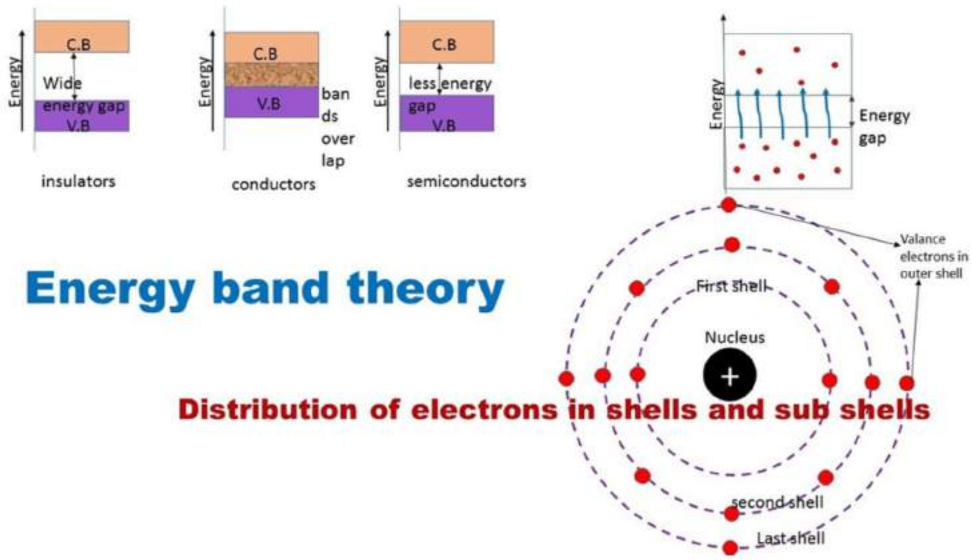
Chapter 14

Semiconductor Electronics: Materials, Devices and Simple Circuits

Energy Bands

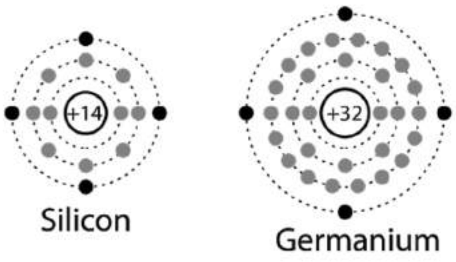
Band Theory of Solids

In a substance, as many atoms are close to each other, the energy levels of the atom form a continuous band, wherein the electrons move. This is called the band theory of sol

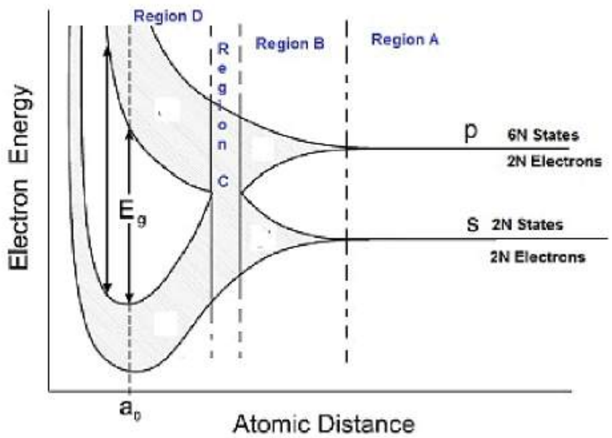


- We know that in an atom, the protons and the neutrons constitute the central part called the nucleus.
- The electrons revolve around the nucleus in defined orbits.
- The orbits are named as 1s, 2s, 2p, 3s, 3p, 3d etc. each of which has a discrete energy level.
- All electrons in the same orbit have the same energy.
- The electrons in the innermost orbits which are completely filled constitute the valence electrons whereas the electrons in the outermost orbit which do not completely fill that shell are called conduction electrons.

- As seen in the diagram below, both Si and Ge have 4 electrons in the outermost shell.



- When in the crystal, the atoms are close to each other and hence they may be the flow of electrons from one atom to another in the conduction band.
- Let us discuss in detail by considering interatomic distance in the X-axis and energy in the Y-axis:
- As seen in the diagram below, the graph is divided into 4 regions – Region A, B, C and D.



Region A

- In region A, the interatomic distance is large between atoms and in region D, the interatomic distance is small.
- Consider that the Si or Ge crystal contains N atoms. Electrons of each atom will have discrete energies in different orbits.
- If the atoms are isolated, that is, separated from each other by a large distance, the electron energy will be the same.

- However, in a crystal, the atoms are close to each other separated by a distance of 2-3 Ao. Hence, electrons interact with each other and also with the neighbouring atoms.
- The overlap or the interaction will be felt more by the electrons in the outermost orbit while the inner electron energies will remain unaffected.
- Hence, in the case of Si and Ge crystals, we need to consider the changes in energies of electron in the outermost orbit only.
- For Si, the outermost orbit is the third orbit ($n = 3$) while for Ge, the outermost orbit is the fourth orbit ($n = 4$).
- The number of electrons in both cases is 4 – namely 2s and 2p. Hence, the outer electrons in the crystal are 4.
- The maximum possible number of outer electrons in the orbit is 8 (2s + 6p electrons).
- This is the case of well-separated or isolated atoms as shown in region A.

Region B

- Suppose the atoms start coming nearer to each other to form a solid.
- The energies of the electrons in the outermost orbit may increase or decrease, due to the interaction between electrons of different atoms.
- The 6N states for $l=1$, which originally had identical energies in the isolated atoms, spread out and form an energy band as shown in the region B.
- Similarly, the 2N states for $l = 0$ splits into a second band separated from the first one.

Region C

- At still smaller spacing, however, there comes a region in which the bands merge with each other.
- The lowest energy state that is a split from the upper atomic level appears to drop below the upper state that has come from the lower atomic level.
- In this region, no energy gap exists where the upper and the lower energy states get mixed.

Region D

- If the distance between the atom further decreases, the energy bands again split apart and are separated by an energy gap E_g.

- The total number of available energy states 8N has been re-apportioned between the two bands (4N states each in the lower and upper energy bands).
- Here there are exactly as many states in the lower band (4N) as there are available valence electrons from the atoms (4N).
- This lower band called the valence band is completely filled while the upper band is completely empty. The upper band is called the conduction band.

Three Types of Energy Bands in A Solid

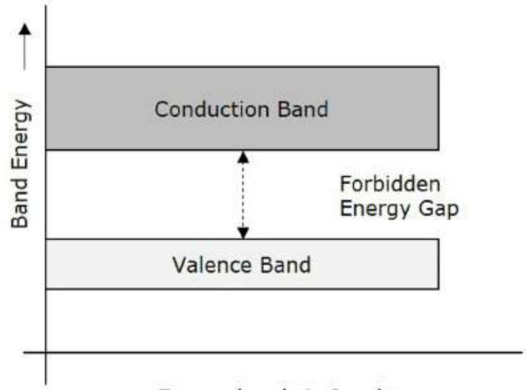
- Valence energy band
- Conduction energy band
- Forbidden energy gap.

Table: Difference between valence, forbidden and conduction energy bands

Valance Energy Band	Forbidden Energy Band	Conduction Energy Band
In this band there are valence electrons.	No electrons are found in this band	In this band the electrons are rarely found
This band may be partially or completely filled with electrons.	This band is completely empty.	This band is either empty or partially filled with electrons.
In this band the electrons are not capable of gaining energy from external electric field.		In this band the electrons can gain energy from electric field.
The electrons in this band do not contribute to electric current.		Electrons in this band contribute in this band contribute to electric current.
In this band there are electrons of outermost orbit of atom which contribute in band formation,		In this band there are electrons which are obtained on breaking the covalent bands,
This is the band of maximum energy in which the electrons are always present.		This is the band of minimum energy which is empty.
This band can never be empty.		This band can be empty.

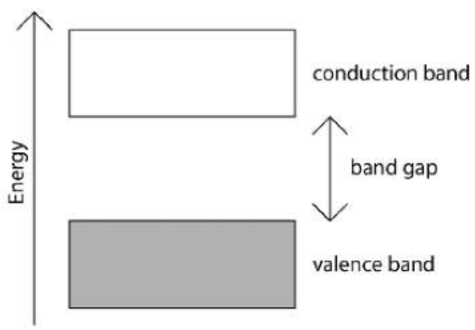
More about Energy Bands

- The conduction band is also known as the first permitted energy band or first band.
- As there are energy levels f electrons in an atom, similarly there are three specific energy bands for the electrons in the crystal formed by these atoms as shown in the figure.



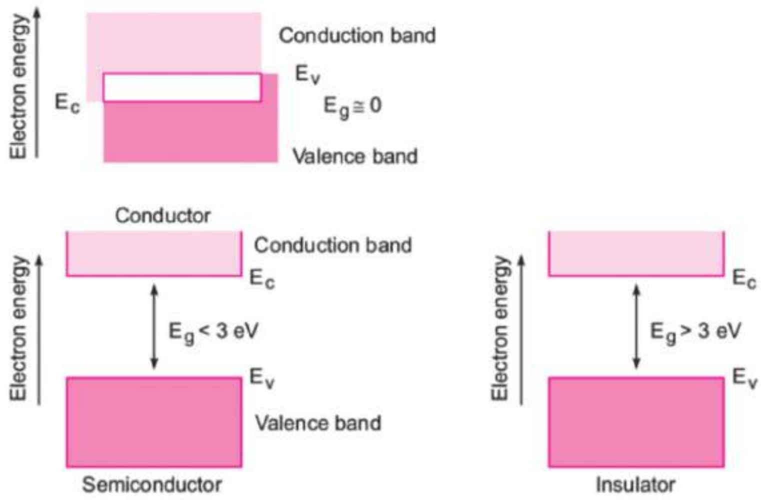
Energy bands in Insulators

- Completely filled energy bands: The energy band, in which the maximum possible number of electrons are present according to capacity is known as completely filled bank.
- Partially filled energy bands: The energy band, in which a number of electrons present is less than the capacity of the band, is known as a partially filled energy band.
- Electric conduction is possible only in those solids which have an empty energy band or partially filled energy band.
- Energy gap or Band gap (E_g):
  The minimum energy which is necessary for shifting electrons from valence band to conduction band is defined as band gap (Eg).
- The forbidden energy gap between the valence band and the conduction band is known as band gap (Eg). i.e. $Eg = Ec - Ev$.



Classification on the basis of energy bands

Depending upon the relative position of the valence band and the conduction band, the solids can be classified into conductors, insulators and semiconductors.



Conductors

- The conduction band and the valence band partly overlap each other and there is no forbidden energy band gap in between.
- The electrons from the valence band can easily move into the conduction band.
- Hence, a large number of electrons are available for conduction.
- The resistance of such materials is low and conductivity is high.

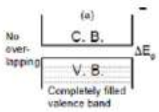
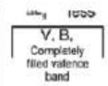
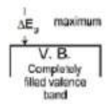
Insulators

- In case of insulators, a large energy gap exists between the valence band and the conduction band.
- The energy gap is so high that the electrons from the valence band cannot move to the conduction band by thermal excitation.
- As there are no electrons in the conduction band, electrical conduction is not possible.

Semiconductors

- A finite but a small energy gap exists between the valence band and the conduction band.
- At room temperature, some of the electrons from the valence band acquire energy and move into the conduction band.
- Hence, at high temperature, semiconductors have conductivity and resistance is also not as high as insulators.
- There are two types – Intrinsic semiconductor and Extrinsic semiconductor.

Table: Difference between Conductors, Semi-conductors and Insulators.

S.No.	Property	Conductors	Semi - conductors	Insulators
1.	Electrical conductivity and its value	Very high 10^{-7} Ω/m	Between those of conductors and insulators i.e. 10^{-7} Ω/m to 10^{-13} Ω/m	Negligible 10^{-13} Ω/m
2.	Resistivity and its value	Negligible Less than 10^{-5} Ω-m	Between those of conductors and insulators i.e. 10^{-5} Ω-m to 10^{5} Ω-m	Very high more than 10^{5} Ω-m
3.	structure			
4.	Energy gap and its value	Zero or very small	More than that in con-ductors but less than that in insulators e.g. in Ge, ΔE_g =0.72 eV is Si, ΔE_g =1.1 eV in Ga As ΔE_g =1.3 eV	Very large e.g. in diamond ΔE_g = 7 eV
5.	Current carriers and current flow	Due to free electrons and very high	Due to free electrons and holes more than that in	Due to free electrons but negligible.

6.	(electrons or holes) at ordinary temperature	Very high	very low	negligible
7.	Condition of valence band and conduction band at ordinary temperature	The valence and conduction bands are completely filled or conduction band is some what empty (e.g. in Na)	Valence band In somewhat empty and conduction band is somewhat filled	Valence band is completely filled and conduction band is completely empty.
8.	Behaviour at 0 K	Behaves like a superconductor.	Behaves like an insulator	Behaves like an insulator
9.	Temperature coefficient of resistance (α)	Positive	Negative	Negative
10.	Effects of temperature on conductivity	Conductivity decreases	Conductivity increases	Conductivity increases
11.	On increasing temperature the number of current carriers	Decreases	Increases	Increases

12.	On mixing impurities their resistance	Increases	Decreases	Remains unchanged
13.	Current flow in these takes place	Easily	Very slow	Does not take place
14.	Examples	Cu. Ag, Au, Na, Pt, Hg etc.	Ge, Si, Ga, As etc.	Wood, plastic, mica, diamond, glass etc.

Classification of Metals, Conductors & Semiconductors

On the basis of conductivity

The conductivity of a material indicates whether they can be classified as metals, semiconductors or insulators
The electrical conductivity is expressed as σ whereas the reciprocal of conductivity is resistivity $\rho = 1/\sigma$

- Metals – Metals have high conductivity and low resistivity ; ρ is of order 10^{-2} to 10^{-8} Ω m ; σ is of order 10^{2} to 10^{8} S/m

Aluminium Metal

- Semiconductors – They have conductivity and resistivity in between metals and insulators; ρ is of order 10^{-5} to 10^{-6} Ω m; σ is of order 10^{5} to 10^{6} S/m

Silicon (Semiconductors)

- Insulators – They have high resistivity and hence low conductivity; ρ is of order 10^{-11} to 10^{-19} Ω m ; σ is of order 10^{2} to 10^{19} S/m

Wood (Insulator)

Classification of semiconductors

The semiconductors can be classified into Elementary type semiconductor and compound type semiconductor

- Elementary type semiconductor - These type of semiconductors are available in natural form like Silicon (Si) and germanium (Ge)
- Compound type semiconductor – When semiconductors are made by compounding the metals, we get compound type semiconductor. They can be further classified into
  - Inorganic semiconductors like CdS, GaAs etc
  - Organic semiconductors like Antracene, doped pthalocyanines
  - Organic polymers – Polypyrole, polyaniline, polythiophene

Semiconductors: Properties & Types

Semiconductors are the materials that have a conductivity between conductors (generally metals) and non-conductors or insulators (such as ceramics). Semiconductors can be compounds such as gallium arsenide or pure elements, such as germanium or silicon. Physics explains the theories, properties and mathematical approach governing semiconductors.

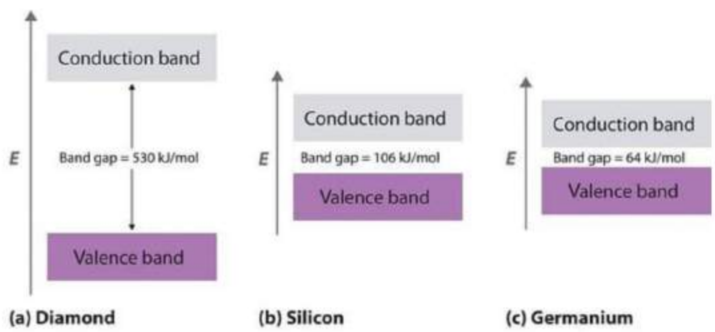
Properties of Semiconductors

- Semiconducting elements are tetra-valent i.e. there are four electrons in their outermost orbit.
- Their lattice is face centered cubic (F.C.C.)

- The number of electrons or cotters is given by

  $n_i = p_i = AT^{3/2}e^{-E_g/2kT}$

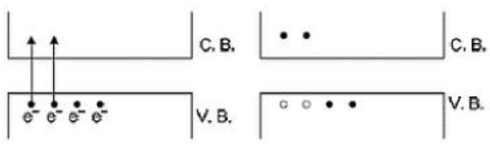
  i.e. on increasing temperature, the number of current carriers increases.
- There are uncharged.
- Semiconductor acts like an insulator at Zero Kelvin. On increasing the temperature, it works as a conductor.
- Due to their exceptional electrical properties, semiconductors can be modified by doping to make semiconductor devices suitable for energy conversion, switches, and amplifiers.
- Lesser power losses.
- Semiconductors are smaller in size and possess less weight.
- Their resistivity is higher than conductors but lesser than insulators.
- The resistance of semiconductor materials decreases with the increase in temperature and vice-versa.



Example of different semi-conductors

- **Holes or cotters**

  (i) The deficiency of electrons in covalent band formation in the valence band in defined as hole or cotter,
  (ii) These are positively charged. The value of positive charge on them is equal to the electron charge.
  (iii) Their effective mass is less than that of electrons.
  (iv) In an external electric field, holes move in a direction opposite to that of electrons i,e. they move from positive to negative terminal.
  (v) They contribute to current flow.
  (vi) Holes are produced when covalent bonds in valence band break.

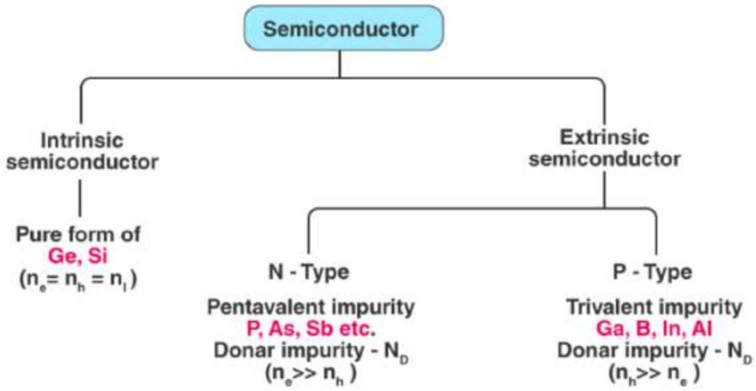


Transfer of electrons from valence band to conduction band

Types of Semiconductor

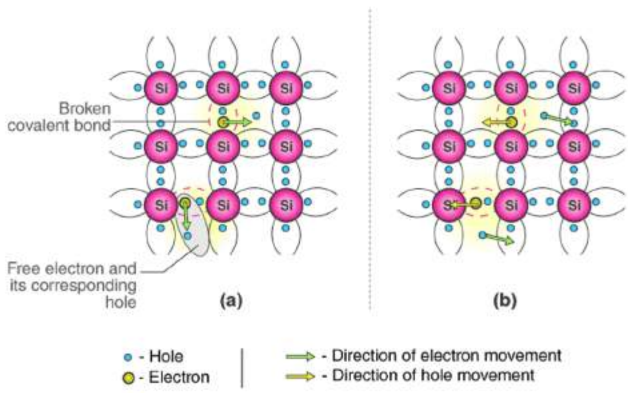
Semiconductors can be classified as:

- Intrinsic Semiconductor
- Extrinsic Semiconductor



Intrinsic Semiconductor

- An intrinsic type of semiconductor material is made to be very pure chemically. It is made up of only a single type of element.



Conduction Mechanism in Case of Intrinsic Semiconductors (a) In absence of electric field (b) In presence of electric Field

- Germanium (Ge) and Silicon (Si) are the most common type of intrinsic semiconductor elements. They have four valence electrons (tetravalent).

They are bound to the atom by covalent bond at absolute zero temperature.

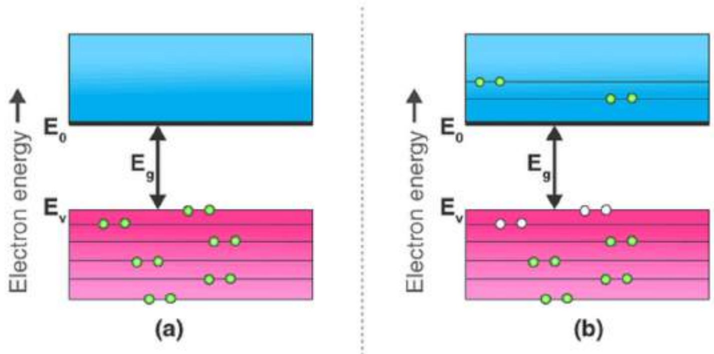
- When the temperature rises, due to collisions, few electrons are unbounded and become free to move through the lattice, thus creating an absence in its original position (hole). These free electrons and holes contribute to the conduction of electricity in the semiconductor. The negative and positive charge carriers are equal in number.
- The thermal energy is capable of ionizing a few atoms in the lattice, and hence their conductivity is less.

➢ The Lattice of Pure Silicon Semiconductor at Different Temperatures

- At absolute zero Kelvin temperature: At this temperature, the covalent bonds are very strong and there are no free electrons and the semiconductor behaves as a perfect insulator.
- Above absolute temperature: With the increase in temperature few valence electrons jump into the conduction band and hence it behaves like a poor conductor.

➢ Energy Band Diagram of Intrinsic Semiconductor

- The energy band diagram of an intrinsic semiconductor is shown below:



(a) Intrinsic Semiconductor at T = 0 Kelvin, behaves like an insulator (b) At t>0, four thermally generated electron pairs

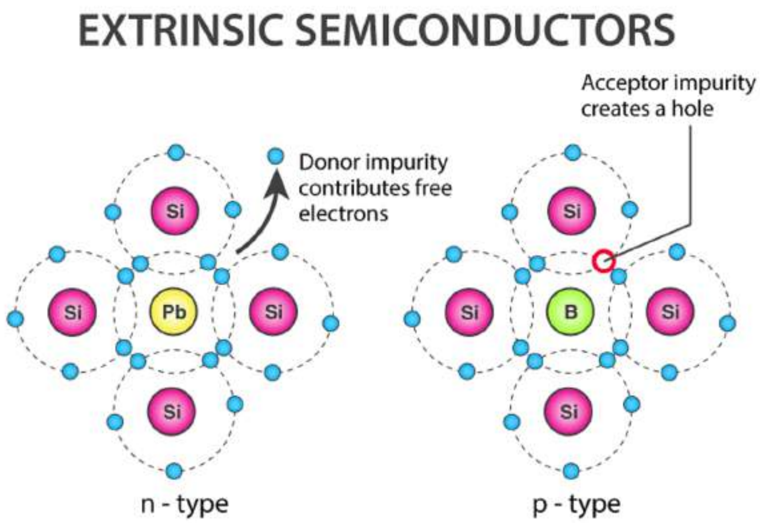
- In intrinsic semiconductors, current flows due to the motion of free electrons as well as holes. The total current is the sum of the electron

current Ie due to thermally generated electrons and the hole current Ih
Total Current (I) = Ie + Ih

- For an intrinsic semiconductor, at finite temperature, the probability of electrons to exist in conduction band decreases exponentially with increasing bandgap (Eg) $n = n_0 e^{\frac{-E_g}{2K_bT}}$
Where,
E_g = Energy bandgap
K_b = Boltzmann's constants

Extrinsic Semiconductor

- The conductivity of semiconductors can be greatly improved by introducing a small number of suitable replacement atoms called **impurities**.



- The process of adding impurity atoms to the pure semiconductor is called **doping.**
- Usually, only 1 atom in 107 is replaced by a dopant atom in the doped semiconductor.
- An extrinsic semiconductor can be further classified into:
  (i) N-type Semiconductor
  (ii) P-type Semiconductor

Table: Difference between intrinsic and extrinsic semiconductors

S.No.	Intrinsic semiconductors	Extrinsic semiconductors
1.	Pure Ge or Si is known as intrinsic semiconductor	The semiconductor, resulting from mixing impurity in it, is known as extrinsic semiconductors.
2.	Their conductivity is low (because only one electron in 10^9 contribute)	Their conductivity is high
3.	The number of free electrons (m in conduction band Is equal to the number of holes p_i in valence band.)	In these $n_i \neq p_i$
4.	These are not practically used	These are practically used
5.	In these the energy gap is very small	In these the energy gap is more than that in pure semiconductors.
6.	In these the Fermi energy level lies in the middle of valence band and conduction	In these the Fermi level shifts towards valence or conduction energy bands.

➢ **Properties of Extrinsic Semiconductors**

- At absolute zero temperature (0 K) there are no free electrons in them.
- At room temperature, the electron-hole pair in sufficient number are produced.
- Electric conduction takes place via both electrons and holes.
- The drift velocities of electrons and holes are different.
- The drift velocity of electrons (V_{dn}) is greater than that of holes (V_{dp}).
- The total current is $I = I_n + J_p$.

- In connecting wires the current flows only via electrons.
- The current density is given by:

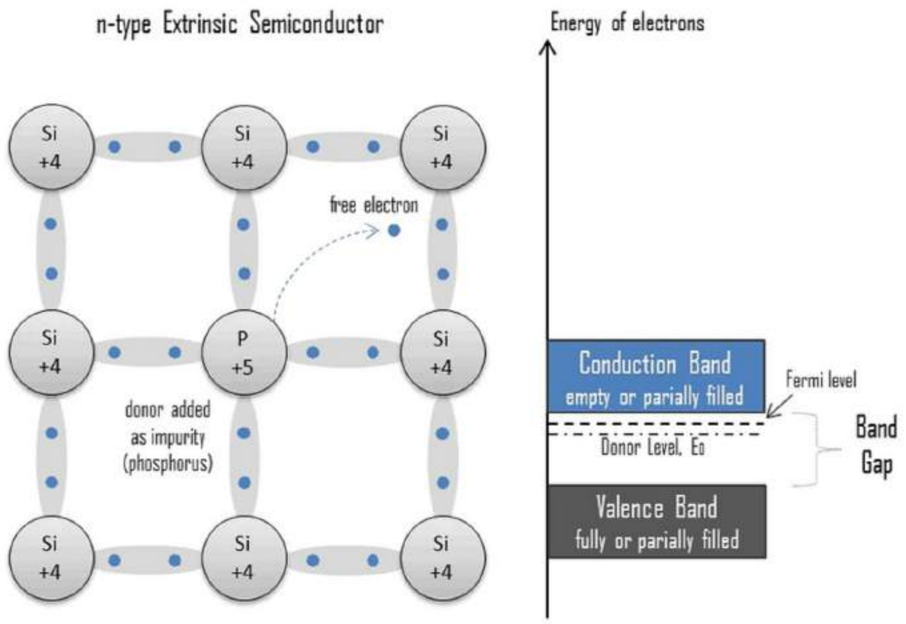
  $J = {}_{nq}V_{dn} + {}_{pq}V_{dp}$

  $\vec{J} = {}_{nqm_n}E + {}_{pqm_p}E = s\vec{E}$

  Where V_{dn} = drift velocity of electrons
  μ_n = mobility of electrons
  V_{dp} = drift velocity of holes
  μp = mobility of holes
- The electric conductivity is given by $s = nq(m_n + m_p)$.
- Mobility of electron $m_n = V_{dn} / E$.
- Mobility of holes $m_p = V_{dp}/E$.
- At room temperature $s_{Ge} > s_{Si}$ because $n_{Ge} > n_{Si}$ where $n_{Ge} = 2.5' \, 10^{13}/cm^3$ and $n_{Si} = 1.4' \, 10^{10}/cm^3$.

Extrinsic Semiconductor: N-type & P-type Semiconductors

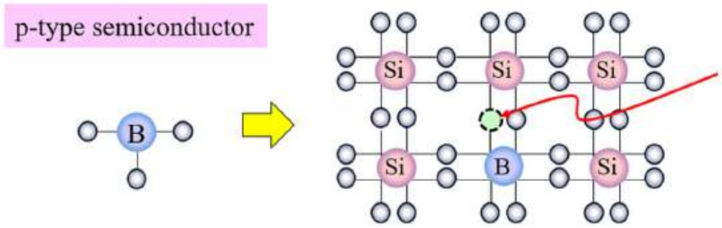
N-Type Semiconductor



- Mainly due to electrons
- Entirely neutral
- I = Ih and nh >> ne
- Majority – Electrons and Minority – Holes

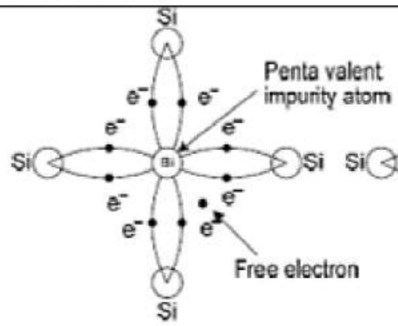
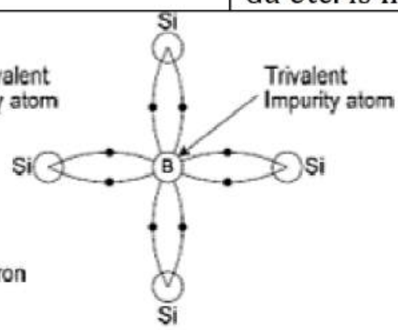
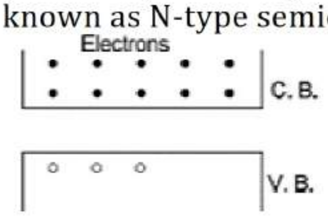
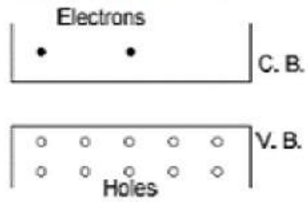
- When a pure semiconductor (Silicon or Germanium) is doped by pentavalent impurity (P, As, Sb, Bi) then, four electrons out of five valence electrons bonds with the four electrons of Ge or Si.
- The fifth electron of the dopant is set free. Thus, the impurity atom donates a free electron for conduction in the lattice and is called "Donar.
- Since the number of free electron increases by the addition of an impurity, the negative charge carriers increase. Hence, it is called n-type semiconductor.
- Crystal as a whole is neutral, but the donor atom becomes an immobile positive ion. As conduction is due to a large number of free electrons, the electrons in the n-type semiconductor are the **majority carriers** and holes are the **majority carriers.**

P-Type Semiconductor



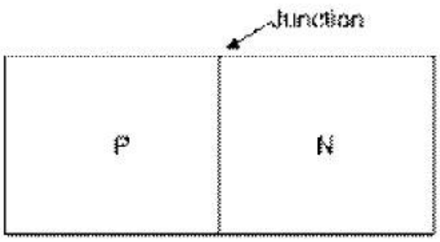
- Mainly due to holes
- Entirely neutral
- I = Ih and nh >> ne
- Majority – Holes and Minority – Electrons
- When a pure semiconductor is doped with a trivalent impurity (B, Al, In, Ga) then, the three valence electrons of the impurity bonds with three of the four valence electrons of the semiconductor.
- This leaves an absence of electron (hole) in the impurity. These impurity atoms which are ready to accept bonded electrons are called "Acceptors".
- With the increase in the number of impurities, holes (the positive charge carriers) are increased. Hence, it is called p-type semiconductor.
- Crystal as a whole is neutral, but the acceptors become an immobile negative ion. As conduction is due to a large number of holes, the holes in the p-type semiconductor are **majority carriers** and electrons are **majority carriers.**

Table: Difference between N-type and P-type semiconductors

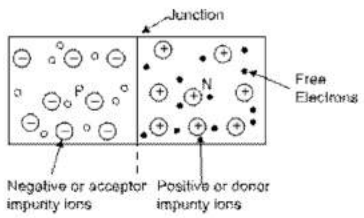
S.No.	N-type semiconductors	P-type semiconductors
1.	In these the impurity of some pentavalent element like P, As, Sb, Bi, etc. is mixed	In these, the impurity of some trivalent element like b, Al, In, Ga etc. is mixed
2.		
3.	in these the impurity atom donates one electrons, hence these are known as donor type semiconductors	In these, the impurity atom can accept one electron, hence these are known as acceptor type semiconductors.
4.	In these the electrons are majority current carriers and holes are minority current carriers, (i.e. the electron density is more than hole density $n_n >> n_p$)	In these the holes are majority current carriers and electrons are minority current carriers i.e. $n_p >> n_n$
5.	In these there is majority of negative particles (electrons) and hence are known as N-type semiconductors 	In these there is majority of positive particles (cotters) and hence are known as P-type semiconductors. 
6.	in these the donor energy level is close to the conduction band and far away from valence band.	In these the acceptor energy level is close to the valence band and far away from conduction band.

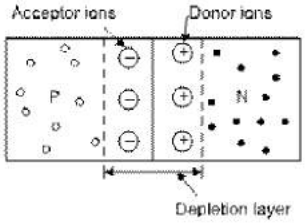
P N Junction Formation

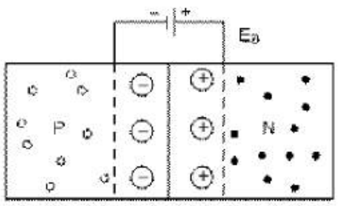
(a) The device formed by joining atomically a wafer of P-type semiconductor to the wafer of N-type semiconductor is known as P-N junction.



(b) There are three processes of making junctions
(i) Diffusion
(ii) Alloying
(iii) Growth
In majority of cases P-N junction is formed by diffusion process. The impurity concentration is maximum at surface and decreases gradually inside the semiconductor.
(c) Conduction of current in P-N Junction:







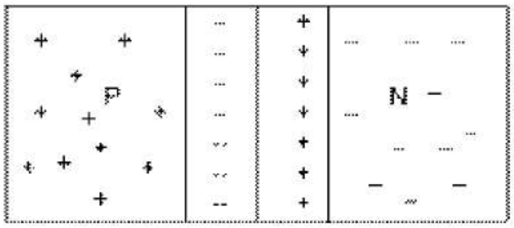
(i) In P-N junction the majority cotters in P-region and majority electrons in N-region start diffusing due to concentration gradient and thermal disturbance towards N-region and P-region respectively and combine respectively with electrons and cotters and become neutral.
(ii) In this process of neutralization there occurs deficiency of free current carriers near the junction and layers of positive ions in N-region and negative ions in P-

region are formed. These ions are immobile. Due to this an imaginary battery or internal electric field is formed at the junction which is directed from N to P.

(a) The region on both sides of P-N junction in which there is deficiency of free current carriers, is known as the depletion layer.

(b) Its thickness is of the order of 1 micro m (= 10^{-6})

(c) On two sides of it, there are ions of opposite nature. i.e. donor ion (+ve) on N-side and acceptor ions (–ve) on P-side.

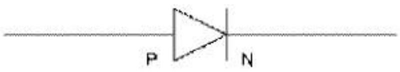


(d) This stops the free current carriers to crossover the junction and consequently a potential barrier is formed at the junction.

(e) The potential difference between the ends of this layer is defined as the contact potential or potential barrier (V_B).

(f) The value of V_B is from 0.1 to 0.7 volt which depends on the temperature of the junction. It also depends on the nature of semiconductor and the doping concentration. For germanium and silicon its values are 0.3 V and 0.7 V respectively.

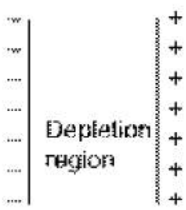
(h) Symbolic representation of diode:



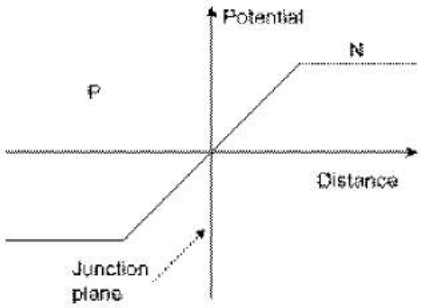
(ii) The direction of current flow is represented by the arrow head.

(iii) In equilibrium state current does not flow in the junction diode.

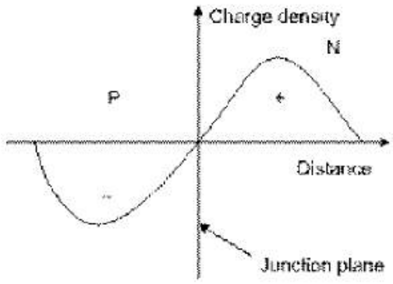
(iv) In can be presumed to be equivalent to a condenser in which the depletion layer acts as a dielectric.



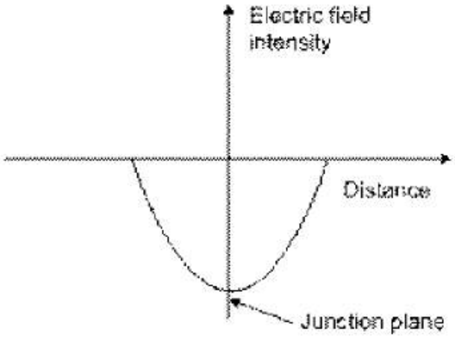
(v) Potential distance curve at P-N Junction



(vi) Charge density curve at P-N Junction



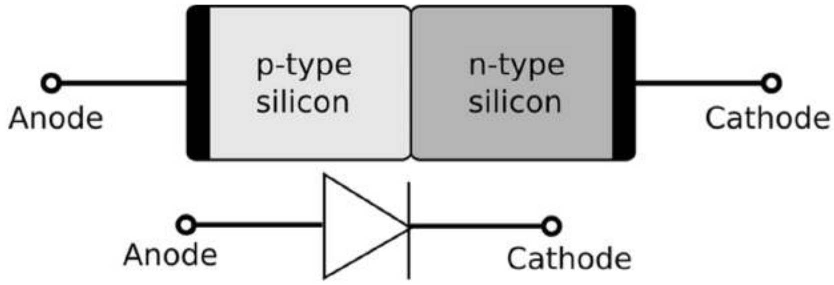
(vii) Curve between electric field and distance near P-N junction



P-N Junction Diode: Forward & Reverse Bias

p-n Junction Diode

- A semiconductor diode is a p-n junction with metallic contacts provided at the ends for the application of an external voltage
- Thus p-n junction diode is a two terminal device represented as

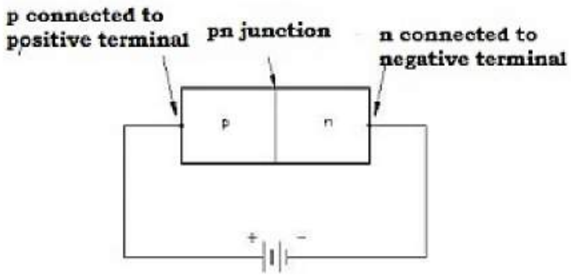


- The equilibrium potential barrier can be altered by applying an external voltage V across the diode

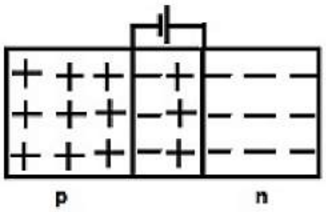
There are two methods of biasing a p-n unction – Forward bias and reverse bias

Forward biasing

- If the positive terminal of the external battery is connected to the p-side and the negative terminal of the external battery is connected to the n-side, then the p-n junction is said to be forward biased



- The direction of the applied voltage V is in a direction opposite to that of the potential barrier setup at the junction

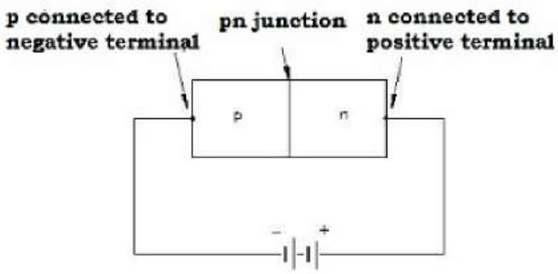


- As a result of this, the depletion layer width decreases and the barrier height is reduced. The effective barrier height under forward bias is $V_B - V$
- If the applied voltage V is small, the barrier potential will be reduced only slightly below the equilibrium value. Hence, only small number carriers will possess energy to cross the junction. Thus, the current is small

- If the applied voltage V is large, the barrier potential will be reduced significantly. Hence, the current is significant
- Due to the applied voltage, the electrons from the n-side cross the depletion region and reach the p-side. Similarly, the holes from the p-side reach the n-side
- As electrons reach the p-side and electrons are minority carriers in p-region, the forward bias is also known as minority carrier injection
- At the junction, the minority carrier concentration increases significantly
- Due to concentration gradient, the injected electrons on p-side diffuse from the junction edge of p-side to the other end of the p-side
- Similarly, the injected holes on the n-side diffuse from the junction edge of n-side to the other end of n-side
- The motion of charged carriers on either side gives rise to current and is usually measured in mA
- The total diode forward current is sum of hole diffusion current and conventional current due to electron diffusion

Reverse biasing

- If the positive terminal of the external battery is connected to the n-side and the negative terminal of the external battery is connected to the p-side, then the p-n junction is said to be reverse biased



- The direction of the applied voltage is same as that of the barrier potential.
- As a result, the barrier height increases and the depletion region widens due to change in electric field.
- The effective barrier height is $V_B + V$.
- This suppresses the flow of electrons from n region to p region and holes from the p region to n region. Hence, diffusion current decreases.
- The electric field direction of the junction is such that if electrons on p-side or holes on n-side in their random motion come close to the

junction, they will be swept to its majority zone. This gives rise to drift current of order of few μA.

- The diode reverse current is not much dependent on the applied voltage. Even a small voltage is sufficient to sweep the minority carriers from one side of the junction to the other side of the junction.
- The current under reverse bias is essentially voltage independent up to a critical reverse bias voltage, known as breakdown voltage V_{BE}.
- When $V = V_{BE}$, the diode reverse current increases sharply. If the current is not limited, the p-n junction will get destroyed.

Digital Electronics & Logic Gates

What is Digital Electronics?

Digital electronics is defined as
The branch of electronics that deals with digital data in the form of codes. There are only two codes in digital electronics, and they are 0 and 1. 0 is considered to be low logic while 1 is considered to be high logic.

Components of Digital Electronics

Digital electronics or the digital circuit comprises various components that perform specific functions. These components are divided into two categories:

- Active components
- Passive components

The **active components** are the transistors and diodes while the **passive components** are the capacitors, resistors, inductors, etc.

Active Components

1. **Diodes:**
   Diodes are manufactured using semiconductor materials. They are used for allowing the flow of current in a particular direction. Different types of diodes are used in the construction of the digital circuit.
2. **Transistors:**
   A semiconductor device with three terminals is known as a transistor. The main function of the transistor is to amplify the signal, and it is also used as a switching device.

Passive Components

1. **Capacitors and Inductors:**
   The main function of the capacitor is to store electrical energy. A capacitor is made using two conducting plates and between these plates, an insulator is placed. The change in the current is resisted with the help of an inductor. They are used for storing electric energy in the magnetic field.
2. **Battery and Switch:**
   The conversion of chemical energy into electric energy takes place because of the battery. It is used as a source of energy. The flow of electric current is controlled by using a switch.
3. **Resistors:**
   The flow of current in the circuit is opposed by the resistor. The fixed resistor and variable resistor are the two types of resistors. All the resistors work on the basis of Ohm's law.

Advantages of Digital System Over Analog System

- The transmission of data in digital systems takes place without degradation due to noise when compared to an analog system.
- The digital system comes with noise-immunity, which makes the storage of data easier. Whereas the analog system undergoes wear and tear, which degrades the information in storage.
- The digital system comes with an interface with computers which makes it easy to control the data. The system can be kept bug free by updating the software. This feature is not available in the analog system.

Disadvantages of Digital System

Though the digital system has noise-immunity and better storage it does have disadvantages too:

- The energy consumed by the digital system is more compared to the analog system. This energy is consumed in calculations and signal processing which results in the generation of heat.
- These systems are expensive.
- The digital systems are fragile, that is if one of the digital data is misinterpreted, the final data will change completely.
- Taking care of analog issues in digital systems could be demanding as analog components are used in designing the digital system.

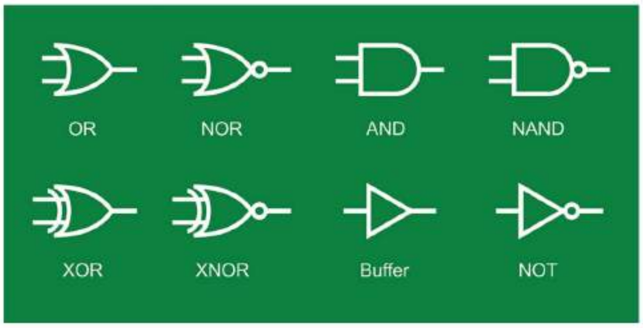
Applications of Digital Circuits

Digital electronics or digital circuits are an integral part of electronic devices and here are the uses of digital circuits:

- The display of digital watches is designed based on digital circuits.
- Rocket science and quantum computing use digital electronics.
- The automatic doors work on the principle of digital electronics.
- Everyday encounters with traffic lights are based on digital circuits.

Logic Gate

A digital circuit that allows a signal to pass through it, only when few logical relations are satisfied, is called a logic gate.



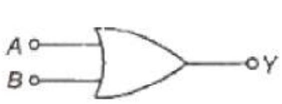
Truth Table

A table that shows all possible input and output combinations is called a truth table.

Basic Logic Gates

(i) OR Gate It is a two input and one output logic gate.

Symbol



Truth table

A	B	Y = A + B
0	0	0
0	1	1
1	0	1
1	1	1

Boolean expression Y = A + B (Y equals A OR B)
(ii) **AND Gate** It is a two input and one output logic gate

Symbol

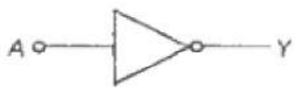
Truth table

A	B	Y = A·B
0	0	0
0	1	0
1	0	0
1	1	1

Boolean expression Y = A · B (Y equals A AND B)

(iii) **NOT Gate** It is a one input and one output logic gate.

Symbol



Truth table

A	$Y = \overline{A}$
0	1
1	0

Boolean expression $Y = \overline{A}$ (Y equals NOT A)

Combination of Gates

(i) **NAND Gate** When output of AND gate is applied as input to a NOT gate, then it is called a NAND gate.

Symbol

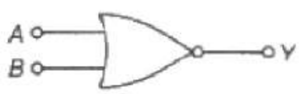
Truth table

A	B	$Y = \overline{A \cdot B}$
0	0	1
0	1	1
1	0	1
1	1	0

Boolean expression Y = A * B (Y equals negated of A AND B)

(ii) **NOR Gate** When output of OR gate is applied as input to a NOT gate, then it is called a NOR gate.

Symbol



Truth table

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

Boolean expression Y = A + B (Y equals negated of A OR B)

- The Boolean expression obey commutative law associative law as well as distributive law.

1. $A + B = B + A$
2. $A \cdot B = B \cdot A$
3. $A + (B + C) = (A + B) + C$

- Demorgan's theorems
  1. $\overline{A + B} = \overline{A} * \overline{B}$
  2. $\overline{A} * \overline{B} = \overline{A} + \overline{B}$

Zener diode

A normal p-n junction diode allows electric current only in forward biased condition. When forward biased voltage is applied to the p-n junction diode, it allows large amount of electric current and blocks only a small amount of electric current. Hence, a forward biased p-n junction diode offer only a small resistance to the electric current.

When reverse biased voltage is applied to the p-n junction diode, it blocks large amount of electric current and allows only a small amount of electric current. Hence, a reverse biased p-n junction diode offer large resistance to the electric current.

If reverse biased voltage applied to the p-n junction diode is highly increased, a sudden rise in current occurs. At this point, a small increase in voltage will rapidly increases the electric current. This sudden rise in electric current causes a junction breakdown called zener or avalanche breakdown. The voltage at which zener breakdown occurs is called zener voltage and the sudden increase in current is called zener current.

A normal p-n junction diode does not operate in breakdown region because the excess current permanently damages the diode. Normal p-n junction diodes are not designed to operate in reverse breakdown region. Therefore, a normal p-n junction diode does not operate in reverse breakdown region.

What is zener diode?

A zener diode is a special type of device designed to operate in the zener breakdown region. Zener diodes acts like normal p-n junction diodes under forward biased condition. When forward biased voltage is applied to the zener diode it allows large amount of electric current and blocks only a small amount of electric current.

Zener diode is heavily doped than the normal p-n junction diode. Hence, it has very thindepletion region. Therefore, zener diodes allow more electric current than the normal p-n junction diodes.

Zener diode allows electric current in forward direction like a normal diode but also allows electric current in the reverse direction if the applied reverse voltage is greater than the zener voltage. Zener diode is always connected in reverse direction because it is specifically designed to work in reverse direction.

Zener diode definition

A zener diode is a p-n junction semiconductor device designed to operate in the reverse breakdown region. The breakdown voltage of a zener diode is carefully set by controlling the doping level during manufacture.

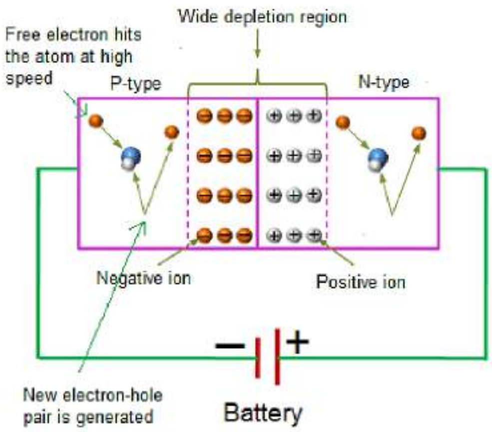
The name zener diode was named after the American physicist Clarance Melvin Zener who discovered the zener effect. Zener diodes are the basic building blocks of electronic circuits. They are widely used in all kinds of electronic equipments. Zener diodes are mainly used to protect electronic circuits from over voltage.

Breakdown in zener diode

There are two types of reverse breakdown regions in a zener diode: avalanche breakdown and zener breakdown.

Avalanche breakdown

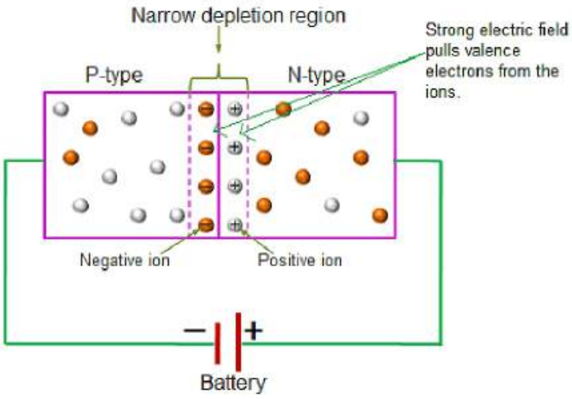
The avalanche breakdown occurs in both normal diodes and zener diodes at high reverse voltage. When high reverse voltage is applied to the p-n junction diode, the free electrons (minority carriers) gains large amount of energy and accelerated to greater velocities.



The free electrons moving at high speed will collides with the atoms and knock off more electrons. These electrons are again accelerated and collide with other atoms. Because of this continuous collision with the atoms, a large number of free electrons are generated. As a result, electric current in the diode increases rapidly. This sudden increase in electric current may permanently destroys the normal diode. However, avalanche diodes may not be destroyed because they are carefully designed to operate in avalanche breakdown region. Avalanche breakdown occurs in zener diodes with zener voltage (V_z) greater than 6V.

Zener breakdown

The zener breakdown occurs in heavily doped p-n junction diodes because of their narrow depletion region. When reverse biased voltage applied to the diode is increased, the narrow depletion region generates strong electric field.



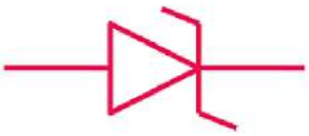
When reverse biased voltage applied to the diode reaches close to zener voltage, the electric field in the depletion region is strong enough to pull electrons from their valence band. The valence electrons which gains sufficient energy from the strong electric field of depletion region will breaks bonding with the parent atom.
The valance electrons which break bonding with parent atom will become free electrons. This free electrons carry electric current from one place to another place. At zener breakdown region, a small increase in voltage will rapidly increases the electric current.

- Zener breakdown occurs at low reverse voltage whereas avalanche breakdown occurs at high reverse voltage.
- Zener breakdown occurs in zener diodes because they have very thin depletion region.
- Breakdown region is the normal operating region for a zener diode.
- Zener breakdown occurs in zener diodes with zener voltage (V_z) less than 6V.

Symbol of zener diode

The symbol of zener diode is shown in below figure. Zener diode consists of two terminals: cathode and anode.

Zener diode symbol



In zener diode, electric current flows from both anode to cathode and cathode to anode.

The symbol of zener diode is similar to the normal p-n junction diode, but with bend edges on the vertical bar.

VI characteristics of zener diode

The VI characteristics of a zener diode is shown in the below figure. When forward biased voltage is applied to the zener diode, it works like a normal diode. However, when reverse biased voltage is applied to the zener diode, it works in different manner.

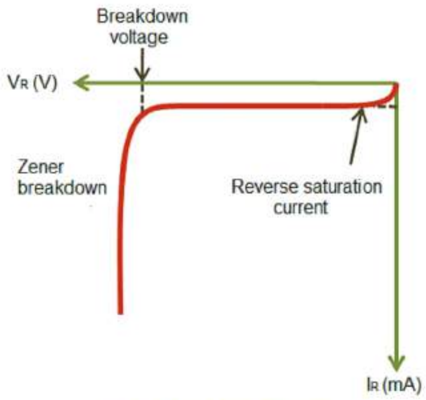


Fig: Zener breakdown

When reverse biased voltage is applied to a zener diode, it allows only a small amount of leakage current until the voltage is less than zener voltage. When reverse biased voltage applied to the zener diode reaches zener voltage, it starts allowing large amount of electric current. At this point, a small increase in reverse voltage will rapidly increases the electric current. Because of this sudden rise in electric current, breakdown occurs called zener breakdown. However, zener diode exhibits a controlled breakdown that does damage the device.

The zener breakdown voltage of the zener diode is depends on the amount of doping applied. If the diode is heavily doped, zener breakdown occurs at low reverse voltages. On the other hand, if the diode is lightly doped, the zener breakdown occurs at high reverse voltages. Zener diodes are available with zener voltages in the range of 1.8V to 400V.

Advantages of zener diode

- Power dissipation capacity is very high
- High accuracy
- Small size
- Low cost

Applications of zener diode

- It is normally used as voltage reference
- Zener diodes are used in voltage stabilizers or shunt regulators.
- Zener diodes are used in switching operations
- Zener diodes are used in clipping and clamping circuits.
- Zener diodes are used in various protection circuits

Types of Diodes

The various types of diodes are as follows:

1. Zener diode
2. Avalanche diode
3. Photodiode
4. Light Emitting Diode
5. Laser diode
6. Tunnel diode
7. Schottky diode
8. Varactor diode
9. P-N junction diode

Forward Biasing Experiment

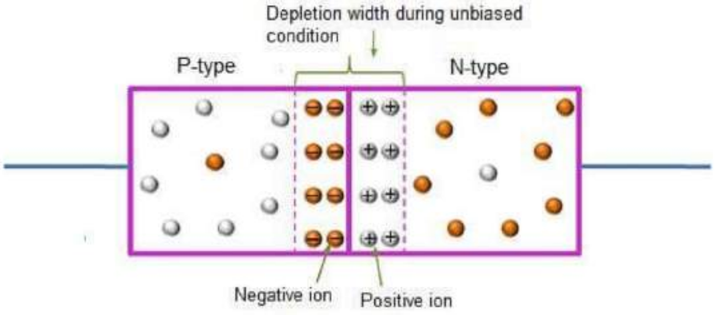
Forward biased p-n junction diode

The process by which, a p-n junction diode allows the electric current in the presence of applied voltage is called forward biased p-n junction diode.

In forward biased p-n junction diode, the positive terminal of the battery is connected to the p-type semiconductor material and the negative terminal of the battery is connected to the n-type semiconductor material.

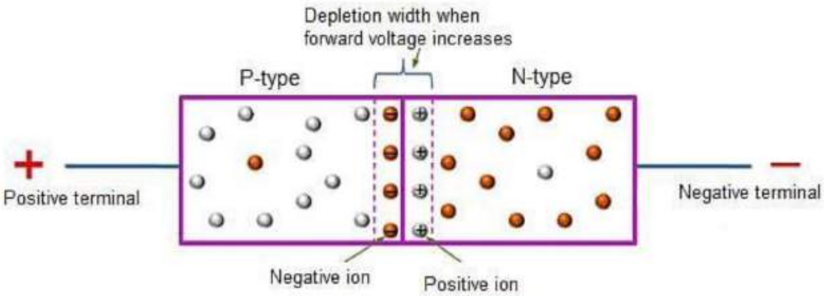
Unbiased diode and forward biased diode

Under no voltage or unbiased condition, the p-n junction diode does not allow the electric current. If the external forward voltage applied on the p-n junction diode is increased from zero to 0.1 volts, the depletion region slightly decreases. Hence, very small electric current flows in the p-n junction diode. However, this small electric current in the p-n junction diode is considered as negligible. Hence, they not used for any practical applications.



Unbiased

If the voltage applied on the p-n junction diode is further increased, then even more number of free electrons and holes are generated in the p-n junction diode. This large number of free electrons and holes further reduces the depletion region (positive and negative ions). Hence, the electric current in the p-n junction diode increases. Thus, the depletion region of a p-n junction diode decreases with increase in voltage. In other words, the electric current in the p-n junction diode increases with the increase in voltage.

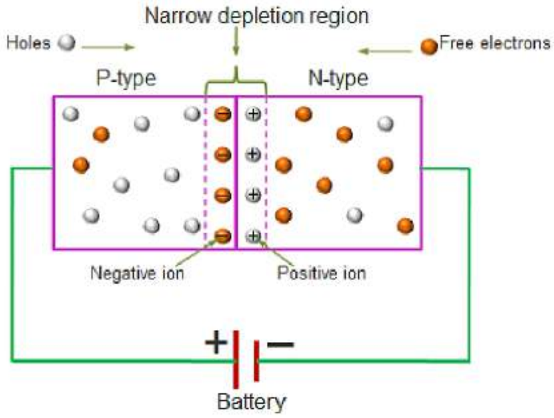


Forward biased

Electron and hole current

Electron current

If the p-n junction diode is forward biased with approximately 0.7 volts for silicon diode or 0.3 volts for germanium diode, the p-n junction diode starts allowing the electric current. Under this condition, the negative terminal of the battery supplies large number of free electrons to the n-type semiconductor and attracts or accepts large number of holes from the p-type semiconductor. In other words, the large number of free electrons begins their journey at the negative terminal whereas the large number of holes finishes their journey at the negative terminal



Forward bias

- The free electrons, which begin their journey from the negative terminal, produce a large negative electric field. The direction of this negative electric field is apposite to the direction of positive electric field of depletion region (positive ions) near the p-n junction.

Due to the large number of free electrons at n-type semiconductor, they get repelled from each other and try to move from higher concentration region (n-type semiconductor) to a lower concentration region (p-type semiconductor). However, before crossing the depletion region, free electrons finds the positive ions and fills the holes. The free electrons, which fills the holes in positive ions becomes valence electrons. Thus, the free electrons are disappeared.

The positive ions, which gain the electrons, become neutral atoms. Thus, the depletion region (positive electric field) at n-type semiconductor near the p-n junction decreases until it disappears.

The remaining free electrons will cross the depletion region and then enters into the p-semiconductor. The free electrons, which cross the depletion region finds the large number of holes or vacancies in the p-type semiconductor and fills them with electrons. The free electrons which occupy the holes or vacancies will becomes valence electrons and then these electrons get attracted towards the positive terminal of battery or terminates at the positive terminal of battery. Thus, the negative charge carriers (free electrons) that are crossing the depletion region carry the electric current from one point to another point in the p-n junction diode.

- Hole current

- The positive terminal of the battery supplies large number of holes to the p-type semiconductor and attracts or accepts large number of free electrons from the n-type semiconductor. In other words, the large number of holes begins their journey at the positive terminal whereas the large number of free electrons finishes their journey at the positive terminal.

The holes, which begin their journey from the positive terminal, produce a large positive electric field at p-type semiconductor. The direction this positive electric field is opposite to the direction of negative electric field of depletion region (negative ions) near the p-n junction.

Due to the large number of positive charge carriers (holes) at p-type semiconductor, they get repelled from each other and try to move from higher concentration region (p-type semiconductor) to a lower concentration region (n-type semiconductor). However, before crossing the depletion region, some of the holes finds the negative ions and replaces the electrons position with holes. Thus, the holes are disappeared.

The negative ions, which lose the electrons, become neutral atoms. Thus, the depletion region or negative ions (negative electric field) at p-type semiconductor near the p-n junction decreases until it disappears.

The remaining holes will cross the depletion region and attracted to the negative terminal of battery or terminate at the negative terminal of battery. Thus, the positive charge carriers (holes) that are crossing the depletion region carry the electric current from one point to another point in the p-n junction diode.

Conclusion

Remember, holes are nothing but vacancies created when the electrons left an atom. In p-type semiconductors, the valence electrons move from one atom to another atom whereas holes move in opposite direction. However, holes are the majority in p-type semiconductor. Hence, holes are considered as the charge carriers in the p-type semiconductor, which carry electric current from one point to another point.

The actual direction of current is the direction of free electrons (from n-side to p-side). However, the conventional direction of electric current is the direction of holes (from p-side to n-side).

Types of Diodes

The various types of diodes are as follows:

- Zener diode
- Avalanche diode
- Photodiode
- Light Emitting Diode
- Laser diode
- Tunnel diode
- Schottky diode
- Varactor diode
- P-N junction diode

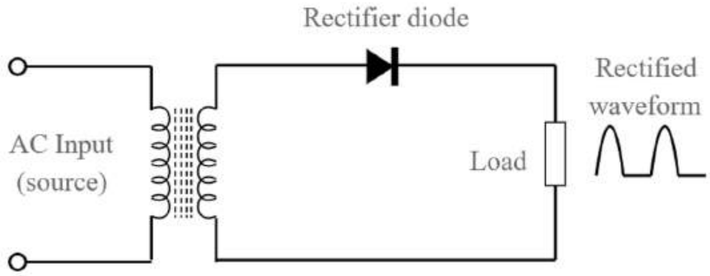
Diode as a Rectifier

Application of junction diode as a Rectifier

- Rectifier is a device which is used for converting alternating current or voltage into direct current or voltage
- A p-n junction diode can be used as a half-wave and full-wave rectifier
- The resistance of a p-n junction diode becomes low when forward biased and becomes high when reverse biased. This is the principle of the working of rectifier

Half-wave Rectifier

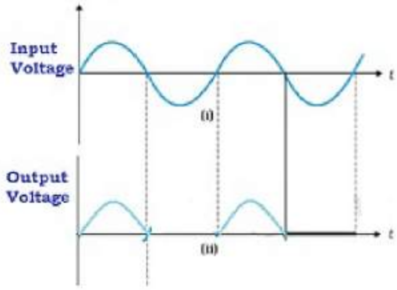
Circuit Diagram



- Transformer with primary and secondary coils
- Diode
- Load resistance R_L

The AC voltage to be rectified is connected between the primary of the transformer
To one coil of the secondary, the p junction of the diode is connected
The output is measured across the load resistance R_L

Input and output



Working

➤ **Case 1**

- During the positive half cycle of the input AC voltage, suppose P1 is negative and P2 is positive
- On account of inductance, S1 becomes positive and S2 becomes negative
- The p-n junction is forward biased and hence the resistance of the p-n junction diode becomes low
- Hence, current flows in the circuit and we get output across the load resistance R_L
- This is indicated in the graph above

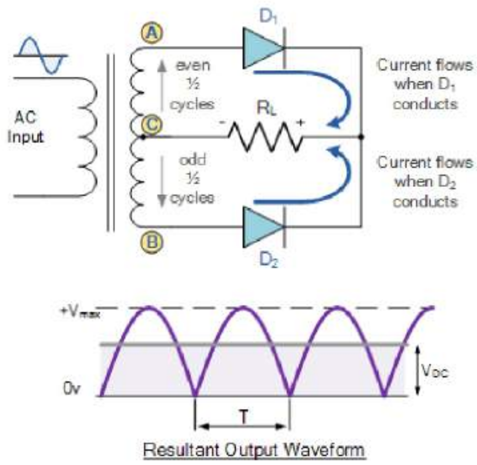
➤ **Case 2**

- During the negative half cycle of the input AC voltage, suppose P1 is positive and P2 is negative
- On account of inductance, S1 becomes negative and S2 becomes positive
- The p-n junction is reverse biased and hence the resistance of the p-n junction diode becomes high
- Hence, no current flows in the circuit and we do not get any output across the load resistance R_L
- This is indicated in the graph above

The above process is repeated. Thus , we have current only in the positive half of the cycle. Hence, if is called as half-wave rectifier
The output signal is not continuous and available as bursts. Hence, this is not of much use.

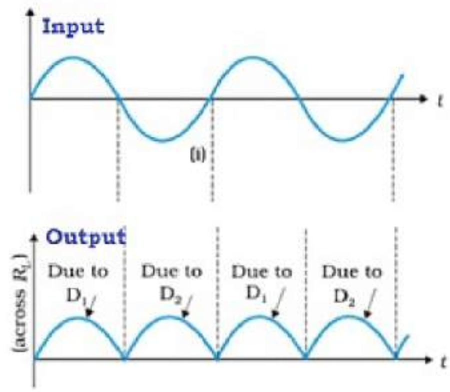
Full Wave Rectifier

➤ Circuit Diagram



- The main difference between half and full wave rectifier in circuit, is the usage of two diodes – D1 and D2

➤ Input and Output



Working

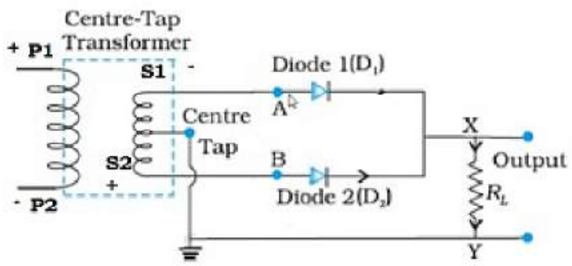
➤ Case 1

- During the positive half of the input cycle of AC voltage, the junction diode D1 is forward biased as shown in the diagram above
- Hence, current flows in the above circuit as indicated
- The diode D2 is reverse biased and hence no current due to D2

- We get output when the same is measured across the load resistance R_L due to the diode D1 alone

➤ **Case 2**

- The circuit diagram for the negative half of the input cycle of AC voltage:



- During the positive half of the input cycle of AC voltage, the junction diode D2 is forward biased as shown in the diagram above.
- Hence, current flows in the above circuit as indicated.
- The diode D1 is reverse biased and hence no current due to D1.
- We get output when the same is measured across the load resistance R_L due to the diode D2 alone

We observe that one of the diode conducts and the flow of current across the load resistance is in the same direction Also, current flows during both cycles of the input AC voltage. However, the output though unidirectional has ripple contents. Ripple contents indicate both AC and DC components
We can get only the DC component by passing it through a filter circuit
The filter circuit consists of Resistance and Capacitance

➤ **Circuit Diagram**

- C has a high capacitance value and serves as a filter circuit
- R_L is a load resistance

➤ **Working**

- The capacitance offers low impedance to AC component and offers infinite impedance to DC component
- Due to this the AC component is bypassed or filtered out
- The DC component produces a voltage drop across the load resistance which is almost DC voltage

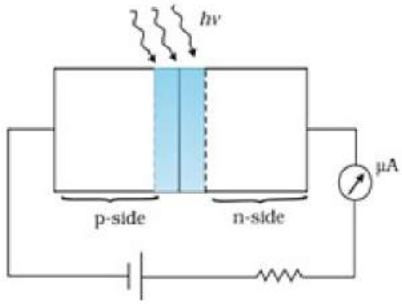
Problem: In half-wave rectification, what is the output frequency if the input frequency is 50 Hz. What is the output frequency of full wave rectifier for the same input frequency?

Solution: Half-wave rectifier –The output voltage is obtained is once in one cycle of input voltage, hence output ripple frequency after half-wave rectification = 50 Hz

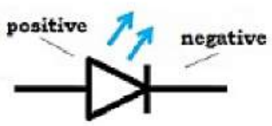
Full-wave rectifier – For one cycle of input voltage, we get output twice in the same direction. Hence, the output after full wave rectification = 100 Hz

Opto Electronic Junction Devices

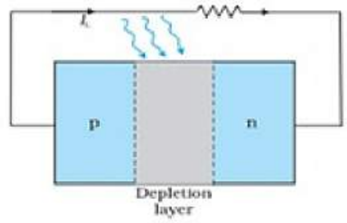
The semiconductor diodes in which the current carriers are generated by the photons (through photo excitation) is called optoelectronic devices Some of the opto electronic junction devices are –Photodiode, Light emitting diode and solar cell. Photodiode – Electron-hole pair is generated due to the illumination of the junction with light.



Light emitting diode – When forward biased properly, this special p-n junction emits light radiation continuously.



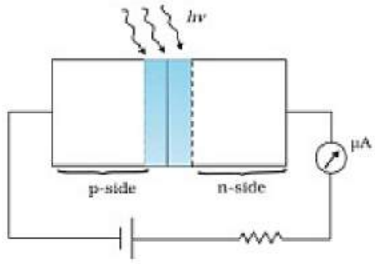
Solar cell–When solar light falls on p-n junction, it generates emf which can be used effectively.



Photodiode

Application – Photodiodes are used for detecting optical signal or they act as photo detectors

➤ **Circuit Diagram**



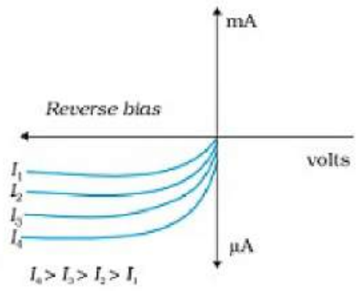
- This is a special p-n junction diode made up of photosensitive semiconducting material
- The diode has a transparent window to allow light to fall on the diode

➤ **Working**

- It is operated under reverse bias below the breakdown voltage.
- When photodiode is illuminated with light (photons), with energy $h\nu$ greater than the energy gap of the semiconductor, the electron-hole pairs are generated due to the absorption of photons, in or near the depletion region of the diode.
- Due to electric field at the junction, electrons and holes are separated before they combine.
- The direction of electric field is such that the electrons reach n-side and the holes reach the p-side.
- The movement of electrons and holes gives rise to emf.
- When external load is connected, current flows. The magnitude of the photocurrent depends on the intensity of incident light.
- In reverse bias, we can observe that as intensity increases, the current also increases.

➤ **Characteristics**

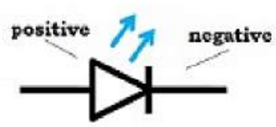
- The characteristic of a photodiode is shown below:



Problem: A p-n photodiode is fabricated from a semiconductor with band gap of 2.8 eV. Can it detect a wavelength of 6000 nm?

Solution: $E_g = 2.8$ eV; $\lambda = 600$ nm $= 600 * 10^{-9}$
We know, Energy $E = hc / \lambda$
$= 6.6 * 10^{-34} * 3 * 10^{8} / 600 * 10^{-9} * 1.6 * 10^{-19}$ eV
$= 2.06$ eV
As $E < E_g$, $2.06 < 2.8$ eV so p-n junction cannot detect the radiation of given wavelength

Light emitting diode



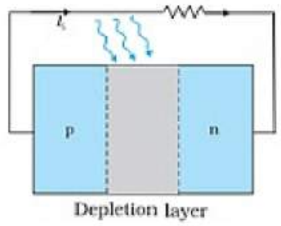
Application – They convert electrical energy into light

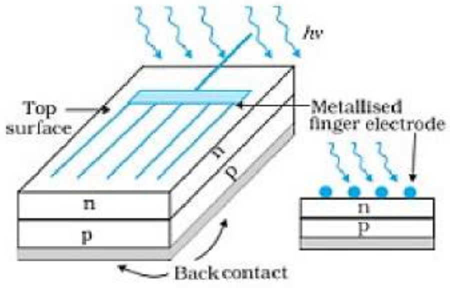
- It is a heavily doped p-n junction which under forward bias emits spontaneous radiation.
- The diode is encapsulated with a transparent cover so that the emitted light can come out.
- When the diode is forward biased, the electrons are sent from n layer to p layer and the holes are sent from p to n.
- Thus, at the boundary due to forward bias, the concentration of the minority carriers increases.
- The excess minority carriers recombine with the majority carriers, near the junction.
- On recombination, energy is released in the form of photons.

- Photons with energy equal to or slightly less than the band gap is emitted.
- When the forward current of the diode is small, the intensity of the light emitted is small.
- As the forward current increases, the intensity of light increases and reaches maximum.
- Further increase in forward current, results in the decrease of light intensity.
- LEDs are thus biased in such a way such that the efficiency is maximum.
- The reverse breakdown voltage of LED is very small (say) 5V. Proper precaution should be taken such that high reverse voltage do not appear across them.
- LEDs have the following advantages over the conventional lamps:
  (i) Low operational voltage and less power
  (ii) Fast action and no warm-up time required
  (iii) Long life
  (iv) Fast on-off switching capacity

Solar cell

Principle–These photo voltaic devices convert the optical radiation into electricity.





Circuit

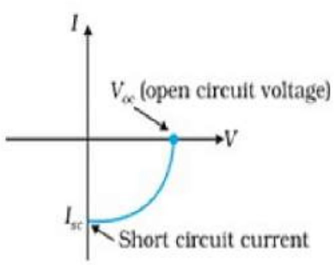
- When solar light falls on a p-n junction, it generates emf.
- As the solar radiation is incident at the junction, the junction area is kept much larger for more power generation.

- A p Si layer of about 300 * 10^{-6}m is taken. About this a still thin layer of about 0.3 * 10^{-6} m n Si layer is grown on one side by the process of diffusion.
- The other side of the p-layer is coated with a metal. This servers as a back contact.
- On the top of n Si layer, metallic grid is deposited. This is called front contact.
- The light is incident on the grid from the top.

Working

- The generation of emf by the solar cell, when light falls on, is due to the following three basic processes – (a) generation (b) separation and (c) collection
- **Generation**
  – The generation of electron-hole paid due to light with energy $h\upsilon >$ E_g close to the junction.
- **Separation**
  – The separation of electrons and holes due to the electric field of the depletion region.
  – The electrons are swept to the n-side and the holes to the p-side.
- **Collection**
  – The electrons reaching the n-side are collected by the front contact and holes reaching the p-side are collected by the back contact.
  – Thus, the p-side becomes positive and the n-side becomes negative giving rise to photo voltage.
  – When external load is connected, a photo current I_L flows through the load.

Graph



- The graph showing the VI characteristics, with V along the X-axis and I along the Y-axis is as given above.
- The graph is indicated in the fourth quadrant as solar cell does not draw current but supplies the same to the load.

Application

- Solar cells are used in power electronic devices in satellites and space vehicles.
- They are also used as power supply in calculators.

Criteria for material selection of material for solar cell

- Band gap between 1.0 and 1.8 eV.
- High optical absorption.
- Electrical conductivity.
- Availability of raw material.
- Cost effective.