Classification of Solids on the basis of their Conductivity and Resistivity:

1- **Metal conductors:** Those solids whose conductivity is very high and resistivity is small.

$\sigma = 10^2$ to 10^8 Sm^{-1} $\rho = 10^{-2}$ to $10^{-8}\Omega m$

2- **Insulators:** Those solids whose conductivity is very small and resistivity is very high.

$\sigma = 10^{-11}$ to 10^{-19} Sm^{-1} $\rho = 10^{11}$ to 10^{19} Ωm

3- **Semi–conductors:** Those solids whose conductivity and resistivity lies between conductors and insulators.

$\sigma = 10^5$ to 10^{-6} Sm^{-1} $\rho = 10^{-5}$ to 10^6 Ωm

Types of semiconductors:

1- Elemental semiconductors: Germanium(Ge) ,Silicon(Si)
2- Compound semiconductors:
   a) Inorganic semiconductors: CdS, GaAs, CdSe, InP etc.
   b) Organic semiconductors: Anthracine, doped pthalocyanines etc.
   c) Organic Polymer: polypyrrole, polyaniline, polythiophene, etc.

Formation of Energy bands in solids: The energy of electrons in an atom is not continuous, but 'quantized.' *The energies of electrons corresponding to each of the allowed orbitals are called* ***Energy levels****.*

In a crystal, the range of energy possessed by electrons in an atom is called ***Energy band.*** Energy band is collection of closely spaced energy levels.

In an isolated atom (separated from each other by a large distance) each electron has discrete energies in different orbits but electron energy is same in each orbit.

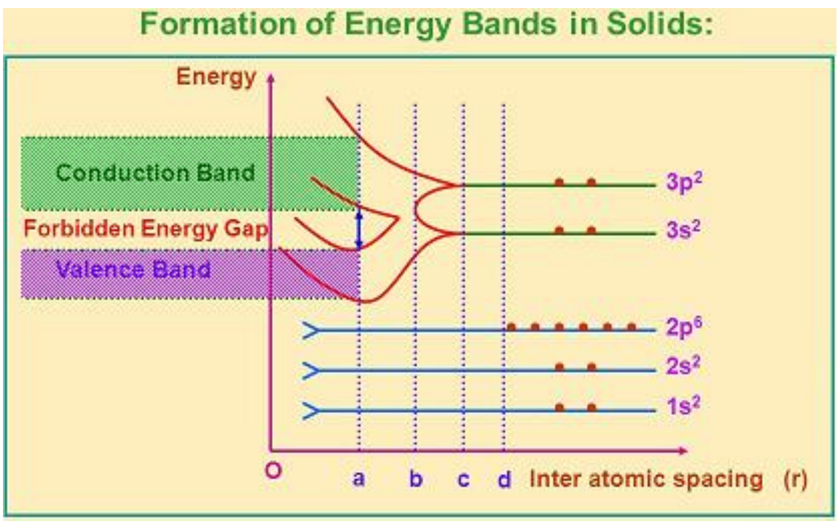
However, in a crystal, the atoms are close to each other (2 to 3 Å) and therefore the electrons of one atom interact with electrons and nucleus of other atom. The interaction is more felt by the electrons in the outermost orbit while the inner orbit electron energies may remain unaffected. Therefore, due to inter atomic interaction their energy levels are modified. These modified energy levels with continuous energy variation form *energy bands*.

There are two type of energy band in solids,

(1) **Valance band:** *The energy band associated with the energy levels of the valence electrons is called the valence band.* This band is always filled completely or partially with electrons, but can **never be empty**. Valence electrons are not capable of gaining energy from external electric field so that they can participate in conductivity of electric current.

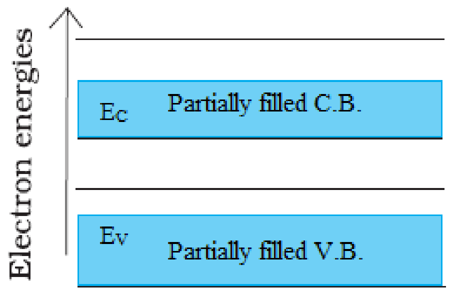
(2) **Conduction band:** *The energy band above the valence band is called the conduction band.* Conduction band is either *empty or partially filled*. Conduction band electrons are capable of gaining energy from external electric field and participate in conductivity of electric current.

In some solids there is some *energy gap between the conduction band and the valence band called Forbidden energy gap* (E_g). For example energy gap for Si is 1.1eV for Ge 0.70 eV and for Carbon 5.4eV. Forbidden Energy gap is completely empty having no electrons. In some solids electrons of valence band may gain energy from external source and cross the energy gap to reach conduction band and now they can participate in conductivity.



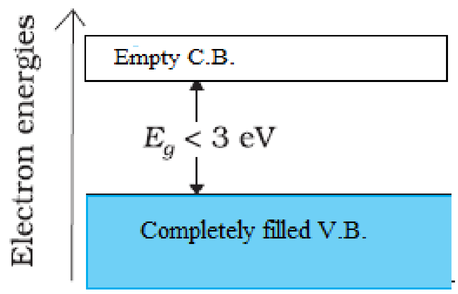
Difference between conductor, semiconductor and insulator on basis of energy band diagram :

Conductor



In conductor valance band and conduction band are partially filled or overlapped. Electrons of C.B. show conductivity when electric field is applied to it.

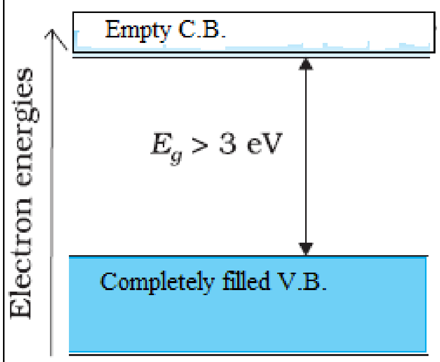
Semiconductor



at 0 K Temperature

In semiconductor C.B. is completely empty at 0 K temperature. Because of the small band gap ($Eg < 3$eV), at room temperature some electrons from valence band can acquire enough energy to cross the energy gap and enter the *conduction band*. These electrons (though small in numbers) can move in the conduction band.Hence, *semiconductors* show small conductivity at room temperature.

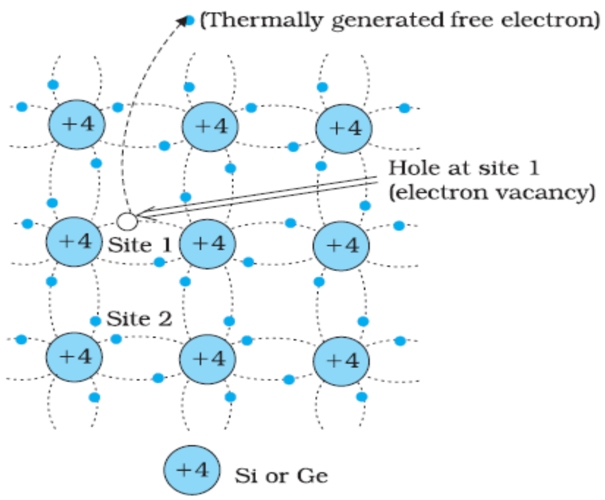
Insulator



There are no electrons in the conduction band, and therefore electrical conduction is not possible. The energy gap ($Eg > 3$ eV) is so large that electrons cannot be excited from the valence band to the conduction band by thermal excitation.

Intrinsic Semiconductor: A pure semiconductor is called intrinsic semiconductor. For example pure Si and Ge.

In crystal structure Si or Ge, each atom of Si or Ge *share* one of its four valence electrons with its four nearest neighbour atoms and one electron from each such neighbour. These shared electron pairs to form a *covalent bond* or a *valence bond*. At 0 K temperatures no electron is free to take part in conductivity hence behaves as insulator. As the temperature increases, thermal energy of electrons increases and some of these electrons may jump to conduction band from valance band leaving behind a vacancy *called hole. Hole* have an effective charge (+e). Due to presence of holes electrons can move freely in valance band.



In intrinsic semiconductors, *the number of free electrons, n_e is equal to the number of holes, n_h*. The total current, I is thus the sum of the electron current I_e and the hole current I_h: $I = I_e + I_h$

Number density (n_i) of charge carrier in intrinsic semiconductor is given by $n_i^2 = n_e n_h$

Doping: The process of adding desirable impurity to the pure semiconductor is called doping. The impurity atom added is called dopants. Doping is done at few ppm level. After doping semiconductor material obtained is still neutral (have no charge) as dopant atom is added to them not electrons/charge particle and atom as a hole is electrically neutral.

Purpose of doping: Doping is done to increase the conductivity of semiconductor at desired level and to make conductivity of doped semiconductor almost independent on change in temperature.

Selection of dopants: The size of dopant atom must be nearly equal to the size of dopant atom so that it does not distort the original pure semiconductor lattice

13 Group P type dopant	**14 Group**	**15 Group** N type dopant
B 5	**C** 6	**N** 7
Al 13	**Si** 14	**P** 15
Ga 31	**Ge** 32	**As** 33
In 49	**Sn** 50	**Sb** 51

There are two type of dopants used in doping with tetravalent Si or Ge.

(i) **Pentavalent/Donar impurities** (valency 5); like Arsenic (As), Antimony (Sb), Phosphorous (P), etc.

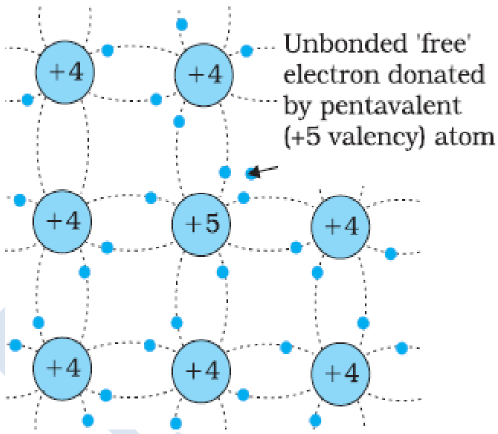
(ii) **Trivalent/Accepter impurities** (valency 3); like Indium (In), Boron (B), Aluminium (Al), etc.

Methods of doping: (i) By mixing dopant atom to the pure semiconductor in molten state.
(ii)By heating pure semiconductor in environment of dopant atom
(iii) By bombarding semiconductor with dopant atom.

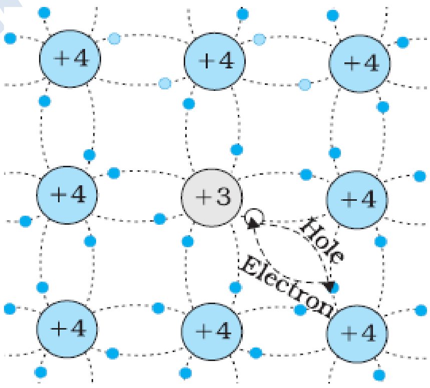
Extrinsic Semiconductor: When a pure semiconductor is doped with suitable/desirable impurity the material obtained is called extrinsic semiconductor. In extrinsic semiconductor *number electron is not equal to number of hole.* Electrical conductivity of extrinsic semiconductor is given by

$\sigma = 1 / \rho = e\,(n_e\,\mu_e + n_h\,\mu_h)$

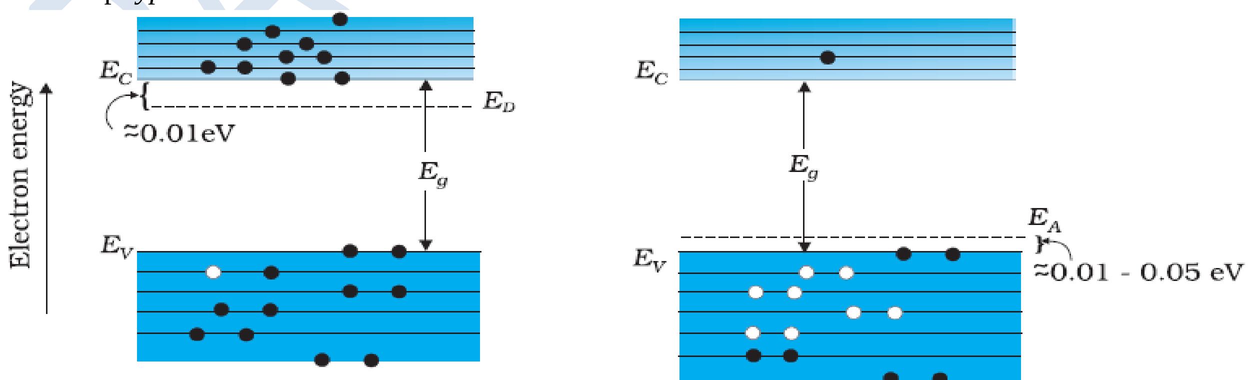
There are two type of extrinsic semiconductor.



(i) n-type semiconductor: When a pure semiconductor is doped with pentavalent impurity n-type semiconductor is obtained. When an dopant atom of +5 valency element occupies the position of an atom in the crystal lattice of Si, four of its electrons bond with the four silicon neighbours while the fifth electron remains very weakly bound to its parent atom. Since impurity atom donate one free electron to conduction band of semiconductor so this dopant atom is called *donor atom. The energy level occupied by donated electron in the dopant atom is called donor level*(E_D = 0.01eVfor Si) Thus a very small ionisation energy required to make this electron free and even at room temperature (thermal energy 0.03eV) it will be free to move in the lattice of the semiconductor and show conductivity. In n-type semiconductor number of electrons n_e is due to the electrons contributed by donors and those generated intrinsically, while the total number of holes n_h is only due to the holes from the intrinsic source. So *number of electrons (majority charge carrier) is much more than number of holes (minority charge carrier) so called n-type semiconductor. 'n' for negative.*



(ii) p-type semiconductor: This type of semiconductor is obtained when Si or Ge is doped with a trivalent impurity like Al, B, In, etc. The dopant has one valence electron less than Si or Ge and, therefore, this atom can form covalent bonds with three neighbouring Si atoms but does not have any electron to offer to the fourth Si atom. So the bond between the fourth neighbour and the trivalent atom has a vacancy or hole which can accept electron, this trivalent atom is called *acceptor atom. The energy level in which the acceptor atom accept electron from valance band of Si is called the acceptor level*(E_A) One acceptor atom gives one *hole* for conduction. These holes are in addition to the intrinsically generated holes while the source of conduction electrons is only intrinsic generation. Thus, for this type of material, *the holes are the majority carriers and electrons are minority carriers.* Therefore, extrinsic semiconductors doped with trivalent impurity are called p-*type semiconductors*.

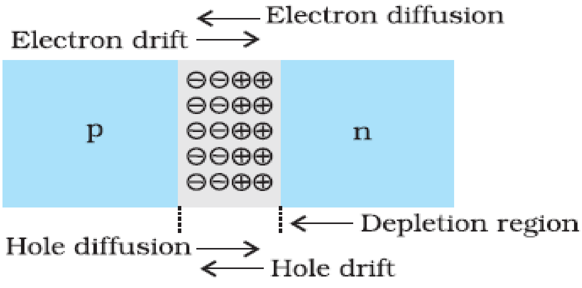


(a) $T > 0K$
one thermally generated electron-hole pair + 9 electrons from donor atoms

(b) $T > 0K$

Energy bands of (a) n-type semiconductor at $T > 0K$, (b) p-type semiconductor at $T > 0K$.

p-n Junction Formation: A pn-junction can be formed by growing p and n-type impurities to a block of pure Si/Ge crystal or joining p and n-type *wafers* to each other by melting at junction. A pn-junction can't be formed by simply placing p and n-type wafers in contact to each other because two separate semiconductors cannot have a continuous contact at atomic level, there is always discontinuity for flowing charge carriers at junction.

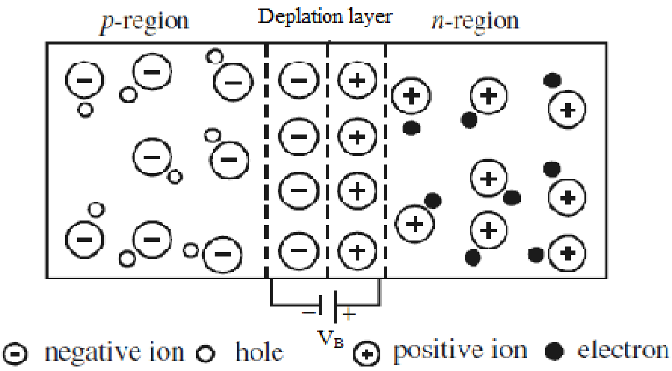


p-n junction formation process

Two important processes occur during the formation of a p-n junction: *diffusion* and *drift*. As we know that in an n-type semiconductor, the concentration of electrons is more as compared to the concentration of holes. Similarly, in a p-type semiconductor, the concentration of holes is more than the concentration of electrons. During the formation of p-n junction *due to the concentration gradient across p-sides and n- sides, holes diffuse from p-side to n-side (p→n) and electrons diffuse from n-side to p-side (n→ p). This motion of charge carriers gives rise to a current called diffusion current.*

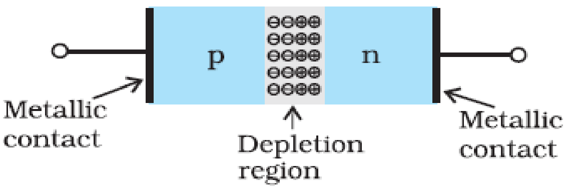
When an electron diffuses from n → p, it leaves behind an ionized donor (positive charge) on n-side, which is immobile as it is bonded to the surrounding atoms. As the electrons continue to diffuse from n → p, a layer of positive charge (or positive space-charge region) on n-side of the junction is developed. Similarly, when a hole diffuses from p → n due to the concentration gradient, it leaves behind an ionised acceptor (negative charge) which is also immobile. As the holes continue to diffuse, a layer of negative charge (or negative space-charge region) on the p-side of the junction is developed this layer is called *depletion layer*. *The space-charge region on either side of the junction which is depleted of free charge carrier known as depletion layer. The width of depletion layer depends on types of biasing and extent of doping (greater the extent of doping smaller is the width of depletion layer)*. The thickness of depletion region is of the order of one-tenth of a micrometre.

Due to the positive space-charge region on n-side of the junction and negative space charge region on p-side of the junction, an electric field is developed. Due to this field, an electron from p-side of the junction moves to n-side and a hole from n-side of the junction moves to p-side. *The motion of charge carriers due to the electric field across the depletion layer produces a current called drift current, which is opposite in direction to the diffusion current.* Initially, diffusion current is large and drift current is small. As the diffusion process continues drift current increases until the *diffusion current equals the drift current and now a p-n junction is formed. In a p-n junction under equilibrium there is no net current.*

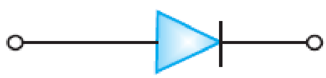


The loss of electrons from the n-region and the gain of electron by the p-region cause a difference of potential across the junction of the two regions. The polarity of this potential is such that it oppose further flow of charge carriers on either side of junction this potential is called *barrier potential*(V_B). The value of barrier potential depends on nature of semiconductor, doping level and temperature. For Si and Ge value of barrier potential is 0.7V and 0.3V respectively.

Semiconductor Diode: A p-n junction diode is a two terminal semiconductor device which is used to rectify a.c.



Semiconductor diode,

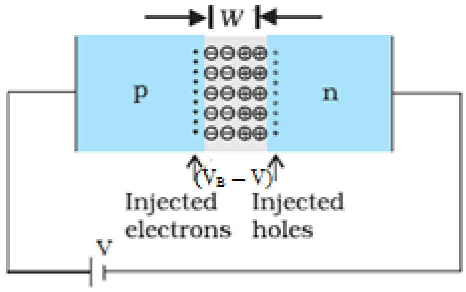

Symbol for p-n junction diode.

(The direction of arrow indicates the conventional direction of current when the diode is under forward bias).

Biasing: *The process of connecting a p-n junction diode to battery is called biasing.* Biasing is done in two ways,

(i) Forward biasing (ii)Reverse biasing

Forward Biasing: When p-side of junction diode is connected to high potential and n-side the junction diode is connected to low potential junction diode is said to be in forward bias.



Forward bias minority carrier injection

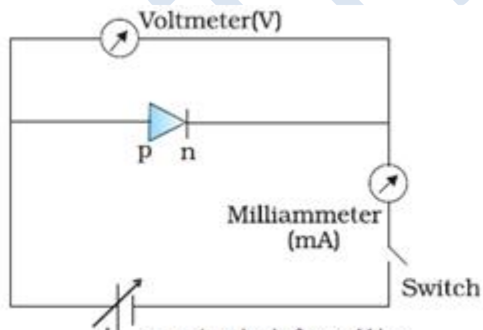
The direction of the applied voltage (V) is opposite to the barrier potential V_B. As a result, *thickness of depletion layer decreases (due to this resistance of depletion layer decreases)* and *the effective barrier potential is* $(V_B - V)$.

Due to the applied voltage, electrons from n-side repel to the p-side (where they are minority carries) and holes from p-side cross the junction and reach the n-side (where they are minority carries). This process under forward bias is known as *minority carrier injection*. At the junction boundary, on each side, the minority carrier concentration increases significantly compared to the locations far from the junction. Due to this concentration gradient, the injected electrons on p-side diffuse from the junction edge of p-side to the other end of p-side. Likewise, the injected holes on n-side diffuse from the junction edge of n-side to the other end of n-side. This motion of electrons and holes gives rise to current.

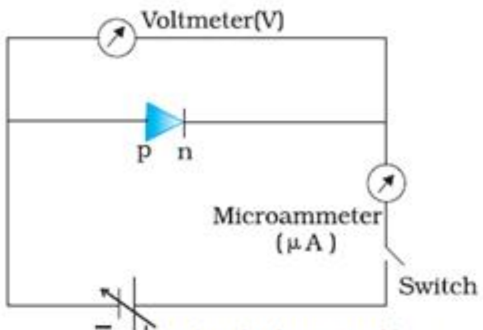
Reverse Biasing: When p-side of junction diode is connected to low potential and n-side the junction diode is connected to high potential junction diode is said to be in reverse bias..

The direction of applied voltage is same as the direction of barrier potential. The depletion region thickness increases due to the change in the electric field *(due to this resistance of depletion layer increases)* and *the effective barrier potential is* $(V_B + V)$.

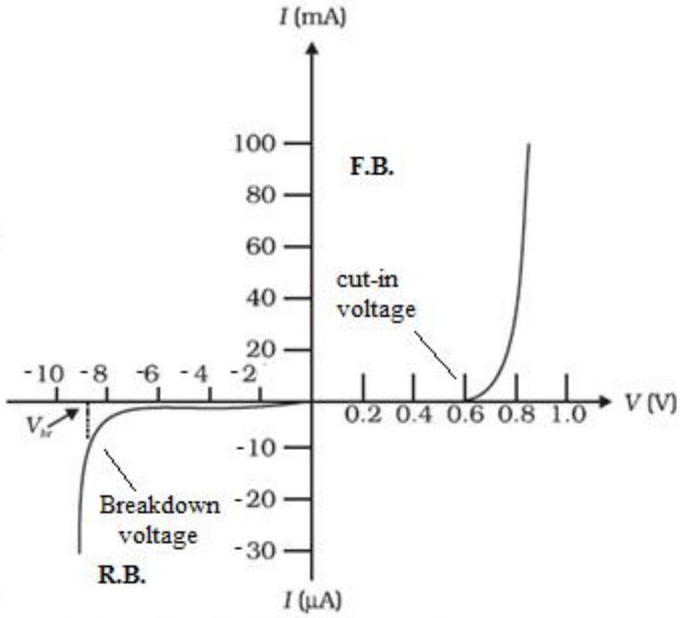
When diode is in reverse bias the electric field direction of the junction is such that, a small voltage is sufficient to sweep the minority carriers from one side of the junction to the other side of the junction, This drifting of minority charge carriers gives rise to a current, which is almost independent on the applied voltage and called *reverse saturation current, this current is dependent on concentration of the minority carrier on either side of the junction*. *The value of reverse voltage across the pn-junction at which reverse current increases sharply is known* ***breakdown voltage*** **(V_{br})**.



pn-junction in forward bias



pn-junction in reverse bias



V-I characteristics of pn-junction diode

VI-Characteristic of a pn-junction diode: A graph plotted between voltage across pn-junction and current flowing through it is called V-I Characteristic.

Forward Characteristic:

1) V-I graph is not straight line i.e. Ohm's law is not obeyed.
2) Resistance across junction is low.
3) Up to *cut-in voltage/knee voltage* (0.7V for Si and 0.2V for Ge diode) current increases negligibly with increase in voltage.
4) After cut-in voltage, current increases exponentially with increase in voltage.

Reverse Characteristic:

1) VI-graph is not straight line.
2) Resistance across junction is high.
3) Initially a very small current is obtained called *Reverse saturation current (Leakage current)*, which is almost independent on applied voltage. Reverse saturation current is due to minority charge carrier and is dependent on doping concentration, diffusion length and device temperature.
4) At *Breakdown-voltage/Peak inverse voltage* current increases suddenly to a large value.

Dynamic Resistance (r_d): The ratio of change in applied voltage ΔV to corresponding change in currentΔI.

$$r_d = \frac{\Delta V}{\Delta I}$$

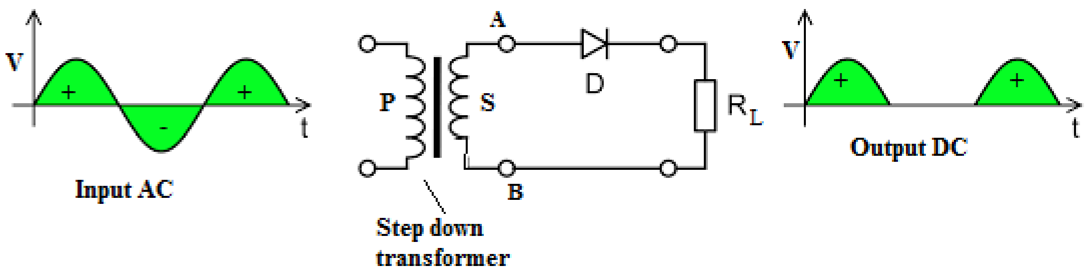
Rectifier: It is a device which is used to convert alternate current to direct current and the process is called *rectification*.

Principle: It works on the principle that when a pn-junction diode is in forward bias it offers low resistance and current passes through it, but when it is in reverse bias it offers high resistance and almost no current flow through it. This property of diode is used to rectify alternate current.

The rectifiers are of two types:

1) Half wave rectifier
2) Full wave rectifier

Half wave Rectifier: It consists of a transformer, a junction diode D and a load resistance R_L. Transformer lowers voltage, diode rectifies it and output is obtained across load resistance.



When positive half cycle of AC is applied to end A, and at same time end B is negative. The diode D is in forward bias and current is obtained through R_L; output wave form is same as positive half cycle of input AC. During negative half cycle of applied voltage end A becomes negative and B positive. The diode is in reverse biased and no current flows; no voltage appears across R_L. In the next positive half cycle, again we get output voltage which is unidirectional and pulsating.

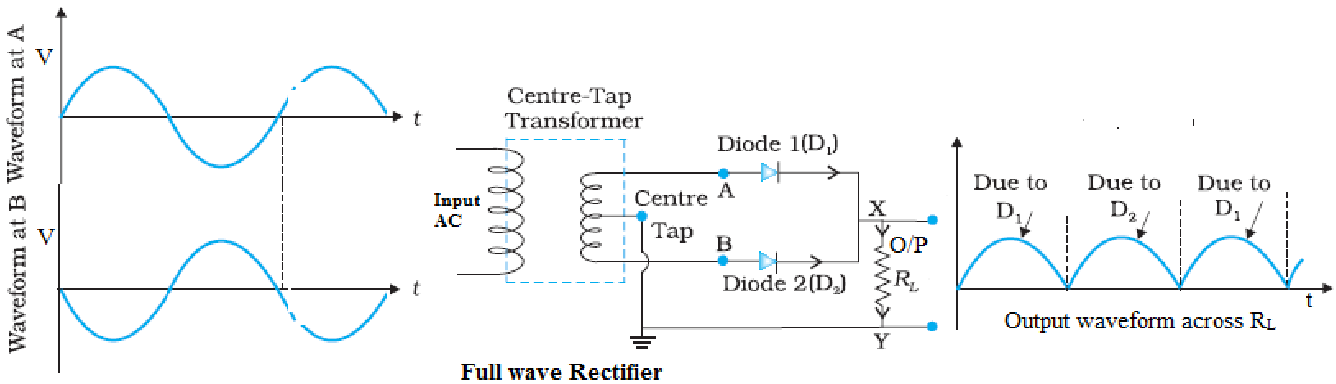
Note: In half wave rectifier the frequency of input and output signal is same.

Full wave Rectifier: It consists of a centre tap transformer, two junction diodes D_1 and D_2 and a load resistance R_L. p-end of both junction diodes D_1 and D_2 are connected to secondary coil of transformer and n-end of both diode is connected to centre tap of transformer T with a load resistance R_L.

During the positive half cycle of AC input, end A is positive and end B is negative with respect to the centre tap T. Then diode D_1 gets forward bias and conducts current along path AD_1XYTA. During same time diode D_2 is in reverse bias and does not conducts current. During the negative half cycle of AC input, end B is positive and end A is negative with respect to the centre tap T. Then diode D_2 gets forward bias and conducts current along path BD_2XYTB. During same time diode D_1 is in reverse bias and does not conducts current.

During both half cycles current have same sense along R_L so a pulsating unidirectional current is obtained along R_L.

Note: In full wave rectifier the frequency of output signal is double as that of input signal as two ripples are obtained in one cycle of input.

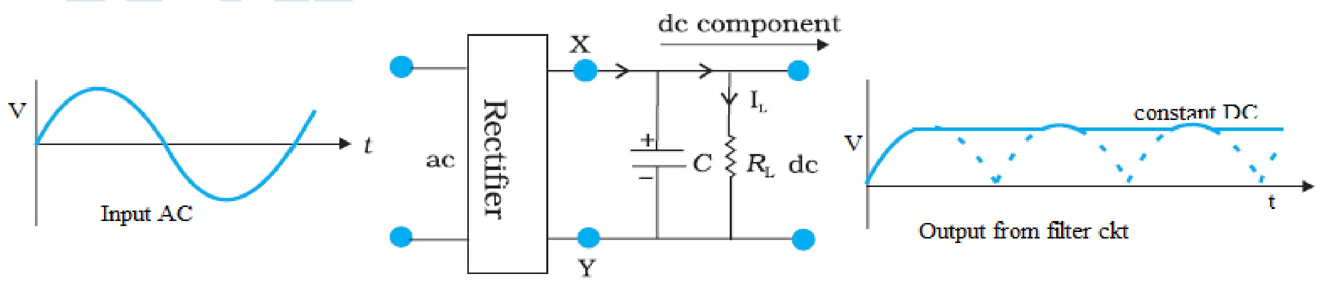


Full wave Rectifier

Difference between half wave rectifier and full wave rectifier:

S.No.	Half wave rectifier	Full wave rectifier
1.	Only one diode is used	Two diodes is used
2.	Ordinary transformer is used	Centre tap transformer is used
3.	only alternate half cycles of applied alternating signal are converted into direct current	Whole cycle of applied alternating signal is converted into direct current.
4.	Rms value of current $I_{rms} = \frac{I_\circ}{2}$	Rms value of current $I_{rms} = \frac{I_\circ}{\sqrt{2}}$
5.	$I_{dc} = \frac{I_\circ}{\pi}$	$I_{dc} = \frac{2I_\circ}{\pi}$
6.	Value of dc component is less than ac in output	Value of dc component is more than ac in output
7.	It's efficiency is about 40.6%	It's efficiency is about 81.2%

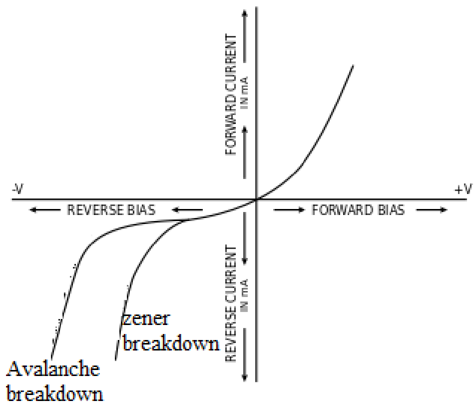
Filter Circuits: Current obtained from rectifier circuit is pulsating so to get steady DC output from the pulsating voltage *Filter circuit* is used which *filter* out the *ac ripple* and give a *pure dc* voltage, so called filters circuit . It consists of a capacitor, parallel to the load R_L (or an inductor in series with R_L) is connected across the output terminals of rectifier.. When input voltage increase the voltage across the capacitor is rising, it gets charged to the peak voltage of the rectified output. When input voltage decreases, capacitor gets discharged through the load and the voltage across it begins to fall but in next half-cycle of rectified output it again gets charged to the peak value and hence voltage across load R_L remains constant. The *output voltage* obtained by using capacitor input filter is nearer to the *peak voltage* of the rectified voltage.



A full-wave rectifier with capacitor filter

Reverse Breakdown of junction diode: *The amount of reverse bias voltage at which current passing through junction diode is increases abruptly is called reverse breakdown voltage* and the process is called breakdown. It doesn't means that the diode has been damaged physically. There are two breakdown processes,

1) Zener breakdown
2) Avalanche breakdown

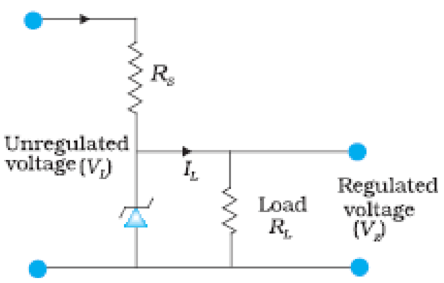


Zener breakdown: This process *occurs in heavily doped junction diodes*. When a large reverse bias voltage is applied across junction diode, it setup a high electric field (as width of depletion layer is small) which enables *tunnelling of electrons* from the valence to the conduction band of a semiconductor, leading to a large number of free minority carriers, which suddenly increases the reverse current. Since this breakdown in junction diode is due to band to band tunneling and known as Zener breakdown.

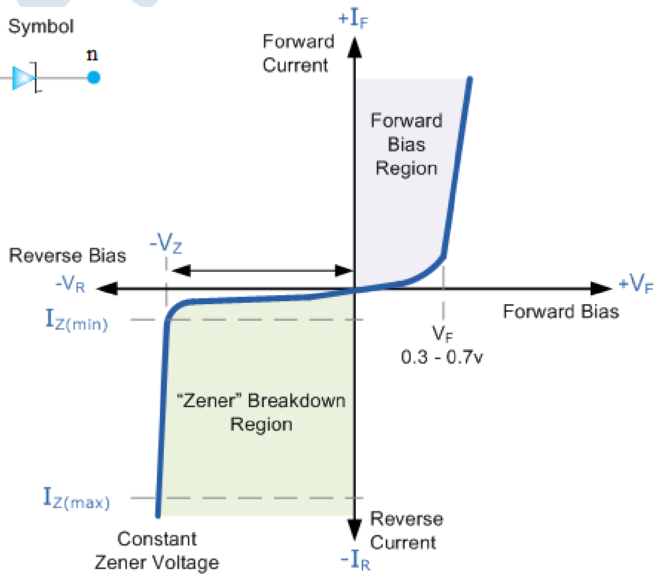
Avalanche breakdown: This process occurs in *lightly doped* junction diode. Here electric field is not strong enough to produce Zener breakdown as width of depletion layer is large. When applied voltage is large (more than Zener breakdown voltage) it breaks the covalent bonds and electron-hole pairs are generated. Newly generated charge carriers are accelerated by the electric field which results in more collision and generates avalanche of charge carriers so current increases sharply. This is known as avalanche breakdown.

Zener diode as a Voltage Regulator: Zener diode is used to get a constant DC voltage from the DC unregulated output of a rectifier. These diodes are made by heavily doped n and p type semiconductors; the quantity of doping of semiconductors is kept different so that their breakdown voltages are different. In that way, zener diodes different voltage levels have different voltage capacity.

Zener diode: A Zener diode is a diode which allows current to flow in the forward direction in the same manner as an ideal pn-junction diode, but also permits it to flow in the reverse direction when the voltage is above a certain value known as the breakdown voltage, "Zener knee voltage", "Zener voltage", "avalanche point", or "peak inverse voltage".



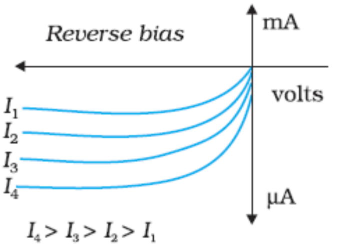
Zener diode as a voltage regulator



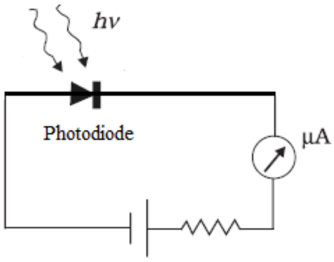
Principle: When a zener diode is operated in reverse breakdown region, the voltage across it remains constant which is equal to breakdown voltage (V_Z) for a large change in reverse current. This property is used as voltage regulator.

Working: The unregulated dc voltage, filtered output of a rectifier is connected to the Zener diode through a series resistance Rs such that the Zener diode is reverse biased. If the input voltage increases, the current through Rs and Zener diode also increases. This increases the voltage drop across Rs without any change in the voltage across the Zener diode. This is because in the breakdown region, Zener voltage remains constant even though the current through the Zener diode changes. Similarly, if the input voltage decreases, the current through Rs and Zener diode also decreases. The voltage drop across Rs decreases without any change in the voltage across the Zener diode. Thus any increase/decrease in the input voltage results in, increase/decrease of the voltage drop across Rs without any change in voltage across the Zener diode. Thus the Zener diode acts as a voltage regulator.

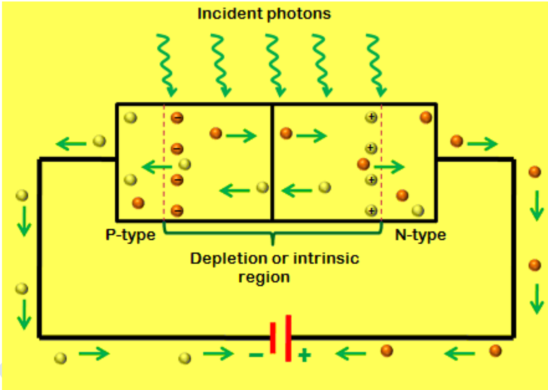
Optoelectronic junction devices:



I-V Characteristic of Photodiode



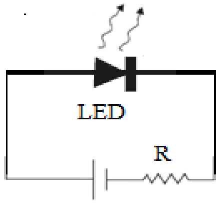
(1)Photodiode: A Photodiode is a special purpose p-n junction diode which shows conductivity only when light of suitable frequency falls on it. It is also called as photo-detector, a light detector, and photo-sensor. It is *operated under reverse bias*. *Its main function is to convert optical signal to electrical signal.*



Working Principle: It works on Photovoltaic effect. It fabricated with a photosensitive material and coated with a transparent window so that light can reach to its junction. When light (photons) of energy ($h\nu$) greater than the energy gap (Eg) of the semiconductor falls on photodiode, then electron-hole pairs are generated near the depletion region due to the absorption of photons(energy packets). Due to electric field of the junction, electrons and holes are separated and electrons reach n-side and holes reach p-side giving rise to a current.

Use: Photodiode is used as a photo-detector to detect optical signals and in remote control of TV, VCR etc.

(2)Light emitting diode (LED): It is a heavily doped p-n junction diode which *main function is to convert electrical signal to optical signal*. The diode is encapsulated with a transparent cover so that emitted light can come out. *The semiconductor used for fabrication of visible LEDs must have a band gap of 1.8* eV- *3* eV. The compound semiconductor Gallium Arsenide – Phosphide ($GaAs_{1-x}P_x$) is used for making LEDs



When diode is in *forward biased*, electrons are sent from n $\rightarrow$ p (where they are minority carriers) and holes are sent from p $\rightarrow$ n (where they are minority carriers). At the junction boundary the concentration of minority carriers increases as comparison to the unbiased condition. These excess minority carriers recombine with majority carriers near the junction. On recombination, the energy is released in the form of photons. Here *intensity of light emitted light is dependent on forward current of the diode with increase in current, intensity of emitted light increases.*

Principle: Electro-luminous

Use: (i) LEDs are used in multimeters, digital watches, mobile phone, calculators and instrument displays (ii) used in remote controls, burglar alarm systems, optical communication, etc.

LEDs have the following advantages over conventional incandescent low power lamps:

(i) Low operational voltage and less power.

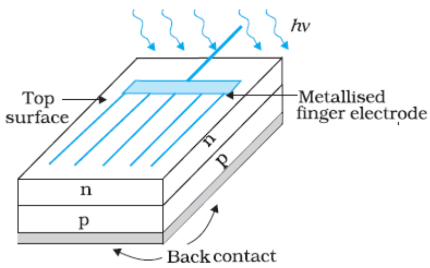
(ii) Fast on-off switching capability and no warm-up time required.

(iii) Long life and ruggedness.

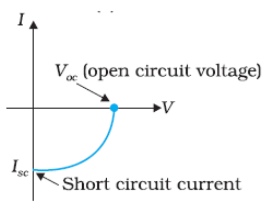
Solar cell: It is a device which converts solar energy in to electric energy.

Principle: Photovoltaic effect.

Construction and working: A thin layer (~0.3 μm) of n-type material (Si) is grown over p-Si wafer by diffusion process. The other side of p-Si is coated with a metal (back contact). On the top of n-Si layer, metal finger electrode is deposited which acts as a front contact. The generation of emf by a solar cell, when light falls on, it is due to the following three basic processes,



p-n junction Solar cell



V-I Characteristics of Solar cell

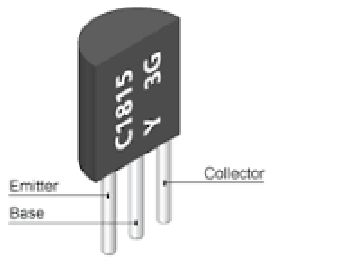
(i) **Generation** of e-h pairs due to light (with $h\nu > Eg$) close to the junction;

(ii) **Separation** of electrons and holes due to electric field of the depletion region. Electrons are swept to n-side and holes to p-side;

(iii) **Collection** the electrons reaching the n-side are collected by the front contact and holes reaching p-side are collected by the back contact. Thus p-side becomes positive and n-side becomes negative giving rise to *photovoltage*.

When an external load is connected a photocurrent starts flows through the load.

Use: Solar cells are used to power electronic devices in satellites and space vehicles, charge storage batteries and also as power supply to some calculators, watches.



The junction transistor: Transistor is a three terminal semiconductor device consisting of two p-n junctions. Transistor was invented by, John Bardeen and Walter Brattain at Bell Telephone Laboratories, United States. The term transistor was coined by John R. Pierce as a contraction of the term ***transfer of resistor*** (*Trans-resistance/Transistor*).

Transistor is of two types,

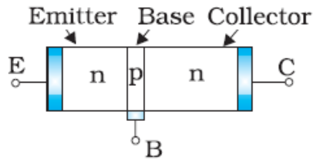
(a) n-p-n Transistor: It consists of a very thin slice of p-type semiconductor sandwiched between two small blocks of n- type semiconductor.

The left side block is called *emitter* (E) middle slice is called *base* (B) and right blocks is called *collector* (C).

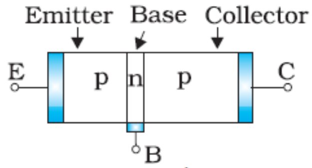
Emitter - heavily doped- moderate thickness -supplies the majority carriers for current flow

Collector- moderately doped- thicker than emitter - collects majority carriers coming from emitter

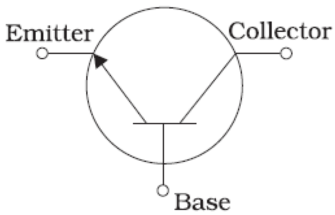
Base-lightly doped-very small in thickness-controls the passage of charge – carriers from the emitter to the collector.



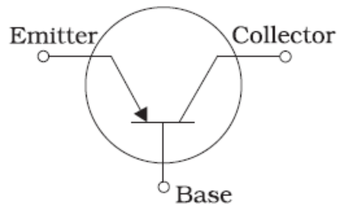
npn-Transistor



pnp-Transistor



Symbal of npn-Transistor

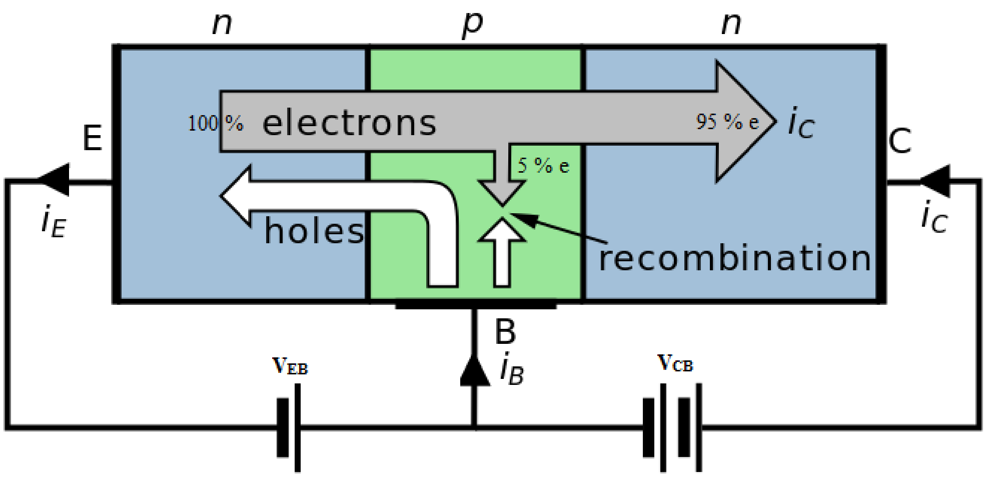


Symbal of pnp-Transistor

(b) p-n-p Transistor: It consists of a very thin slice of n-type semiconductor sandwiched between two small blocks of p-type semiconductor.

Transistor Action:

(i) Working of NPN transistor: The emitter-base junction is forward biased whereas the collector-base junction is reversed biased so the resistance of emitter-base junction low while resistance of collector-base junction is high.



Electrons which are majority charge carrier in emitter are pushed into the base by negative terminal of battery V_{EB} resulting in emitter current I_e. Since base region is thin and lightly doped so about 5% of coming electrons are neutralized in base region by electron-hole recombination and resulting in base current I_B. The remaining 95% electrons pass over to the collector, due to positive potential of battery V_{CB} resulting in collector current I_C.

As one electron reaches to the positive potential of battery V_{CB} at same time one electron flow from negative terminal of V_{CB} to positive terminal of V_{EB} and one electron from negative terminal of battery V_{EB} to emitter. When electron coming from emitter combines with hole in base, the deficiency of hole in base is compensated by the breakage of covalent bond there. The electron so released flow to the positive terminal of battery V_{EB}. Thus in NPN transistors current is carried by electron both in the external circuit as well as inside the transistor. The relation between these current is given by $I_E = I_B + I_C$

(ii) Working of p-n-p transistor: The emitter – base junction is in forward bias by a battery V_{EB}, while the base – collector junction is in reverse – bias by another battery V_{CB}, which have high potential then V_{EB}.

Under the forward – bias, the hole in the emitter (p – region) move towards the base, while the electrons in the base (n- region) move towards the emitter. Since, the base is very thin, most of the holes (about 95%) entering it pass on to the collector, while a very few of them (about 5 %) combine with the electrons present in the base. As soon as a hole combines with an electron, a fresh electron leaves the negative pole of the battery V_{EB} and enters the base. At the same moment, an electron leaves the emitter through terminal E and enters the positive pole of the battery V_{EB}.

This creates a hole in the emitter which starts moving towards the base. Thus, a small current flows in the base – emitter circuit.

The holes entering the collector move under its reverse – bias (which aids them) and reach the terminal C. as soon as a hole reaches C, an electron leaves the negative pole of the battery V_{CB} and neutralizes the hole. At the same moment, a covalent bond is broken in the emitter, the electron produced leaves the emitter through the terminal E and enters the positive pole of the battery V_{EB}, and the hole produced moves towards the base. Thus, a current flows in the collector – emitter circuit.

The small current which leaves the base terminal B is called the 'base – current' I_B, while the large current which leaves the collector terminal is called the 'collector – current' i_C. Both these currents combine to enter the emitter terminal E and constitute the emitter – current I_E. $I_E = I_B + I_C$

Characteristics of transistor: *Common emitter configuration:* The circuit diagram for determining the characteristic curves of a p-n-p transistor in common-emitter configuration is given below.

(a) ***Input characteristics:*** The V-I characteristic curves drawn between base current I_B versus base-emitter voltage V_{BE} at constant collector-emitter voltage V_{CE} is called input characteristics. This curve show following characteristic,

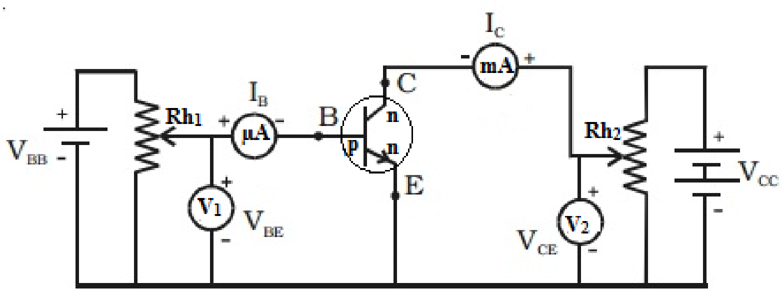


Fig. n-p-n Transistor in common eitter mode

(i) The input current I_B is zero till base emitter voltage V_{BE} is less than barrier voltage, This V-I characteristic curve is similar to that of a forward-biased PN-diode as base-emitter junction of transistor is like to a PN-junction forward biased diode.

(ii) The input resistance of a common emitter (CE) circuit is greater than that of common-base (CB) circuit.

(iii) The input characteristic is only slightly dependent on V_{CE}.

Input resistance: The ratio of change in base-emitter voltage (ΔV_{BE}) to the corresponding change in the base current (ΔI_B) at constant collector-emitter voltage V_{CE} is called input resistance. The input resistance of a common emitter circuit is of the order of a few hundred ohms

i.e. $$r_i = \left[\frac{\Delta V_{BE}}{\Delta I_B}\right]_{V_{CE}=\text{Constant}}$$

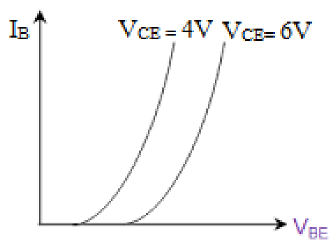


Fig. Input characterstic of Transistor in CE mode

(b) ***Output characteristics:*** The V-I characteristics curve drawn between collector current I_c versus collector-emitter voltage V_{CE} at a fixed value of base current I_B. The characteristic curves show,

(i) When V_{CE} is increased from 0 to 1 V the I_C increases and then after collector current becomes almost constant and independent of V_{CE}. The value of V_{CE} up to which I_C changes is called the *Knee voltage* . Above knee voltage a small increase in collector current is observed with increase of V_{CE} due to widening of depletion layer and capturing a few more majority charge carriers before electron-hole combinations occur in base region.

(ii) Output current I_C dependent on input current I_B.

There are three well defined regions in output characteristic,

(a) *Saturation region:* The region of curves to the left of OA is called the saturation region. In this region transistor act as SWITCHED ON

(b) *Active region:* The central region where the curves are uniform in spacing and slope is called the active region. In this region transistor act as AMPLIFIER.

(c) *Cut-off region:* The region below the line OB is called the cut off region. In this region transistor act as SWITCHED OFF

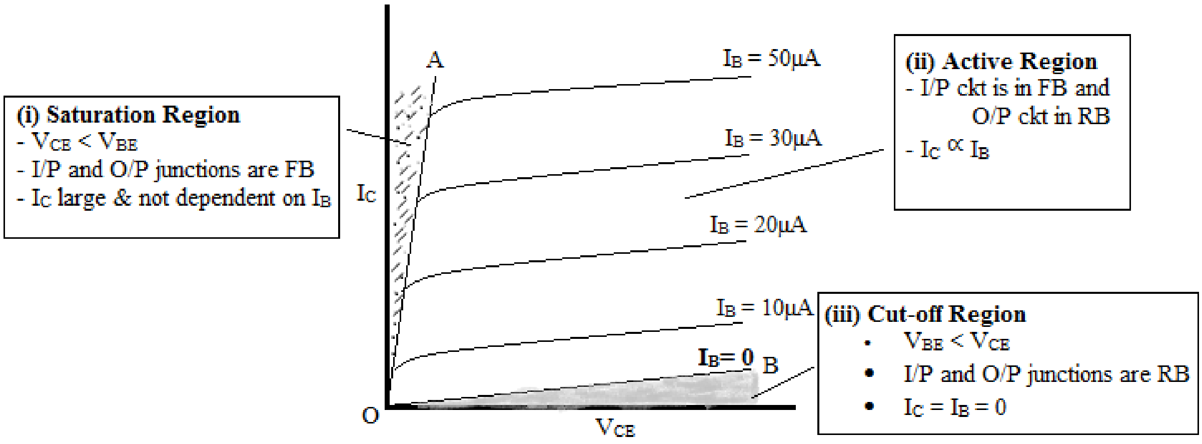
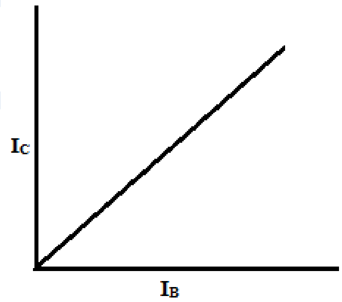


Fig. Output characteristic of transister in CE mode

Output resistance: The ratio of change in collector-emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at constant base current I_B, i.e.,

i.e. $$r_o = \left[\frac{\Delta V_{CE}}{\Delta I_C}\right]_{I_B=\text{Constant}}$$

Transfer characteristics: The graph showing the variation of collector current I_C with base current I_B at constant collector-emitter voltage V_{CE}.

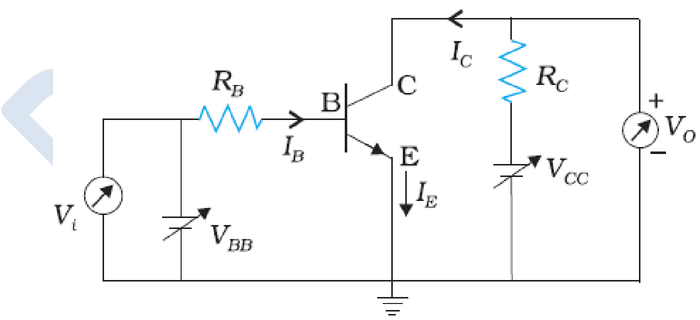


Transfer characteristic

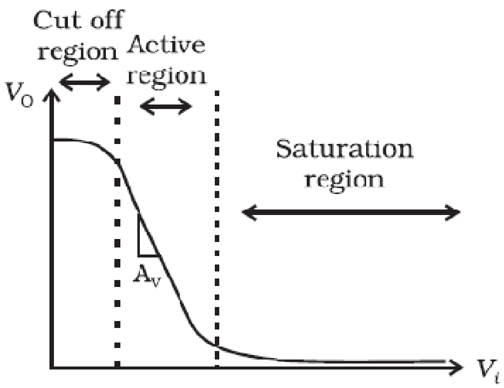
Transistor as a Device:

Transistor as a Switch: When the transistor is used in the *cutoff or saturation state* it acts as a *switch.* Switching circuits are designed in such a way that the *transistor does not remain in active state*. Transistor can be used as switch in computer circuits due to following regions,

1) Transistor small, cheap and have no moving parts.
2) Transistors have long life.
3) They can be switch on and switch off millions of times in a second.



Transistor as Switch



Transfer characteristics

Applying Kirchhoff's voltage rule to the input and output sides of above circuit, we get

Input DC voltage (V_i) = $V_{BB} = I_B R_B + V_{BE}$ and DC output voltage (V_o) =$V_{CE} = V_{CC} - I_C R_C$.

If input voltage 'V_i'is less than 0.6V (for Si transistor), transistor is said to be in *cut off state* and current I_B, I_C and I_E is zero, hence output voltage $V_o = V_{CC}$. As long as *Vi* is *low* and unable to forward-bias the transistor, *Vo* is *high* (at V_{CC}) and transistor is not conducting it is said to be *switched off.*

When *Vi* becomes greater than 0.6 V the transistor is in *active state*, which is not useful in switching circuit.

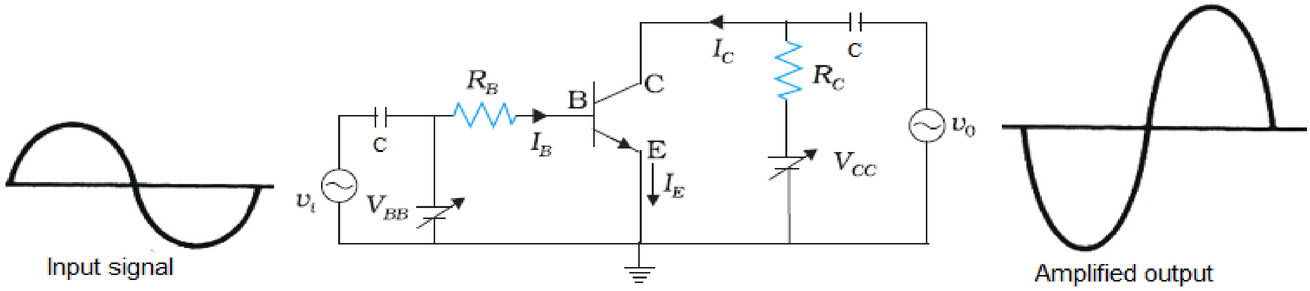
If we further increase *Vi* (say more than 5V), I_C increases almost linearly and so V_o decreases linearly till its value becomes less than about 1.0 V but it never become zero and transistor goes into *saturation state* and transistor is said to be in *switched on* state.
As long as *Vi* is *low* and unable to forward-bias the transistor, *Vo* is *high* (at V_{CC}). If *Vi* is *high* enough to drive the transistor into saturation, then *Vo* is *low*, very near to zero. When the transistor is not conducting it is said to be *switched off* and when it is driven into saturation it is said to be *switched on*.

Alternatively, we can say that a *low* input to the transistor gives a *high* output and a *high* input gives a *low* output.

Transistor as Amplifier: Amplifier is a device which is used to increase amplitude of input signal (Voltage, current or power), and this process is called as amplification. When transistor is used in *active state* it acts as Amplifier.

Working: when a signal of small sinusoidal voltage with amplitude *Vi* is applied to input side it superposed over the dc base bias voltage V_{BB}, then the base current I_B will have sinusoidal variations. As a result the collector current I_C also will have sinusoidal variations, producing in corresponding change in output voltage V_o. We can block dc voltages by using large capacitors and obtain a sinusoidal voltage.
Output voltage is obtained according to equation, $Vcc = V_{CE} + IcR_L$

$$Vo = V_{CE} = Vcc - IcR_L$$



Transistor as Amplifier in CE mode

Phase relationship between input and output signals: When positive half cycle of weak input ac signal is feed to BE input circuit, it favours forward biasing of base emitter circuit, due to which I_B increases and consequently I_C increases. As a result of this output voltage V_O decreases and becomes less positive or becomes negative.
When negative half cycle of weak input ac signal is feed to BE input circuit, it decreases I_B and consequently I_C decreases. Since collector is connected to positive terminal of the battery V_{CC} therefore decrease in I_C means output voltage V_o becomes less negative or becomes positive.
Hence in CE amplifier input and output signals are out of phase i.e. there is a phase difference of 180^o.
Current gain, voltage gain and power gains of CE amplifier:
A.C. Current gain (β_{ac}): The ratio of small change in the collector current (ΔI_C) to the small change in base current (ΔI_B) when collector-emitter voltage (V_{CE}) is kept constant. It is also called current amplification factor or small signal current gain.

$$A_i = \beta_{ac} = \left[\frac{\Delta I_c}{\Delta I_B}\right] V_{CE=\text{ Constant}}$$

D.C. Current gain (β_{dc}): The ratio of collector current (I_C) to the base current (I_B) when collector-emitter voltage (V_{CE}) is kept constant.

$$\beta_{dc} = \left[\frac{I_c}{I_B}\right] V_{CE=\text{ Constant}}$$

A.C. Voltage gain (β_{ac}): The ratio of small change in output voltage (ΔV_{CE}) to the small change in input voltage (ΔV_{BE}) when collector-emitter voltage (V_{CE}) is kept constant.

$$A_v = \frac{\Delta V_{CE}}{\Delta V_{BE}}$$

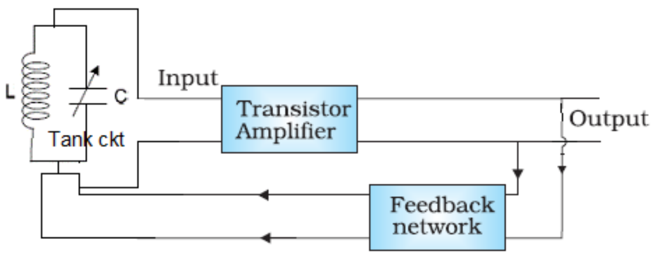
Voltage gain = current gain× resistance gain

A.C. Power gain: The ratio of small change in output power to the small change in input power

$$\text{A.C. Power gain} = \frac{\text{change in output power}}{\text{change in input power}}$$

$$= \frac{(\Delta I_c)^2 R_0}{(\Delta I_B)^2 R_i} = \beta_{ac}{}^2 . \frac{R_0}{R_i}$$

Transistor as an Oscillator: It is an electronic device which converts direct current to alternate current.



Principle of Oscillator

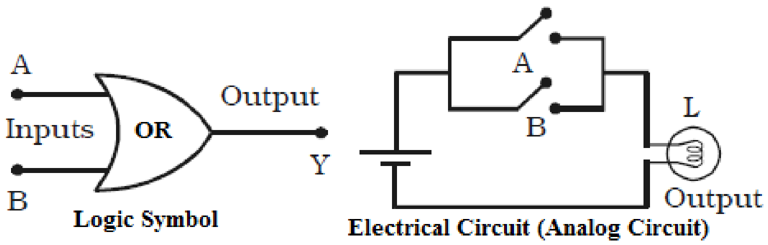
Logic gates: Those circuits which are used to process digital signals are called logic gates. It have one or more inputs but with only one output. The output appears only for certain combination of input logic levels. Logic gates are the basic building blocks of digital circuit. The numbers 0 and 1 represent the two possible states of a logic
circuit. The two states can also be referred to as 'ON and OFF' or 'HIGH and LOW' or 'TRUE and FALSE'.

Basic logic gates: There three basic logic gates, (i) OR (ii) AND (iii) NOT gate

Truth table: All the possible inputs and outputs of a logic circuit are represented in a table called truth table. The numbers 0 and 1 represent the two possible states of a logic circuit. The two states can also be referred to as 'ON and OFF' or 'HIGH and LOW' or 'TRUE and FALSE'.

(i)**OR gate:** An OR gate has two or more inputs but only one output. It is the logic gate in which we get high **1** output if any one or all of the inputs are high **1** otherwise low **0**.

Boolean expression: **Y= A+B** + symbol is OR operator

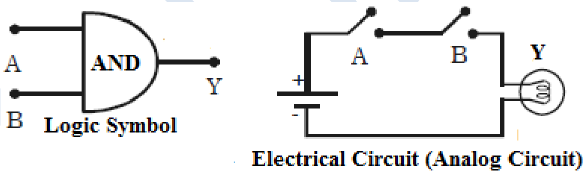


Truth Table

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

(ii)AND gate: An AND gate has two or more inputs but only one output. It is the logic gate in which we get high **1** output if all the inputs are high **1** otherwise low **0**.

Boolean expression: **Y=A.B** '**.**' symbol is AND operator

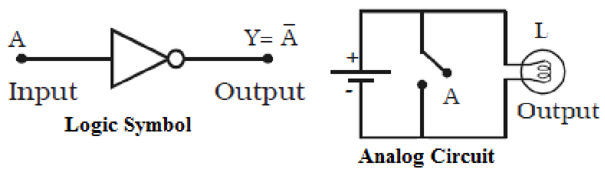


Truth Table

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

(iii)NOT gate: The NOT gate is a logic gate with only one input and one output. It is the logic gate in which we get output if input is low otherwise high. It is also known as inverter.

Boolean expression: **Y =** $\bar{A}$ '**-**' symbol is NOT operator

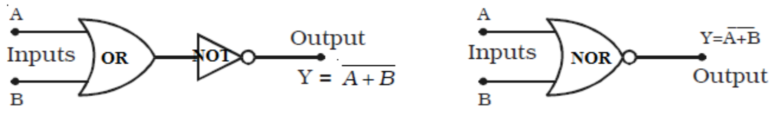


Truth Table

$\bar{A}$	Y
0	1
1	0

Universal logic gates: NAND and NOR gate are called *Universal Gates* because by using any one these gates we can obtain other basic gates like OR, AND and NOT.

NAND gate: This is an AND gate followed by a NOT gate. If inputs A *and* B are both '1', the output Y is '0'.
Boolean expression: Y = $\overline{\boldsymbol{A.B}}$



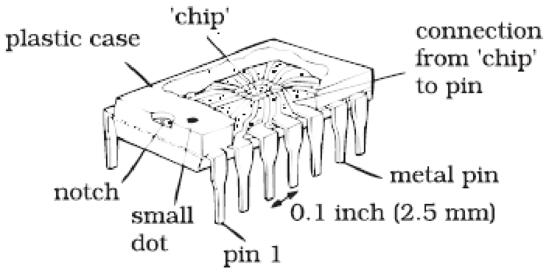
OR gate followed by NOT *Logic Symbol*

NOR gate

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

NOR Gate: A NOT- operation applied *after* OR gate gives a NOT-OR gate (or simply NOR gate). It has two or more inputs and one output. Its output Y is '1' only when both inputs A and B are '0', i.e., neither one input *nor* the other is '1'.
Boolean expression: Y = $\overline{\boldsymbol{A+B}}$

Integrated circuits: To reduce bulkiness of electronic circuit, making it more reliable and shockproof the *entire circuit* (consisting of many passive components like *R* and *C* and active devices like diode and transistor) is fabricated on a small single block (or chip) of a semiconductor has revolutionised the electronics technology. Such a circuit is known as *Integrated Circuit* (IC). It consist many logical gates or circuits are integrated in one single 'Chip'. The most widely used technology is the *Monolithic Integrated Circuit.*



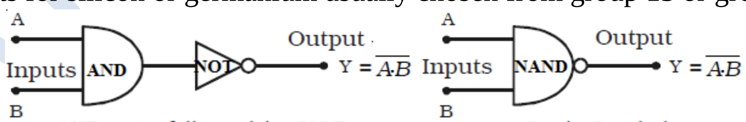
The casing and connection of a 'chip'

Depending on nature of input signals, IC's can be grouped in two categories:
(a) *Linear* or *analogue IC's:* The linear IC's process analogue signals which change smoothly and continuously over a range of values between a maximum and a minimum. The output is more or less directly proportional to the input, i.e., it varies *linearly* with the input. One of the most useful linear IC's is the operational amplifier.
(b) *Digital IC's:* The digital IC's process signals that have only two values. They contain circuits such as logic gates.

Depending upon the level of integration (i.e., the number of circuit components or logic gates), the ICs are termed as Small Scale Integration, SSI (logic gates < 10); Medium Scale Integration, MSI (logic gates < 100); Large Scale Integration, LSI (logic gates < 1000); and Very Large Scale Integration, VLSI (logic gates > 1000).

SOME IMPORTANT QUESTIONS:

1) State with reason why a photodiode is usually operated at a reverse bias.**(1)**
2) Why are elemental dopants for silicon or germanium usually chosen from group 13 or group 15? **(1)**
3) Sn, C, Si and Ge are all group 14 elements. Yet, Sn is a conductor, C is an insulator while Si and Ge are semiconductors. Why?**(1)**



AND gate followed by NOT *Logic Symbol*

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

4) Can the potential barrier across a p-n junction be measured by simply connecting a voltmeter across the junction? **(1)**
5) In a CE transistor amplifier there is power gain. Considering power a measure of energy, does the circuit violate law of conservation of energy? **(1)**
6) Explain why elemental semiconductor cannot be used to make visible LEDs. **(1)**
7) State the factor, which controls (i) wavelength of light and (ii) intensity of light, emitted by a LED. **(2)**
8) Draw energy band diagrams of an n – type and p- type semiconductor at temperature T > 0 K. mark the donor and acceptor energy levels with their energies. **(2)**
9) Briefly explain working of solar cell. Draw its V- I characteristics. **(2)**
10) Obtain AND gate from NOR gate. What are universal logic gates? **(2)**

11) What is the function of base region of a transistor? Why this region is made thin and slightly doped? **(2)**
12) Draw a labeled circuit diagram of a common emitter amplifier using a p-n-p transistor. Explain how the input and output voltage are out of phase by 180^O for a common – emitter transistor amplifiers. **(3)**
13) With the help of a circuit diagram explain the action of npn transistor. **(3)**
14) Briefly explain working of photodiode. How it is used to detect optical signal. Draw its V- I characteristics for two different intensities of illumination. **(3)**
15) Describe briefly, with the help of a diagram, the role of the two important processes involved in the formation of a p-n junction, and explain term 'barrier potential'. **(3)**
16) What are energy bands? How are these formed? Distinguish between a conductor, an insulator and a semiconductor on the basis of energy band diagram. **(5)**
17) State the principle of working of p-n junction diode as a rectifier. Explain with the help of a circuit diagram, the use of p-n diode as a full wave rectifier. Draw a sketch of the input and output waveforms. **(5)**
18) (a) Why is zener diode fabricated by heavily doping both p-and n-sides of the junction? (b) Draw the I-V characteristics of zener diode. (c) Draw the circuit diagram of zener diode as a voltage regulator and briefly explain its working. **(5)**
19) Draw the circuit diagram to study the characteristics of npn transistor in common emitter configuration. Sketch typical (i) input characteristics (ii) output characteristics for such a configuration. Explain how the current gain of transistor is calculated from output characteristics. **(5)**