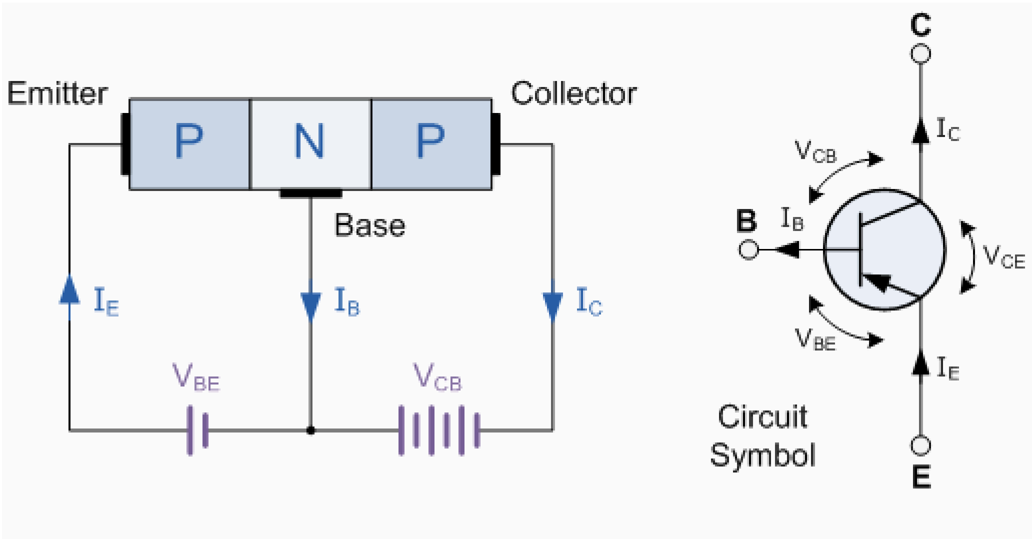
$$I_B = \frac{V_B - V_{BE}}{R_B} = \frac{10 - 0.7}{100k\Omega} = 93\mu A$$

Therefore, Ib = 93µA.

The PNP Transistor

The **PNP Transistor** is the exact opposite to the **NPN Transistor** device we looked at in the previous tutorial. Basically, in this type of transistor construction the two diodes are reversed with respect to the NPN type, with the arrow, which also defines the Emitter terminal this time pointing inwards in the transistor symbol. Also, all the polarities are reversed which means that *PNP Transistors* "sink" current as opposed to the NPN transistor which "sources" current. Then, PNP Transistors use a small output base current and a negative base voltage to control a much larger emitter-collector current. The construction of a PNP transistor consists of two P-type semiconductor materials either side of the N-type material as shown below.

A PNP Transistor Configuration



The **PNP Transistor** has very similar characteristics to their NPN bipolar cousins, except that the polarities (or biasing) of the current and voltage directions are reversed for any one of the possible three configurations looked at in the first tutorial, Common Base, Common Emitter and Common Collector. Generally, PNP Transistors require a negative (-ve) voltage at their Collector terminal with the flow of current through the emitter-collector terminals being **Holes** as opposed to **Electrons** for the NPN types. Because the movement of holes across the depletion layer tendsto be slower than for electrons, PNP transistors are generally more slower than their equivalent NPN counterparts when operating.

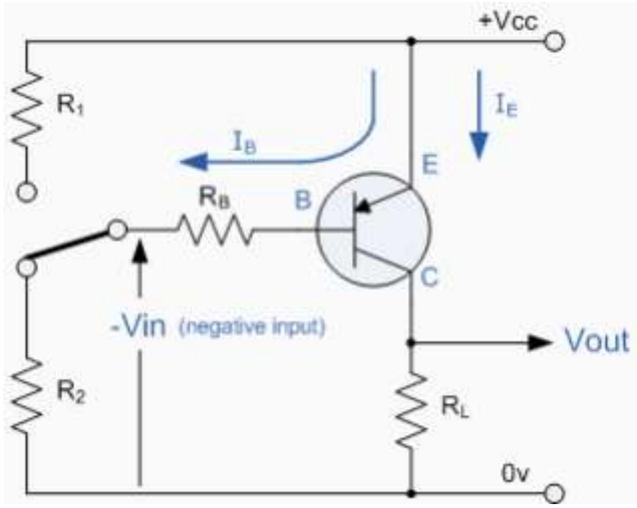
To cause the Base current to flow in a PNP transistor the Base needs to be more negative than the Emitter (current must leave the base) by approx 0.7 volts for a silicon device or 0.3 volts for a germanium device with the formulas used to calculate the Base resistor, Base current or Collector current are the same as those used for an equivalent NPN transistor and is given as.

$$I_E = I_C + I_B$$

$$I_C = \beta I_B \qquad I_B = \frac{I_C}{\beta}$$

Generally, the PNP transistor can replace NPN transistors in electronic circuits, the only difference is the polarities of the voltages, and the directions of the current flow. PNP Transistors can also be used as switching devices and an example of a PNP transistor switch is shown below.

A PNP Transistor Circuit



The **Output Characteristics Curves** for a PNP transistor look very similar to those for an equivalent NPN transistor except that they are rotated by 180° to take account of the reverse polarity voltages and currents, (the currents flowing out of the Base and Collector in a PNP transistor are negative).

Transistor Matching

You may think what is the point of having a **PNP Transistor**, when there are plenty of NPN Transistors available?. Well, having two different types of transistors PNP & NPN, can be an advantage when designing amplifier circuits such as **Class B Amplifiers** that use "Complementary" or "Matched Pair" transistors or for reversible **H-Bridge** motor control circuits. A pair of corresponding NPN and PNP transistors with near identical characteristics to each other are called **Complementary Transistors** for example, a TIP3055 (NPN), TIP2955 (PNP) are good examples of complementary or matched pair silicon power transistors. They have a DC current gain, Beta, (Ic / Ib) matched to within 10% and high Collector current of about 15A making them suitable for general motor control or robotic applications.

Identifying the PNP Transistor

We saw in the first tutorial of this Transistors section, that transistors are basically made up of two **Diodes** connected together back-to-back. We can use this analogy to determine whether a transistor is of the type PNP or NPN by testing its Resistance between the three different leads, Emitter, Base and Collector. By testing each pair of transistor leads in both directions will result in six tests in total with the expected resistance values in Ohm's given below.

- 1. Emitter-Base Terminals - The Emitter to Base should act like a normal diode and conduct one way only.
- 2. Collector-Base Terminals - The Collector-Base junction should act like a normal diode and conduct one way only.

- 3. Emitter-Collector Terminals - The Emitter-Collector should not conduct in either direction.

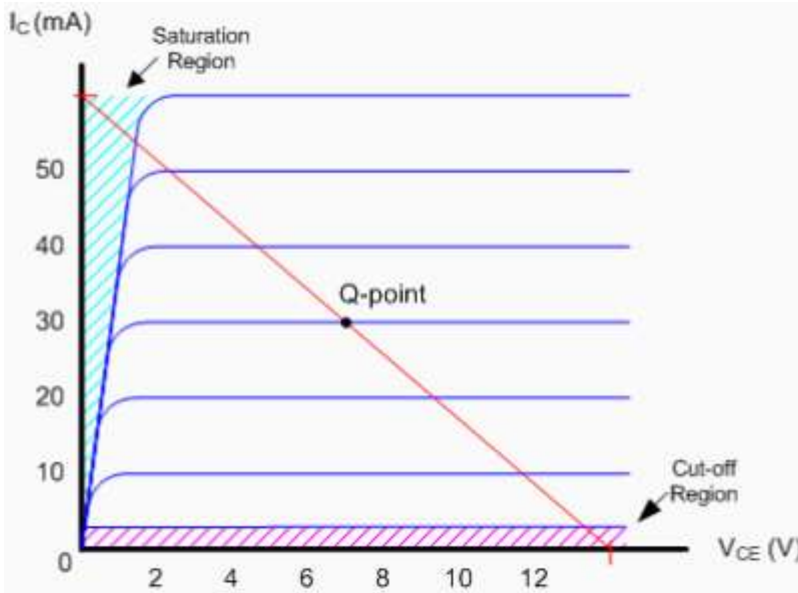
Transistor Resistance Values for the PNP transistor and NPN transistor types

Between Transistor Terminals		PNP	NPN
Collector	Emitter	R_{HIGH}	R_{HIGH}
Collector	Base	R_{LOW}	R_{HIGH}
Emitter	Collector	R_{HIGH}	R_{HIGH}
Emitter	Base	R_{LOW}	R_{HIGH}
Base	Collector	R_{HIGH}	R_{LOW}
Base	Emitter	R_{HIGH}	R_{LOW}

The Transistor as a Switch

When used as an AC signal amplifier, the transistors Base biasing voltage is applied so that it operates within its "**Active**" region and the linear part of the output characteristics curves are used. However, both the NPN & PNP type bipolar transistors can be made to operate as an "ON/OFF" type solid state switch for controlling high power devices such as motors, solenoids or lamps. If the circuit uses the **Transistor as a Switch**, then the biasing is arranged to operate in the output characteristics curves seen previously in the areas known as the "**Saturation**" and "**Cut-off**" regions as shown below.

Transistor Curves



The pink shaded area at the bottom represents the "Cut-off" region. Here the operating conditions of the transistor are zero input base current (Ib), zero output collector current (Ic) and maximum collector voltage (Vce) which results in a large depletion layer and no current flows through the device. The transistor is switched "Fully-OFF". The lighter blue area to the left represents the "Saturation" region. Here the transistor will be biased so that the maximum amount of base current is applied, resulting in maximum collector current flow and minimum collector emitter voltage which results in the depletion layer being as small as possible and maximum current flows through the device. The transistor is switched "Fully-ON".

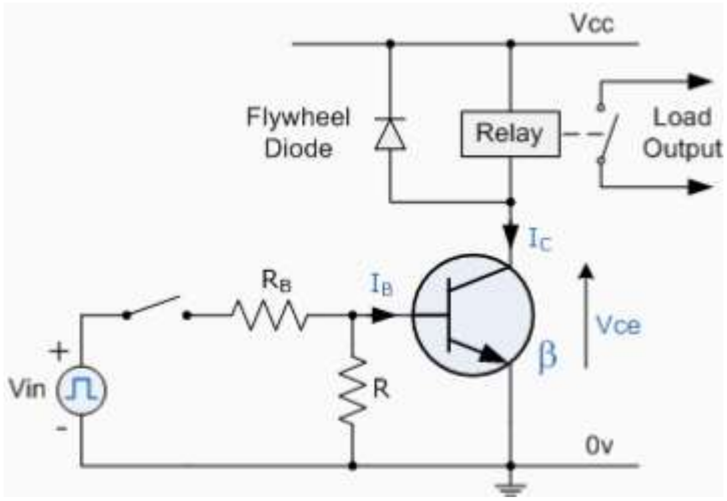
Then we can summarize this as:

- 1. Cut-off Region - Both junctions are Reverse-biased, Base current is zero or very small resulting in zero Collector current flowing, the device is switched fully "OFF".

- 2. Saturation Region - Both junctions are Forward-biased, Base current is high enough to give a Collector-Emitter voltage of 0v resulting in maximum Collector current flowing, the device is switched fully "ON".

An example of an NPN Transistor as a switch being used to operate a relay is given below. With inductive loads such as relays or solenoids a flywheel diode is placed across the load to dissipate the back EMF generated by the inductive load when the transistor switches "OFF" and so protect the transistor from damage. If the load is of a very high current or voltage nature, such as motors, heaters etc, then the load current can be controlled via a suitable relay as shown.

Transistor Switching Circuit



The circuit resembles that of the **Common Emitter** circuit we looked at in the previous tutorials. The difference this time is that to operate the transistor as a switch the transistor needs to be turned either fully "OFF" (Cut-off) or fully "ON" (Saturated). An ideal transistor switch would have an infinite resistance when turned "OFF" resulting in zero current flow and zero resistance when turned "ON", resulting in maximum current flow. In practice when turned "OFF", small leakage currents flow through the transistor and when fully "ON" the device has a low resistance value causing a small saturation voltage (Vce) across it. In both the Cut-off and Saturation regions the power dissipated by the transistor is at its minimum.

To make the Base current flow, the Base input terminal must be made more positive than the Emitter by increasing it above the 0.7 volts needed for a silicon device. By varying the Base-Emitter voltage Vbe, the Base current is altered and which in turn controls the amount of Collector current flowing through the transistor as previously discussed.

When maximum Collector current flows the transistor is said to be **Saturated**. The value of the Base resistor determines how much input voltage is required and corresponding Base current to switch the transistor fully "ON".

Example No1.

For example, using the transistor values from the previous tutorials of: β = 200, Ic = 4mA and Ib = 20uA, find the value of the Base resistor (Rb) required to switch the load "ON" when the input terminal voltage exceeds 2.5v.

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{2.5v - 0.7v}{20x10^{-6}} = 90k\Omega$$

Example No2.

Again using the same values, find the minimum Base current required to turn the transistor fully "ON" (Saturated) for a load that requires 200mA of current.

$$I_B = \frac{I_C}{\beta} = \frac{200mA}{200} = 1mA$$

Bipolar Transistor Configurations

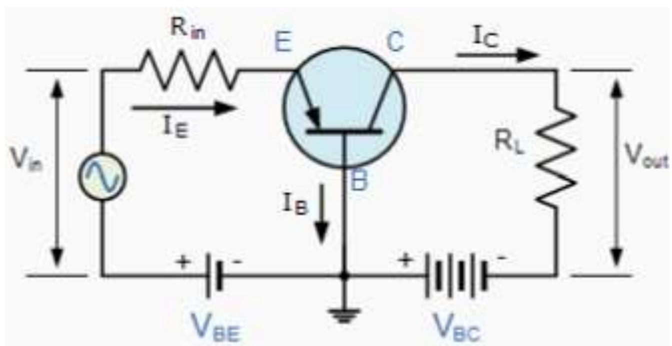
As the **Bipolar Transistor** is a three terminal device, there are basically three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output. Each method of connection responding differently to its input signal within a circuit as the static characteristics of the transistor vary with each circuit arrangement.

- 1. Common Base Configuration - has Voltage Gain but no Current Gain.
- 2. Common Emitter Configuration - has both Current and Voltage Gain.
- 3. Common Collector Configuration - has Current Gain but no Voltage Gain.

The Common Base (CB) Configuration

As its name suggests, in the **Common Base** or grounded base configuration, the BASE connection is common to both the input signal AND the output signal with the input signal being applied between the base and the emitter terminals. The corresponding output signal is taken from between the base and the collector terminals as shown with the base terminal grounded or connected to a fixed reference voltage point. The input current flowing into the emitter is quite large as its the sum of both the base current and collector current respectively therefore, the collector current output is less than the emitter current input resulting in a current gain for this type of circuit of "1" (unity) or less, in other words the common base configuration "attenuates" the input signal.

The Common Base Transistor Circuit



This type of amplifier configuration is a non-inverting voltage amplifier circuit, in that the signal voltages Vin and Vout are in-phase. This type of transistor arrangement is not very common due to its unusually high voltage gain characteristics. Its output characteristics represent that of a forward biased diode while the input characteristics represent that of an illuminated photo-diode. Also this type of bipolar transistor configuration has a high ratio of output to input resistance or more importantly "load" resistance (RL) to "input" resistance (Rin) giving it a value of

"Resistance Gain". Then the voltage gain (Av for a common base configuration is therefore given as:

Common Base Voltage Gain

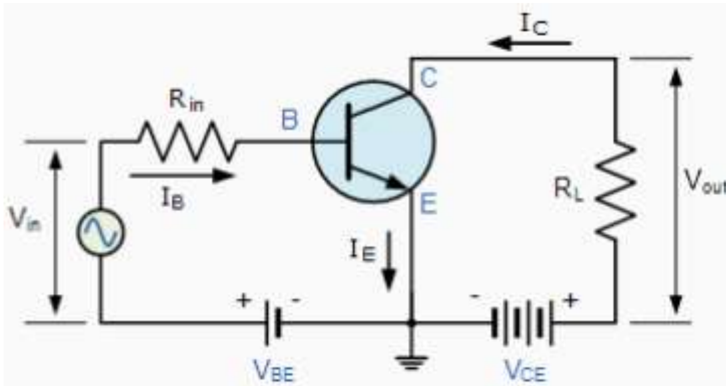
$$A_V = \frac{Vout}{Vin} = \frac{I_C \times R_L}{I_E \times R_{IN}}$$

The common base circuit is generally only used in single stage amplifier circuits such as microphone pre-amplifier or radio frequency (Rf) amplifiers due to its very good high frequency response.

The Common Emitter (CE) Configuration

In the **Common Emitter** or grounded emitter configuration, the input signal is applied between the base, while the output is taken from between the collector and the emitter as shown. This type of configuration is the most commonly used circuit for transistor based amplifiers and which represents the "normal" method of bipolar transistor connection. The common emitter amplifier configuration produces the highest current and power gain of all the three bipolar transistor configurations. This is mainly because the input impedance is LOW as it is connected to a forward-biased PN-junction, while the output impedance is HIGH as it is taken from a reverse-biased PN-junction.

The Common Emitter Amplifier Circuit



In this type of configuration, the current flowing out of the transistor must be equal to the currents flowing into the transistor as the emitter current is given as Ie = Ic + Ib. Also, as the load resistance (RL) is connected in series with the collector, the current gain of the common emitter transistor configuration is quite large as it is the ratio of Ic/Ib and is given the Greek symbol of Beta, (β). As the emitter current for a common emitter configuration is defined as

Ie = Ic + Ib, the ratio of Ic/Ie is called Alpha, given the Greek symbol of α. Note: that the value of Alpha will always

be less than unity.

Since the electrical relationship between these three currents, Ib, Ic and Ie is determined by the physical construction of the transistor itself, any small change in the base current (Ib), will result in a much larger change in the collector current (Ic). Then, small changes in current flowing in the base will thus control the current in the emitter-collector circuit. Typically, Beta has a value between 20 and 200 for most general purpose transistors.

By combining the expressions for both Alpha, α and Beta, β the mathematical relationship between these parameters and therefore the current gain of the transistor can be given as:

$$\text{Alpha}, (\alpha) = \frac{I_C}{I_E} \quad \text{and} \quad \text{Beta}, (\beta) = \frac{I_C}{I_B}$$

$$\therefore I_C = \alpha.I_E = \beta.I_B$$

$$\text{as:} \quad \alpha = \frac{\beta}{\beta + 1} \qquad \beta = \frac{\alpha}{1 - \alpha}$$

$$I_E = I_C + I_B$$

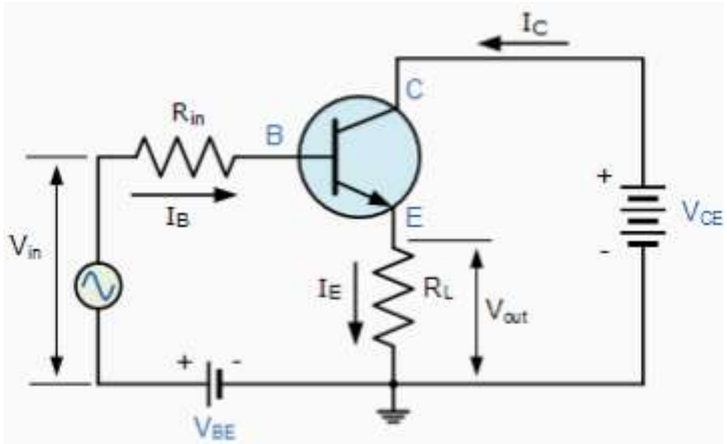
Where: "Ic" is the current flowing into the collector terminal, "Ib" is the current flowing into the base terminal and "Ie" is the current flowing out of the emitter terminal.

Then to summarise, this type of bipolar transistor configuration has a greater input impedance, current and power gain than that of the common base configuration but its voltage gain is much lower. The common emitter configuration is an inverting amplifier circuit resulting in the output signal being 180º out-of-phase with the input voltage signal.

The Common Collector (CC) Configuration

In the **Common Collector** or grounded collector configuration, the collector is now common through the supply. The input signal is connected directly to the base, while the output is taken from the emitter load as shown. This type of configuration is commonly known as a **Voltage Follower** or **Emitter Follower** circuit. The emitter follower configuration is very useful for impedance matching applications because of the very high input impedance, in the region of hundreds of thousands of Ohms while having a relatively low output impedance.

The Common Collector Transistor Circuit



The common emitter configuration has a current gain approximately equal to the β value of the transistor itself. In the common collector configuration the load resistance is situated in series with the emitter so its current is equal to that of the emitter current. As the emitter current is the combination of the collector AND the base current combined, the load resistance in this type of transistor configuration also has both the collector current and the input current of the base flowing through it. Then the current gain of the circuit is given as:

The Common Collector Current Gain

$$I_E = I_C + I_B$$

$$A_i = \frac{I_E}{I_B} = \frac{I_C + I_B}{I_B}$$

$$A_i = \frac{I_C}{I_B} + 1$$

$$A_i = \beta + 1$$

This type of bipolar transistor configuration is a non-inverting circuit in that the signal voltages of Vin and Vout are in-phase. It has a voltage gain that is always less than "1" (unity). The load resistance of the common collector transistor receives both the base and collector currents giving a large current gain (as with the common emitter configuration) therefore, providing good current amplification with very little voltage gain.

Bipolar Transistor Summary

Then to summarise, the behaviour of the bipolar transistor in each one of the above circuit configurations is very different and produces different circuit characteristics with regards to input impedance, output impedance and gain whether this is voltage gain, current gain or power gain and this is summarised in the table below.

Bipolar Transistor Characteristics

The static characteristics for a **Bipolar Transistor** can be divided into the following three main groups.

Input Characteristics:-	Common Base -	$\Delta V_{EB} / \Delta I_E$
	Common Emitter -	$\Delta V_{BE} / \Delta I_B$
Output Characteristics:-	Common Base -	$\Delta V_C / \Delta I_C$
	Common Emitter -	$\Delta V_C / \Delta I_C$
Transfer Characteristics:-	Common Base -	$\Delta I_C / \Delta I_E$
	Common Emitter -	$\Delta I_C / \Delta I_B$

with the characteristics of the different transistor configurations given in the following table:

Characteristic	Common Base	Common Emitter	Common Collector
Input Impedance	Low	Medium	High
Output Impedance	Very High	High	Low
Phase Angle	0^o	180^o	0^o
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

In the next tutorial about **Bipolar Transistors**, we will look at the NPN Transistor in more detail when used in the common emitter configuration as an amplifier as this is the most widely used configuration due to its flexibility and high gain. We will also plot the output characteristics curves commonly associated with amplifier circuits as a function of the collector current to the base current.

The Common Emitter Configuration.

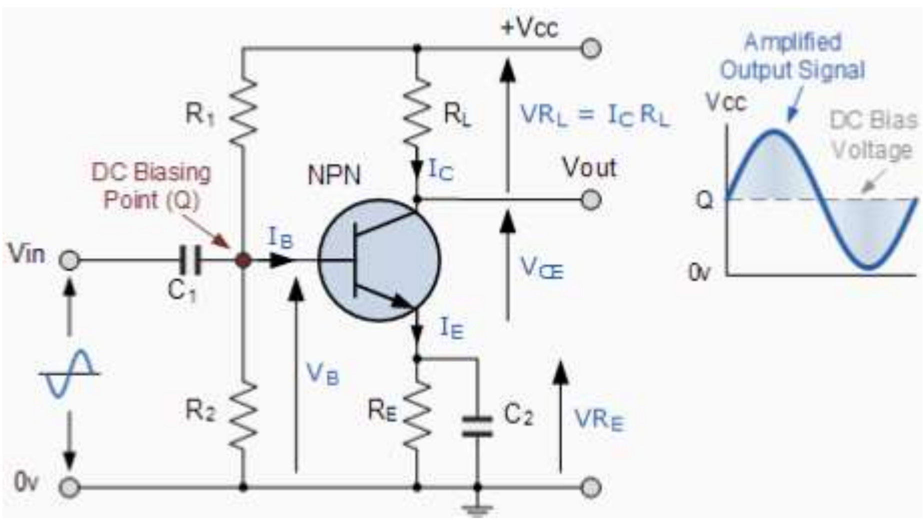
As well as being used as a semiconductor switch to turn load currents "ON" or "OFF" by controlling the Base signal to the transistor in ether its saturation or cut-off regions, **NPN Transistors** can also be used in its active region to produce a circuit which will amplify any small AC signal applied to its Base terminal with the Emitter grounded. If a suitable DC "biasing" voltage is firstly applied to the transistors Base terminal thus allowing it to always operate within its linear active region, an inverting amplifier circuit called a single stage common emitter amplifier is produced.

One such *Common Emitter Amplifier* configuration of an NPN transistor is called a **Class A Amplifier**. A "Class A Amplifier" operation is one where the transistors Base terminal is biased in such a way as to forward bias the Base- emitter junction. The result is that the transistor is always operating halfway between its cut-off and saturation regions, thereby allowing the transistor amplifier to accurately reproduce the positive and negative halves of any AC input signal superimposed upon this DC biasing voltage. Without this "Bias Voltage" only one half of the input waveform would be amplified. This common emitter amplifier configuration using an NPN transistor has many applications but is commonly used in audio circuits such as pre-amplifier and power amplifier stages.

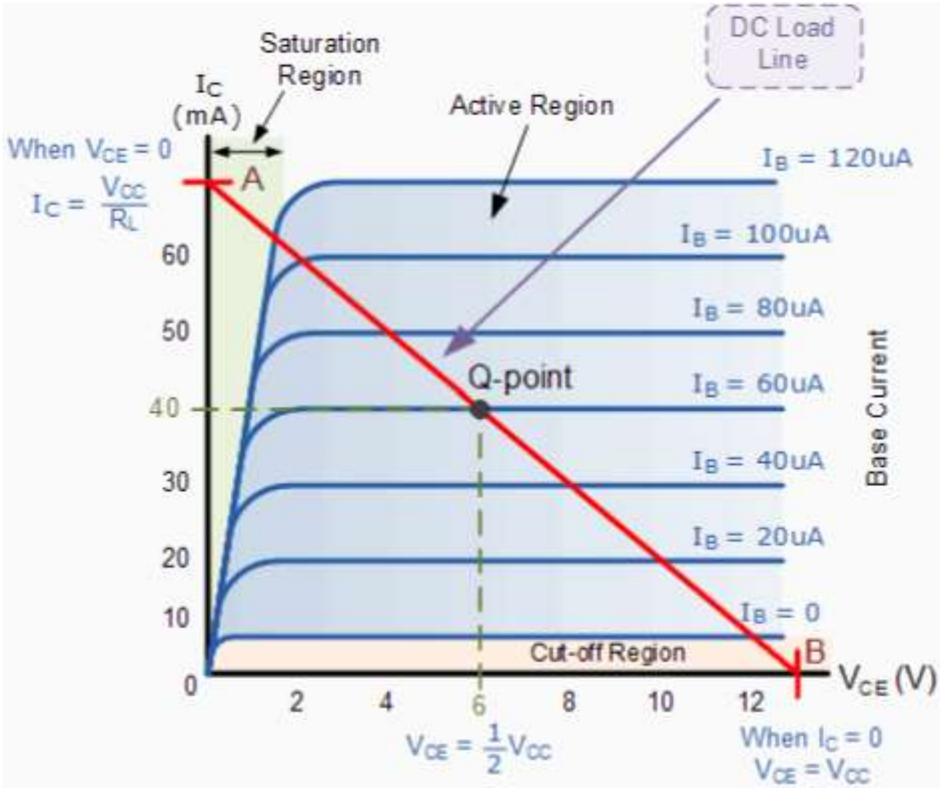
With reference to the common emitter configuration shown below, a family of curves known as the **Output Characteristics Curves**, relates the output collector current, (I_c) to the collector voltage, (V_{ce}) when different values of Base current, (Ib) are applied to the transistor for transistors with the same β value. A DC "Load Line" can also be

drawn onto the output characteristics curves to show all the possible operating points when different values of base current are applied. It is necessary to set the initial value of Vce correctly to allow the output voltage to vary both up and down when amplifying AC input signals and this is called setting the operating point or Quiescent Point, **Q- point** for short and this is shown below.

Single Stage Common Emitter Amplifier Circuit



Output Characteristics Curves for a Typical Bipolar Transistor



The most important factor to notice is the effect of Vce upon the collector current Ic when Vce is greater than about

1.0 volts. We can see that Ic is largely unaffected by changes in Vce above this value and instead it is almost entirely controlled by the base current, Ib. When this happens we can say then that the output circuit represents that of a "Constant Current Source". It can also be seen from the common emitter circuit above that the emitter current Ie is the sum of the collector current, Ic and the base current, Ib, added together so we can also say that " Ie = Ic + Ib " for the common emitter configuration.

By using the output characteristics curves in our example above and also Ohm´s Law, the current flowing through the load resistor, (RL), is equal to the collector current, Ic entering the transistor which inturn corresponds to the supply voltage, (Vcc) minus the voltage drop between the collector and the emitter terminals, (Vce) and is given as:

$$\text{Collector Current, } I_C = \frac{V_{CC} - V_{CE}}{R_L}$$

Also, a straight line representing the **Load Line** of the transistor can be drawn directly onto the graph of curves above from the point of "Saturation" (A) when Vce = 0 to the point of "Cut-off" (B) when Ic = 0 thus giving us the "Operating" or **Q-point** of the transistor. These two points are joined together by a straight line and any position along this straight line represents the "Active Region" of the transistor. The actual position of the load line on the characteristics curves can be calculated as follows:

$$\text{When}: \left(V_{CE} = 0\right) \; I_C = \frac{V_{CC} - 0}{R_L}, \; I_C = \frac{V_{CC}}{R_L}$$

$$\text{When}: \left(I_C = 0\right) \; 0 = \frac{V_{CC} - V_{CE}}{R_L}, \; V_{CC} = V_{CE}$$

Then, the collector or output characteristics curves for **Common Emitter NPN Transistors** can be used to predict the Collector current, Ic, when given Vce and the Base current, Ib. A Load Line can also be constructed onto the curves to determine a suitable Operating or **Q-point** which can be set by adjustment of the base current. The slope of this load line is equal to the reciprocal of the load resistance which is given as: $-1/R_L$

In the next tutorial about **Bipolar Transistors**, we will look at the opposite or compliment form of the NPN Transistor called the **PNP Transistor** and show that the PNP Transistor has very similar characteristics to their NPN transistor except that the polarities (or biasing) of the current and voltage directions are reversed.