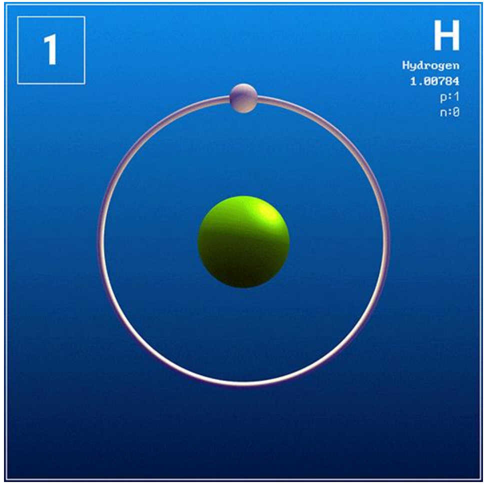
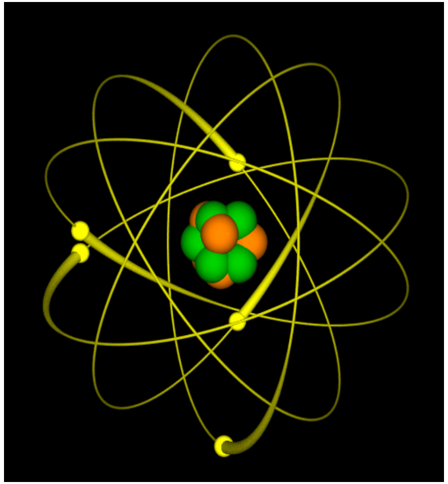
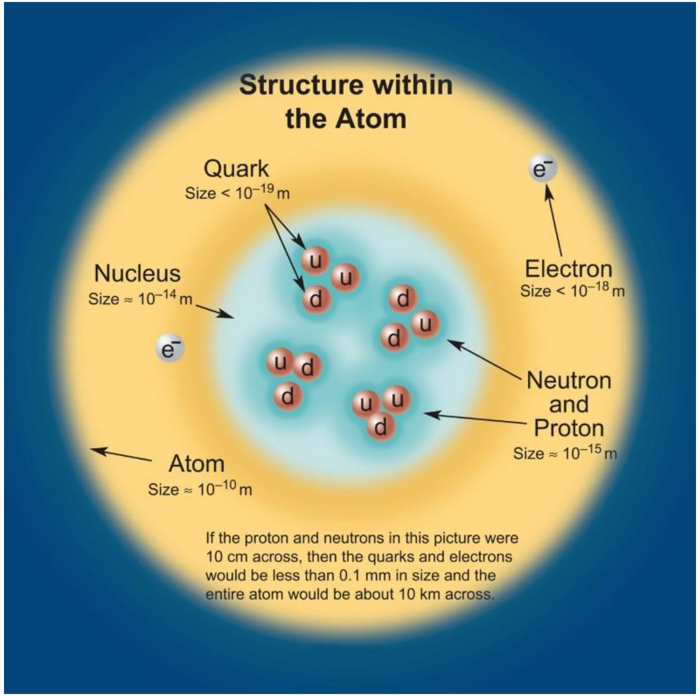
Semiconductor Physics

Unit I

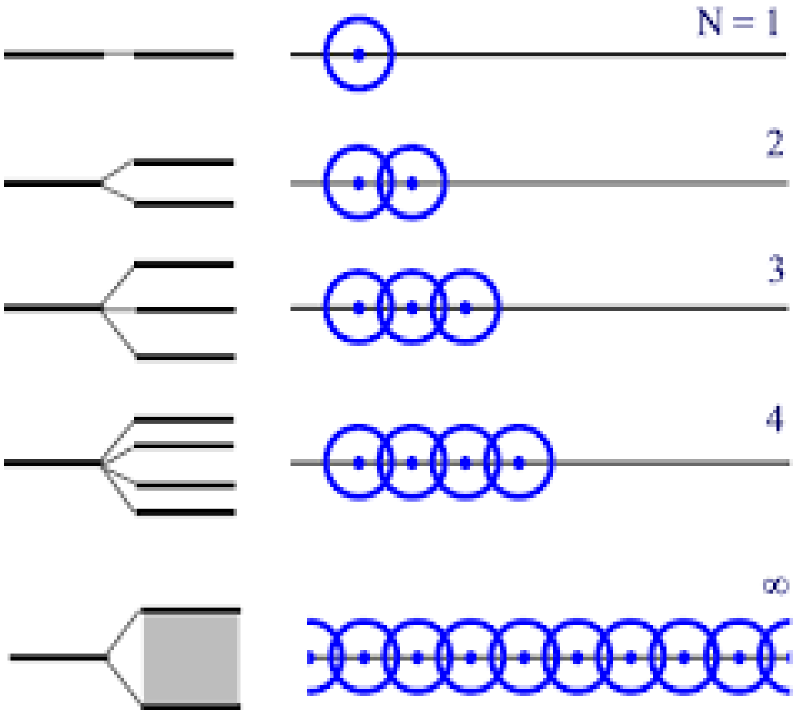
Band Formation in Solid
Atomic Structure

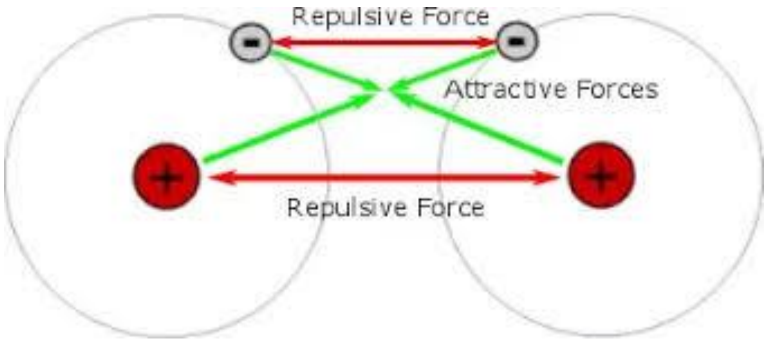


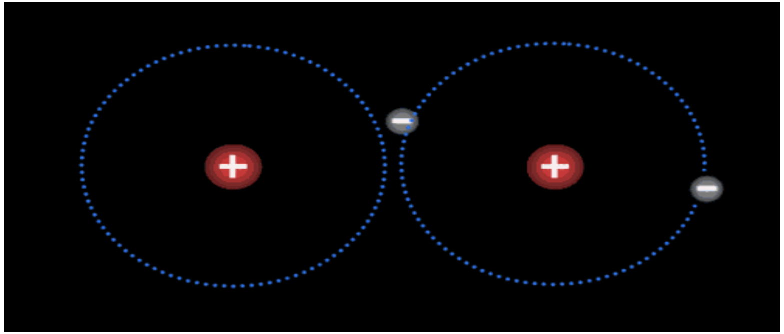




Splitting of Energy level

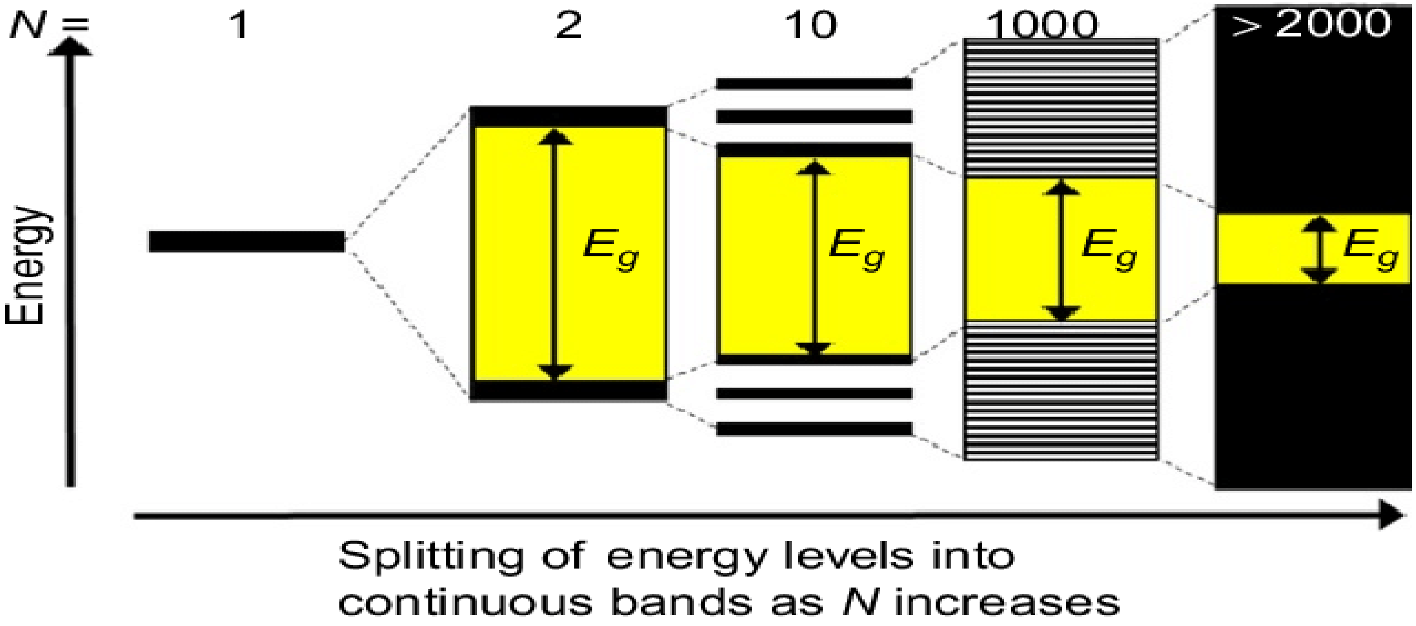




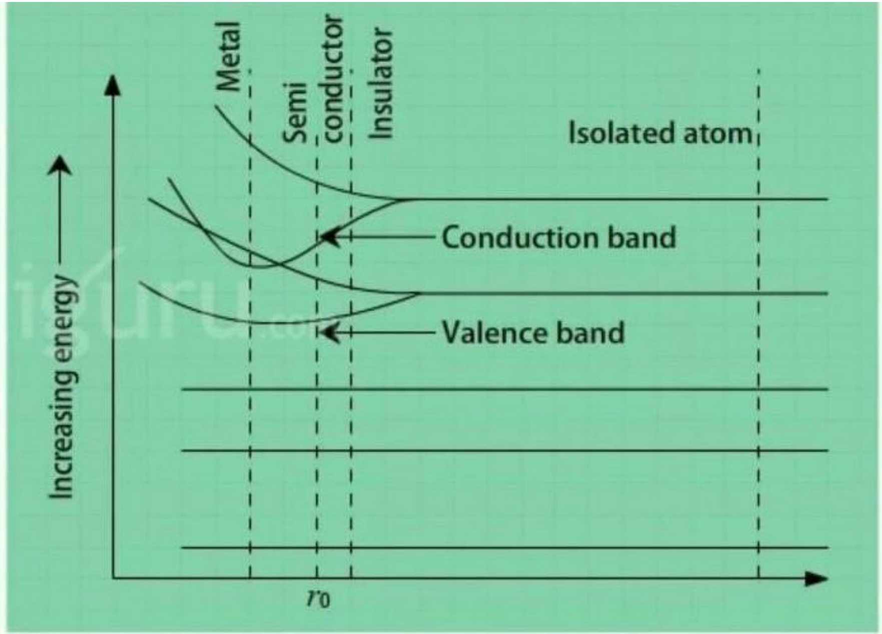


Formation of Energy Band

Splitting of energy levels which are closely spaced for Virtual continuum called Energy Band.



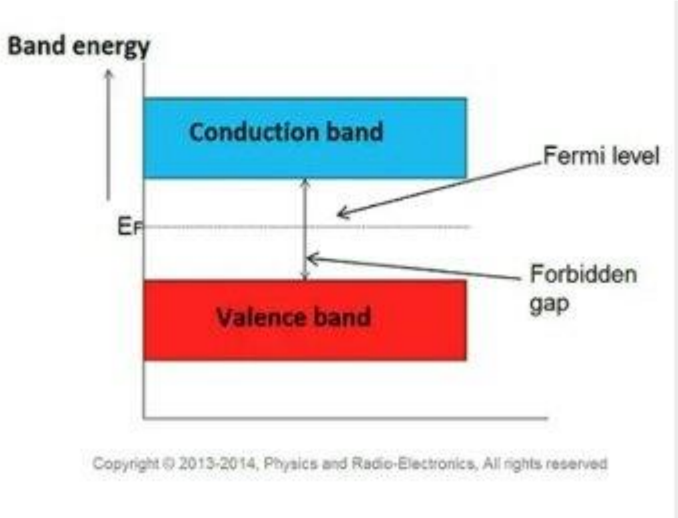
- With decrease the inter atomic distance Valance band & Conduction band over lap with each other.
- The equilibrium spacing determines the forbidden energy gap & type of element.



Formation of bands in a hypothetical solid

Energy Bands in solids

- **Valence Band** – The band is formed by the series of energy levels consist of valance electrons known as valance band.it is partially or completely filled depend upon nature of crystal.
- **Conduction Band**-The band is formed by the series of energy levels consist of conduction electrons known as conduction band.it is partially or completely empty depend upon nature of crystal.
- **Forbidden Band**-valance band & conduction band are separated by a gap known as Forbidden gap. It is the series of energy levels between top of valance band & bottom of conduction band.

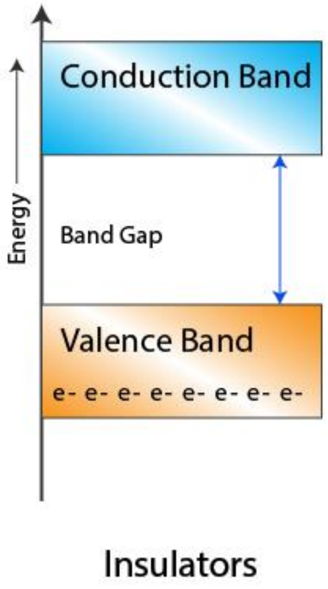


Types of Solids

On the bases of forbidden energy solid is divide in to three types

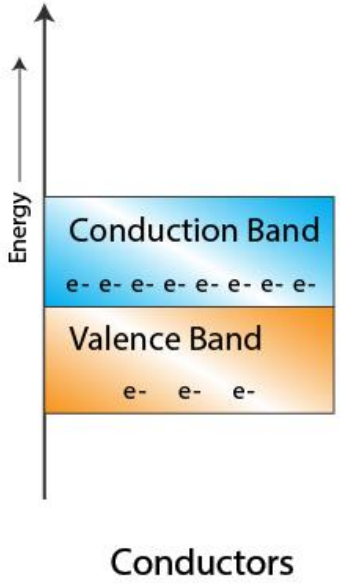
Insulator

- The material in which forbidden gap is very large is known as an insulator.
- Band gap energy (Eg) is ≥ 5eV.
- Under normal condition electron can not jump from valance band to the conduction band.
- The transfer of electron from valance band to the conduction band required high activation energy is of the order of temp.of thousand of degrees.
- Insulator have very low conductivity & very high resistivity.
- Examples:Wood,Plastics,Rubber etc



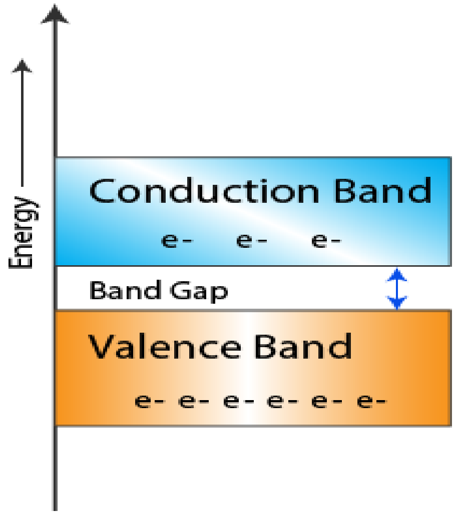
Conductor

- The material in which there is no forbidden gap or overlaps between valance band & conduction band is known as Conductor.
- Band gap energy (Eg) is 0 eV.
- Electrons easily transfer from valance band to the conduction band.
- At room temp. Have high electrical conductivity.
- Examples:Silver, Copper, Gold etc



Semiconductor

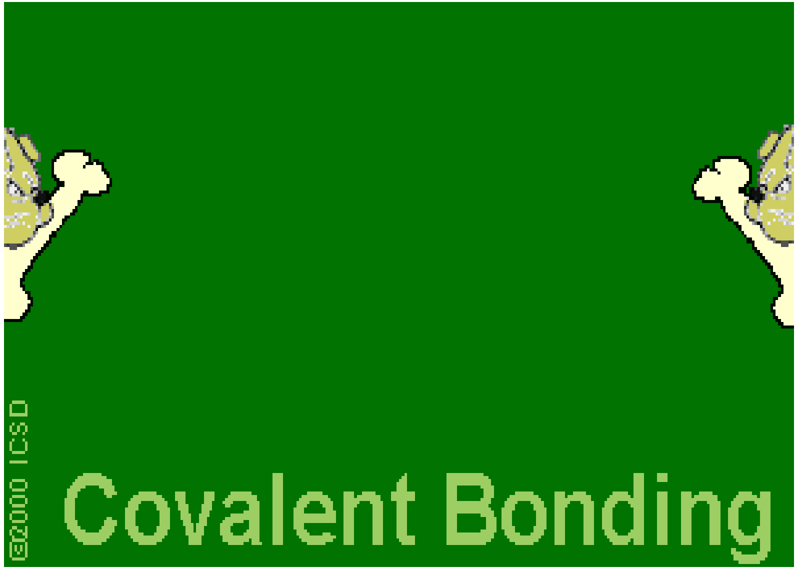
- ❖The material whose conductivity lies between conductor & insulator is known as Semiconductor.
- ❖Band gap energy (Eg) is ≤ 2eV.
- ❖At 0°k it behaves like an insulator & at room temp. It behaves like conductor.
- ❖Electron required some electrical or optical energy to jump from valance band to the conduction band.
- ❖At 0°k its resistivity is high & at room temp. Its conductivity is high.
- ❖Examples: Silicon (Eg=1.12 eV),Germanium(Eg=0.72 eV)

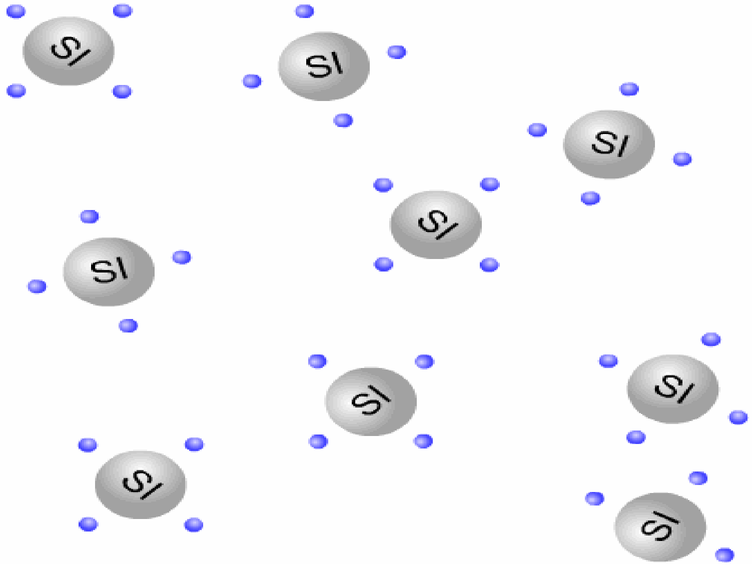


Semiconductors

Covalent bond

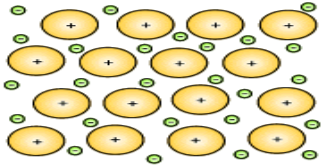
- Bond which is formed due to the sharing of electron.
- Sharing of electron between two some or different type of atoms.





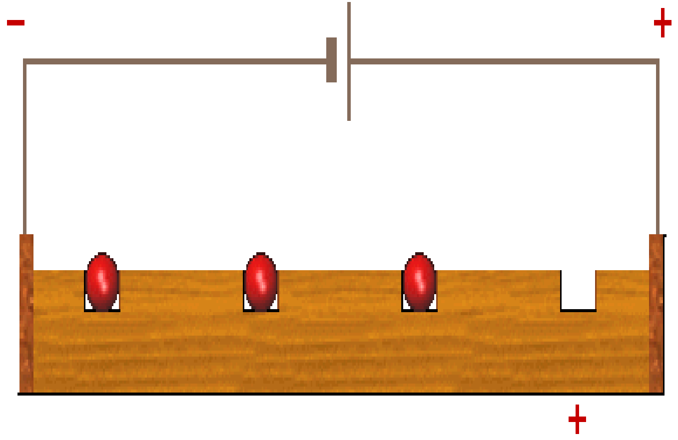
Bounded & Free Electron

- At absolute 0°k atoms are tightly bound with other.
- With increase in temp. covalent bond breaks & electron becomes free.
- This electron free to move through out the crystal like gas molecules.
- When electric field is applied this free electron drift towards the positive electrode which gives the current.
- With free motion this electron collide with one of the broken covalent bond & combine with hole.
- Form electron & hole pair ,covalent bond is completed.
- Thus free electron becomes bounded.



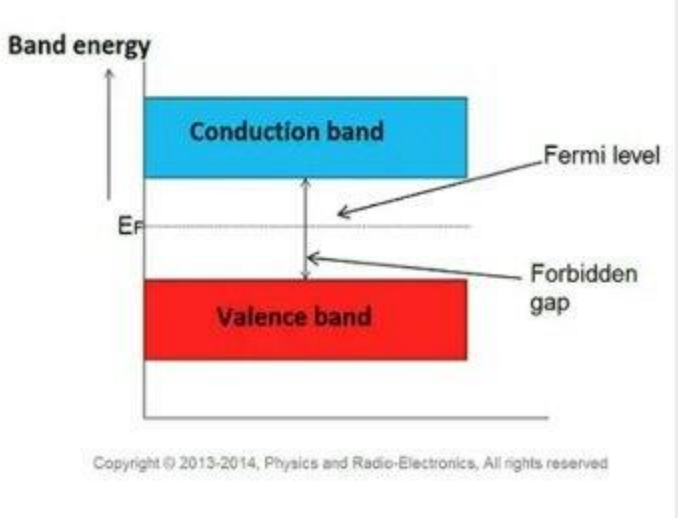
Hole

- ❖The vacancy of electron is called hole.
- ❖When covalent bond broken due to the supply of energy, electron becomes free thus form a Quantum vacancy.
- ❖Removal of negative charge create positive charge.
- ❖This positive charge vacancy attract electron from adjacent bond and hole is shifted to position of attracted electron.
- ❖Created hole move in the crystal like free electron but in opposite direction.
- ❖In presence of electric field holes are drift towards the negative electrode.



Fermi Level in Semiconductor

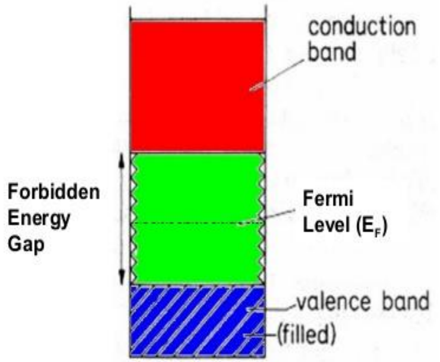
- ❖ V.B & C.B are separated by Forbidden energy gap.
- ❖ Fermi level lies in the middle of Forbidden gap.
- ❖ Energy level corresponding to the center of gravity of conduction electrons & holes weighted according to their energies.



Fermi level in Intrinsic Semiconductor

- ❖ In intrinsic semiconductor equal no. of electrons & Holes .
- ❖ Concentration of electrons decreases above the bottom of C.B
- ❖ Concentration of holes decreases below the top of V.B
- ❖ Center of gravity of electrons & holes lies exactly at the middle of forbidden Gap.

Fermi Energy Diagram for Intrinsic Semiconductors



The Fermi level (E_F) lies at the middle of the forbidden energy gap.

Electron Distribution Function

$$n(E)\Delta E = g(E)\,f(E)\Delta E$$

Where,

n(E)ΔE – No. of electrons per unit volume in with energy between E & E+ΔE

g(E) – No. of energy state per unit volume in energy range ΔE.

F(E)-Distribution function or probability that finding an electron in Energy state E

ΔE – Energy Interval.

Fermi Dirac Distribution Function.

- Fermi-Dirac gives this function in 1926.
- This function F(E) gives the carrier occupancy of energy level.
- The equation gives the distribution of electron among the energy level as function of temperature known as Fermi-Dirac distribution function.

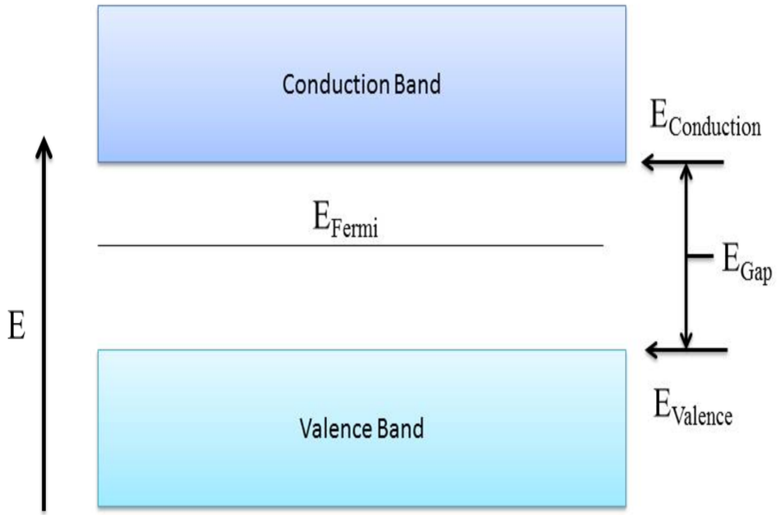
$$f_F(E) = \frac{1}{1 + exp\left(\frac{E - E_F}{kT}\right)}$$

Derivation: Fermi energy level lies at the center of Forbidden Gap.

Prove that $$E_f = \frac{E_c + E_v}{2}$$

Assumptions

- ❖All the electron in conduction band have energy Ec & valance band have energy Ev.
- ❖The width of valance band & conduction band is very small as compare to the width of Forbidden gap.



Let Nc & Nv be the nunmer of electrons in conduction band & number of electrons in valance band.

N be the total number of electrons in both the bands.

$$N = Nc + Nv \quad \text{..........(1)}$$

Now $$f(Ec) = \frac{Nc}{N}$$

$$Nc = Nf(Ec) \quad \text{........(2)}$$

But $$f(Ec) = \frac{1}{1+e^{[Ec-Ef/kT]}}$$

Eq(2) becomes

$$Nc = \frac{N}{1+e^{[Ec-Ef/kT]}} \quad \text{............(3)}$$

Similarly $$Nv = \frac{N}{1+e^{[Ev-Ef/kT]}} \quad \text{.........(4)}$$

From Eq.(1)

$$N = \frac{N}{1+e^{[Ec-Ef/kT]}} + \frac{N}{1+e^{[Ev-Ef/kT]}}$$

$$1 = \frac{1}{1+e^{[Ec-Ef/kT]}} + \frac{1}{1+e^{[Ev-Ef/kT]}}$$

$$\left(1+e^{[Ec-Ef/kT]}\right)\left(1+e^{[Ev-Ef/kT]}\right)=1+e^{[Ev-Ef/kT]}+1+e^{[Ec-Ef/kT]}$$

$$\left(1+e^{[Ec-Ef/kT]}\right)\left(1+e^{[Ev-Ef/kT]}\right)=1+e^{[Ev-Ef/kT]}+1+e^{[Ec-Ef/kT]}$$

$$1+e^{[Ev-Ef/kT]}+e^{[Ec-Ef/kT]}+e^{[Ec+Ev-2Ef/kT]}=1+e^{[Ev-Ef/kT]}+1+e^{[Ec-Ef/kT]}$$

$$e^{[Ec+Ev-2Ef/kT]}=1$$

Taking log on both the sides

$$\therefore\ Ec+Ev-2Ef=0$$

$$\therefore 2Ef=Ec+Ev$$

$$\therefore Ef=\frac{Ec+Ev}{2}$$

At all the temp. ie T>0° k probability of occupancy of Fermi level is 50%

- An electrons in solids obys Fermi Dirac Statistics
- A/c to this distribution of electron among the energy level as function of temperature given by

$$f(E) = \frac{1}{1+e^{[E-Ef/kT]}}$$

Since f(E) represent probability, its value lies between 0 &1

Let T=0°k, kT=0

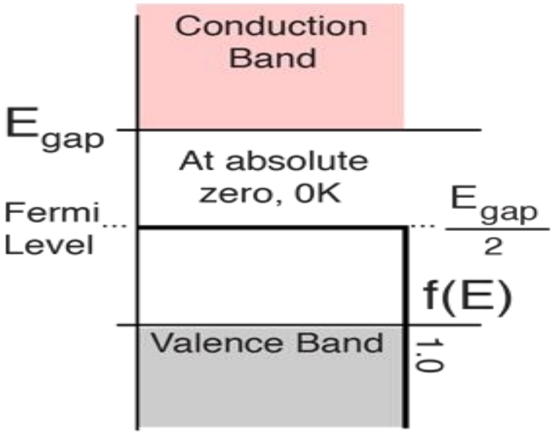
Case-I

When E< Ef , (E-Ef) is Negative ,then $[E-Ef/kT] = -\infty$

Fermi function becomes

$$f(E) = \frac{1}{1+e^{-\infty}} = \frac{1}{1+0} = 1$$

Thus at absolute zero temp.all the levels below Ef are filled .



Context of Fermi level
for a semiconductor

Case-II

When E>E*f* , (E-E*f*) is Positive ,then $[E - Ef/kT] = \infty$

Fermi function becomes

$$f(E) = \frac{1}{1+e^{\infty}} = \frac{1}{1+\infty} = 0$$

Thus at absolute zero temp.all the levels above E*f* are empty .

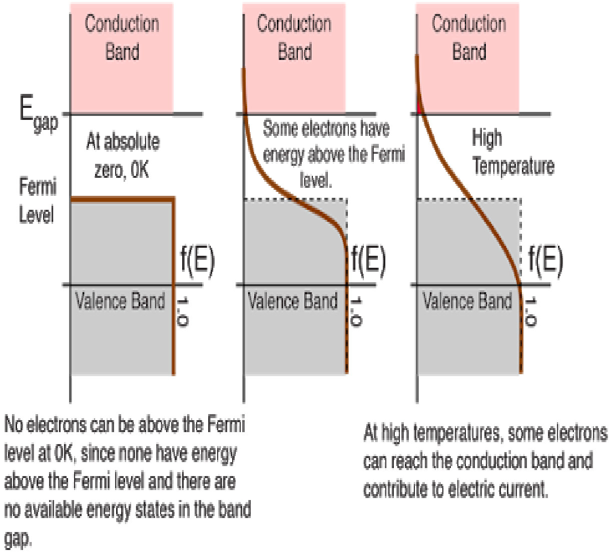
Case-III

For T>0ºk, kT= positive

When E=E*f* ,(E-E*f*) is zero, then $[E - Ef/kT] = 0$

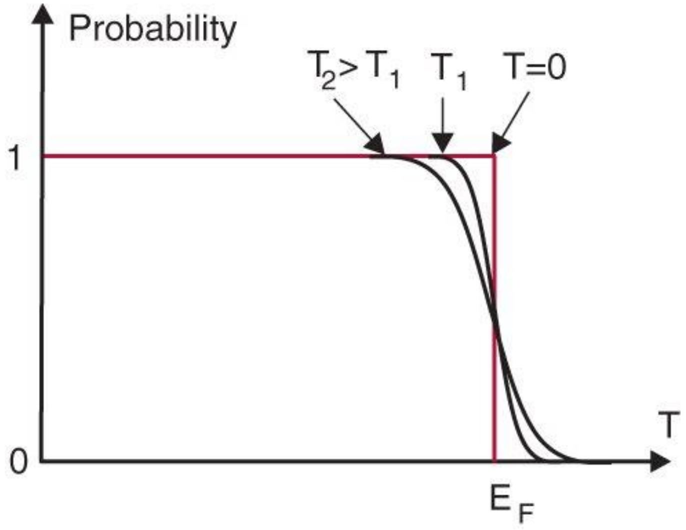
Fermi function becomes

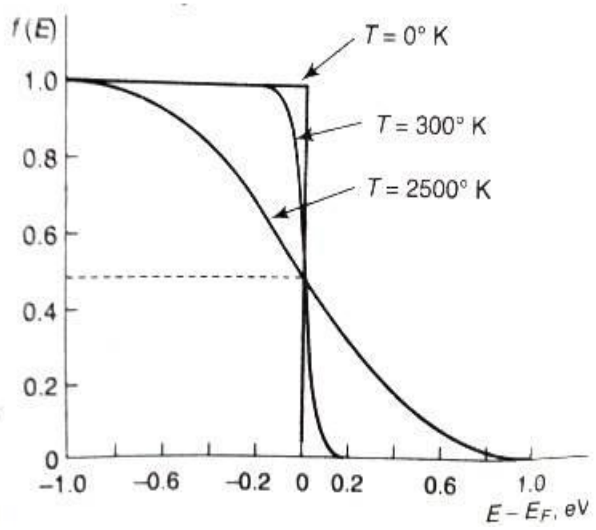
$$f(E) = \frac{1}{1+e^{0}} = \frac{1}{1+1} = \frac{1}{2}$$



Thus distribution function shows that occupation of Fermi level at any non zero temp. is 1/2

- At temp. greater than 0ºk probability distribution function changes from 1 to 0 over energy range of about kT values.
- At T=T1 there are some probability *f*(E) shows that states above E*f* are filled.
- The probability[1-*f*(E)] shows that states below E*f* are empty.





Equation for Concentration 0f Electrons & Holes in Semiconductor

- When semiconductor is heated above $0^{o}K$, Electrons are excited from V.B to C.B.
- Thus Electrons in C.B & Holes in V.B are made available for conduction .
- The no. of Electrons per unit volume in C.B & the no. Holes per unit Volume in V.B called Electron Concentration & hole concentration respectively.
- If density of available energy state in C.B & V.B are known, concentration can be calculated with Feri Dirac distribution function.
- Let f(E) is the probability of occupancy of electron in level “E”at temp.T
- At Equilibrium most of the electrons are present at the bottom of C.B.
- Thus the concentration of conduction electron is

$$n = Ncf(Ec)$$

Where

Nc – Number of energy state in C.B

Ec – Energy for C.B

$f(Ec)$ – Probability of occupation of Ec

$$f(Ec) = \frac{1}{1+e^{(Ec-Ef/kT)}} \ldots\ldots\ldots\ldots(2)$$

At room temp

kT=1.38×10-23×300

kT≈ 0.025 eV is very small as compare to (Ec-Ef)

(Ec-Ef) >>kT

$$e^{(Ec-Ef/kT)} \rangle\rangle 1$$

$$1+e^{(Ec-Ef/kT)} \approx e^{(Ec-Ef/kT)}$$

Putting in eq (2)

$$f(Ec) = \frac{1}{e^{(Ec-Ef/kT)}}$$

$$f(Ec) = e^{-(Ec-Ef/kT)} \ldots\ldots\ldots\ldots(4)$$

putting in eq (1)

$$n = Nc\, e^{-(Ec-Ef/kT)} \ldots\ldots\ldots\ldots(5)$$

But no. of available state in C.B is

$$Nc = 2\left[\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}\right]$$

Putting in eq (5)

$$n = 2\left[\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}\right] e^{-\left(Ec - Ef/kT\right)} \quad \text{..................(6)}$$

Where m_e is the effective mass of electron

- Above equation shows that electron concentration is a function of position of Fermi level in semiconductor.
- As *Ef* moves close to the conduction band (*Ec*-*Ef*) decreases & concentration increases.

- If Nv be the no.of energy state in V.B, then the concentration of Holes in V.B is

$$p = Nv\left[1 - f(Ev)\right]\ldots\ldots\ldots\ldots(1)$$

where, *f(Ev)- Probability of occupation of energy state Ev by electron at temp."T"*

[1-f(Ev)]- Probability of occupation of energy state Ev by Holes

$$1 - f(Ev) = 1 - \frac{1}{1 + e^{(Ev - Ef/kT)}}$$

$$1 - f(Ev) = \frac{1 + e^{(Ev - Ef/kT)} - 1}{1 + e^{(Ev - Ef/kT)}}$$

$$1 - f(Ev) \approx e^{(Ev - Ef/kT)}$$

$$1 - f(Ev) \approx e^{-(Ef - Ev/kT)}$$

……(2)

Putting in eq(1)

$$p = Nv\, e^{-(Ef - Ev/kT)} \quad \ldots\ldots\ldots(3)$$

But no. of available state in V. B are

$$Nv = 2\left[\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}\right]$$

put in eq(3)

$$p = 2\left[\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}\right] e^{-(Ef - Ev/kT)}$$

the above equation shows that hole concentration increases as Fermi level moves closer to the V.B.

Types of Semiconductor

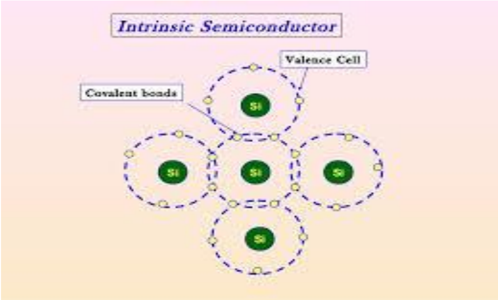
Intrinsic Semiconductor
(Pure)
Ex. Silicon (Si)
Germanium(Ge)
$n_e = n_h = n_i$

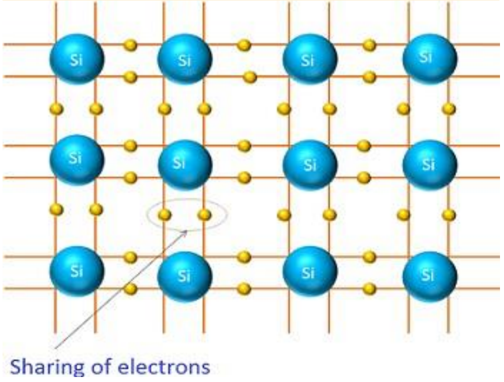
Extrinsic Semiconductor

Semiconductor
Pentavalent impurity
Ex. Phosphorus(P)
Antimony(Sb)
Arsenic(As)
Donor Impurity= N_D
$n_e >> n_h$

Semiconductor
Trivalent impurity
Ex. Gallium(Ga)
Indium(In)
Boron(B)
Aluminum(Al)
Acceptor Impurity= N_A
$n_e << n_h$

Intrinsic Semiconductor





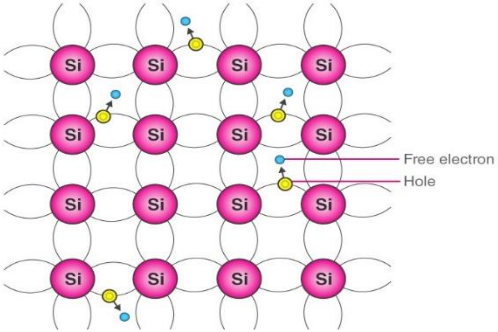
- Pure form of Semiconductor.
- Transformation of electrons to the C.B & generation of Holes in V.B achieved purely due to thermal excitation.
- Produce Equal no. of Electrons & holes called as Intrinsic charge carriers.
- Conductivity is known as Intrinsic conductivity.

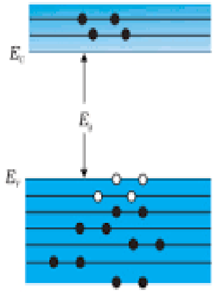
At $0^{o}K$

- Each silicon atom consist of 4 valance electrons .
- At $0^{o}K$ all the electrons are strongly bounded with their parent atoms & spend most of time with neighboring atoms i.e forming covalent bond.
- No. free electrons exist in the solid.
- Thus at $0^{o}K$ semiconductor acts as perfect insulator.

At Room temp.

- Atom gain thermal energy & vibrate about its mean position.
- When electron acquires sufficient energy, breaks the covalent bond & Randomly move in crystal.
- Further increase in temp. free electron jump to the C.B creating hole behind.
- Thus semiconductor behaves as conductor.





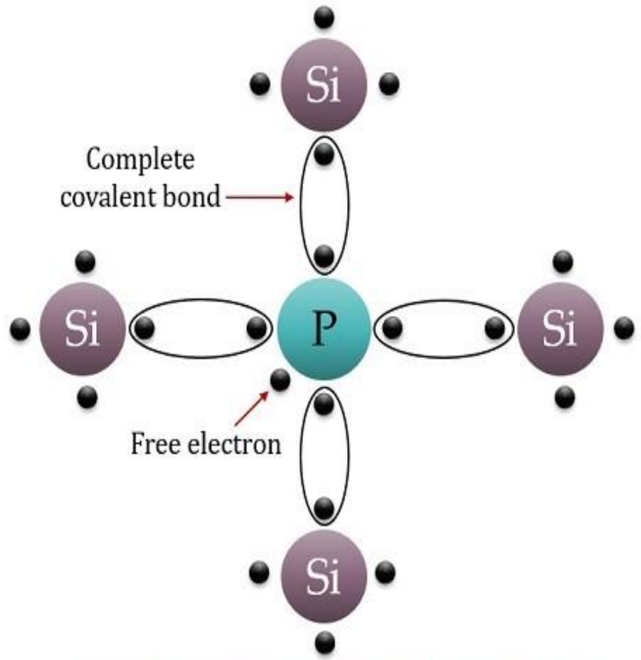
At $T > 0$ K, four thermally generated electron-hole pairs. The filled circles (•) represent electrons and empty fields (○) represent holes.

Extrinsic Semiconductor

- Small amount of impurity is added in pure semiconductor
- The process of addition of impurity is called doping & impurity is called dopant.
- Depending on type of doping Extrinsic semiconductor is of two types N-type & P-type.

N-type Semiconductor

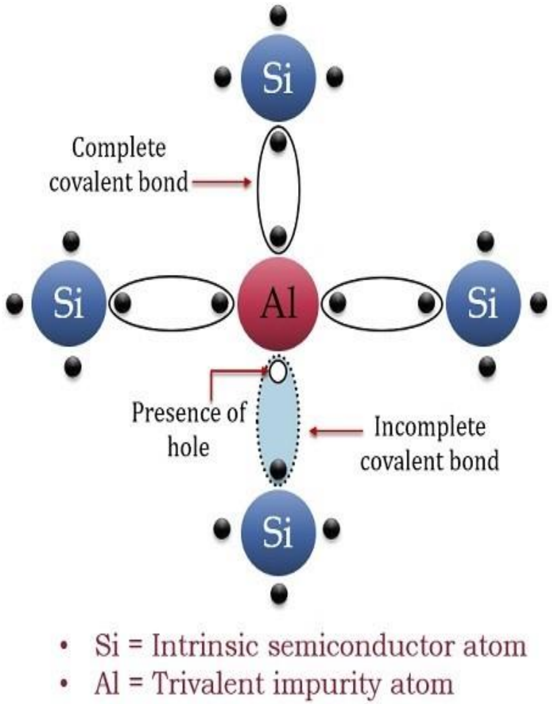
- Semiconductor is doped with pentavalent impurity like Phosphorus, Antimony, Arsenic etc.
- When Phosphorus is added in pure silicon, four electrons of Phosphorus forms covalent bond with four neighboring silicon atoms.
- Fifth electron remains free.
- An impurity gives an excess (a free) electron , hence called as donor impurity.
- In this semiconductor conductivity is due to electrons i.e Negatively charge particles, hence called as N-type Semiconductor.
- Electrons are majority charge carriers & holes are minority charge carriers.
- Fermi level is near the bottom of C.B.



- Si = Intrinsic semiconductor atom
- P = Pentavalent impurity atom

P-type Semiconductor

- Semiconductor is doped with trivalent impurity like Gallium , Indium, Boron, Aluminum etc.
- When aluminum is added in pure silicon, three electrons of Al forms covalent bond with three neighboring silicon atoms.
- One covalent is incomplete with vacancy of electron, create a hole & accept electron from neighboring atoms.
- An impurity accept the electrons , hence called as acceptor impurity.
- In this semiconductor conductivity is due to holes i.e positively charge particles, hence called as P-type Semiconductor.
- Holes are majority charge carriers & electrons are minority charge carriers.
- Fermi level is near the top of V.B.



Law of mass action

The product of electrons & holes concentration in doped semiconductor is constant & is equal to the square of intrinsic carrier density at given temperature.

$$n_i^{\,2} = n.p$$

Charge Neutrality Condition

- Semiconductor (Intrinsic/Extrinsic) it is electrically neutral in its equilibrium condition.
- In N-type no. electrons in C.B must be equal to sum of electrons originated from donor level & electrons excited from the V.B.
- Electrons in donor level leaves behind positive ions & electrons in V.B leaves behind holes.
- Thus total negative charge mobile electrons is equal to total positive charge created in the crystal.

Charge Neutrality condition in

N type

Electron concentration is given by

$n_e = N_D + n_h$

Since $n_e >> n_h$

$n_e \approx N_D$

But A/c to Law of mass action

$n_e\, n_h = n_i^{\,2}$

$$n_h = \frac{n_i^{\,2}}{n_e}$$

$$n_h = \frac{n_i^{\,2}}{N_D}$$

P-type

Holes concentration is given by

$p_h = N_A + p_e$

Since $p_h >> p_e$

$P_h \approx N_A$

But A/c to Law of mass action

$p_h\, p_e = n_i^{\,2}$

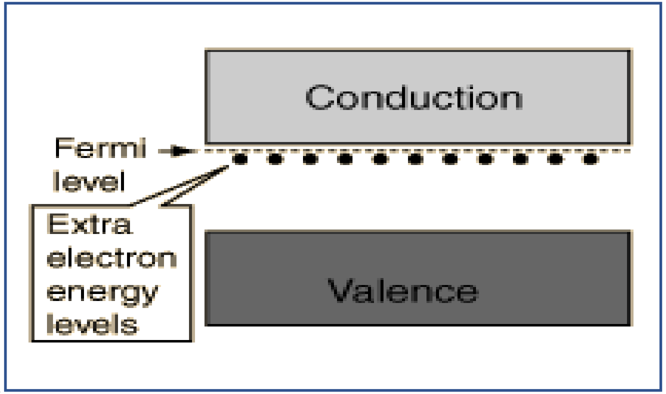
$$p_e = \frac{n_i^{\,2}}{p_h}$$

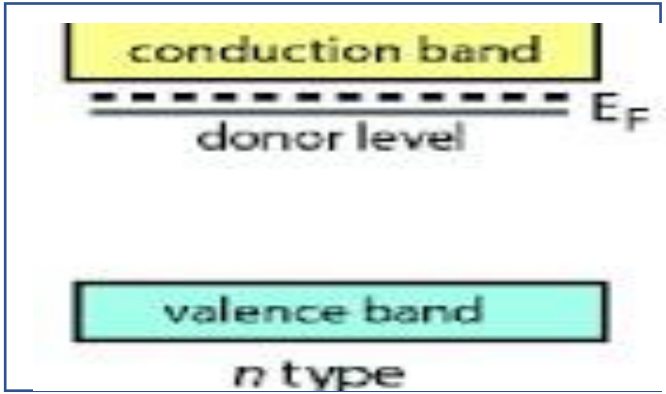
$$p_e = \frac{n_i^{\,2}}{N_A}$$

Position of Fermi level in Extrinsic Semiconductor

N-Type

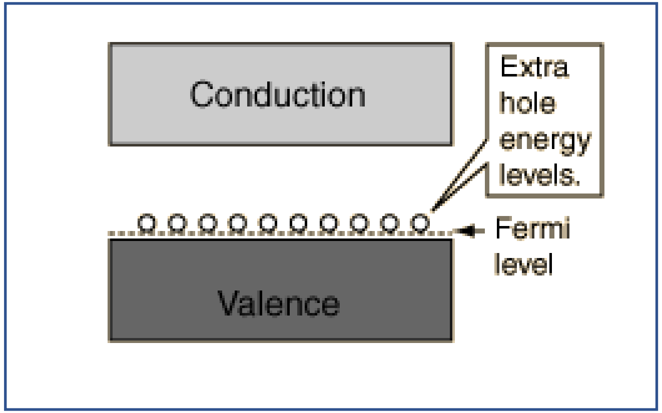
- Pure Si or Ge doped with Pentavalent impurity.
- Addition of such impurity introduced new energy level in Band structure, just below the bottom of C.B
- At 0^oK the level is filled with electrons.
- This level donates electrons to the C.B, Hence called Donor Level.
- At 0^oK Fermi level lies exactly in the middle of bottom of C.B & donor level.
- When temp. increase electrons from donor level jump to the C.B

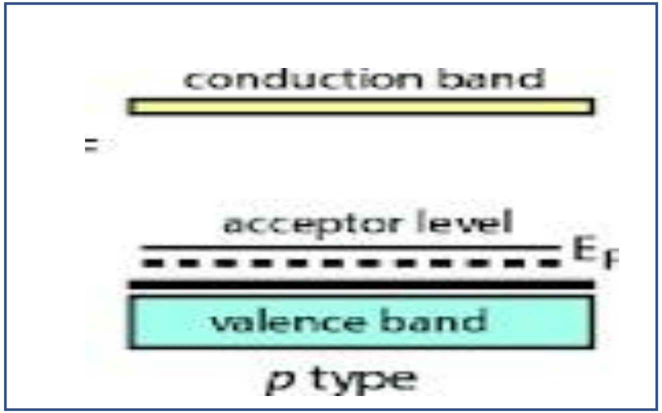




P-Type

- Pure Si or Ge doped with Trivalent impurity.
- Addition of such impurity introduced new energy level in Band structure, just above the top of V.B
- At 0^oK the level is filled with holes.
- This level accept electrons from the V.B, Hence called Acceptor Level.
- At 0^oK Fermi level lies exactly in the middle of top of V.B & acceptor level.
- When temp. increase acceptor level accept the electrons from the V.B .

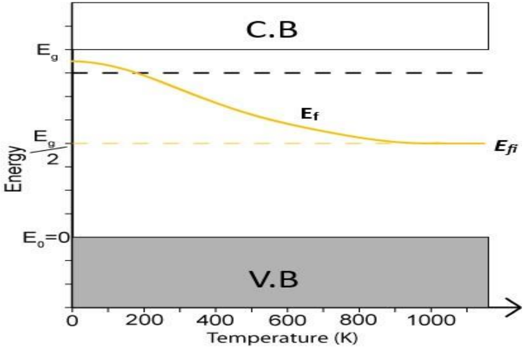


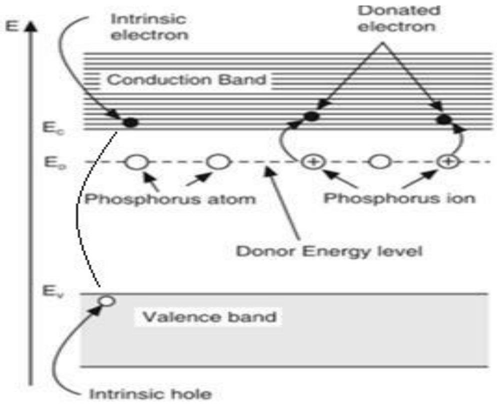


Effect of Temperature on Fermi level in Extrinsic Semiconductor

N-type

- Fermi level lies in the middle of bottom of C.B & donor level at $0^{o}K$.
- With constant impurity concentration as temperature increases the Fermi level moves down wards.
- it passes through the donor level & finally reached at intrinsic level.
- Thus semiconductor behaves like Intrinsic semiconductor.
- At lower temp. some of the donor atoms get ionized i.e electrons jump from donor level to the C.B.
- At certain temp. all the atoms get ionized.
- Beyond this temp. electrons are jump from V.B to C.B.
- Thus Fermi level get shifted down to intrinsic position.

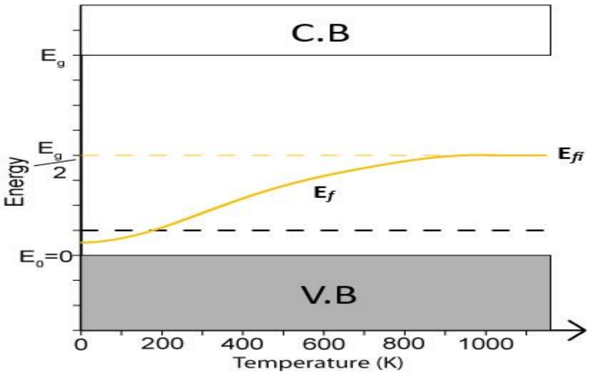


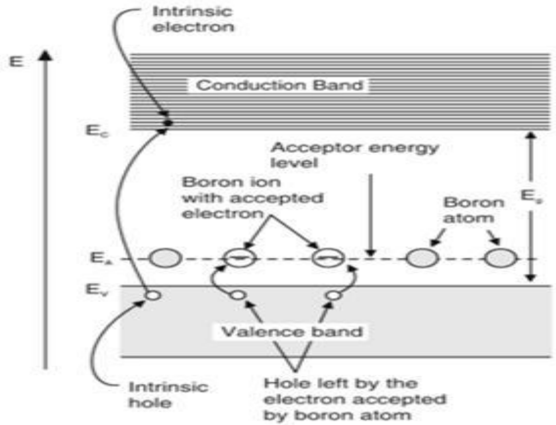


: Energy band diagram of n-type semiconductor

P-Type

- Fermi level lies in the middle of top of V.B & acceptor level at $0^{o}K$.
- With constant impurity concentration as temperature increases the Fermi level moves up wards.
- it passes through the acceptor level & finally reached at intrinsic level.
- At some temp. electrons from V.B excited to acceptor level.
- At certain temp. all the empty state in acceptor level are filled.
- Above this temp. electrons from V.B will jumped to C.B.
- Thus at specific temp. Fermi level remains at intrinsic position.
- P type semiconductor behaves like Intrinsic semiconductor.





. Energy band diagram for a *p*-type semiconductor

Equations of Electrical Conductivity for Semiconductor

For Metal

Electrical conductivity due to electron only.

thus $$\sigma = ne\mu_e$$

Where, n- No. of free e- per unit volume

e- Charge on electron

μ_e- Mobility of electron $\left[\mu_e = \frac{V}{E}\right]$

For Semiconductor

Electrical conductivity due to both electrons & holes

Thus $$\sigma = ne\mu_e + pe\mu_h$$

$$\sigma = e(n\mu_e + p\mu_h)$$

This is the general Equation

Where, n- No. of free e- per unit volume,

p- No. of holes- per unit volume,

μ_e- Mobility of electron,

μ_h- hole mobility,

e- Charge.

For Intrinsic Semiconductor

In Intrinsic Semiconductor no. of free electrons is equal to no. of Holes i.e

$$n = p = n_i$$

Where n_i is intrinsic carrier concentration

$$\sigma = e(n_i\mu_e + n_i\mu_h)$$

$$\sigma = en_i(\mu_e + \mu_h)$$

Conductivity in Extrinsic Semiconductor

For N-Type

$$n >> p$$

$$n \approx N_D$$

Also $n >> p$

$$n\mu_e >> p\mu_h$$

$$n\mu_e + p\mu_h \approx n\mu_e \approx N_D\mu_e$$

Thus the conductivity of N-type semiconductor is

$$\sigma_n = eN_D\mu_e$$

For P-Type

$$p >> n$$

$$p \approx N_A$$

Also $p >> n$

$$p\mu_h >> n\mu_e$$

$$p\mu_h + n\mu_e \approx p\mu_h \approx N_A\mu_h$$

Thus the conductivity of P-type semiconductor is

$$\sigma_p = eN_A\mu_h$$

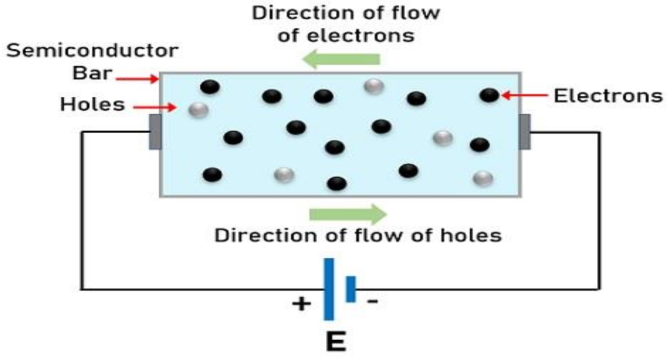
Drift & diffusion in Semiconductor

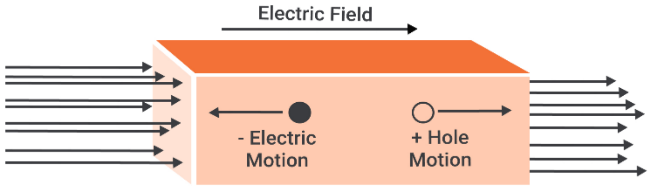
Drift

- In metal the conductivity is due to electrons $J = \sigma E$
- But in semiconductor the electrical conductivity is the sum of conductivity due to electrons & holes
- Thus the net current in semiconductor is $J = J_n + J_p$

$$J = [\sigma_n + \sigma_p]E \Rightarrow J = [ne\mu_e + pe\mu_h]E$$

- When an electric field is applied across semiconductor , electric force act on charges
- due to electric force electrons are moving in the opposite direction of applied electric field & holes are in the direction of electric field.
- This motion of charge carriers due to electric field is called as the drifting & it gives current called drift current.





Diffusion

- Directional movement of charge carriers due to Concentration gradient.
- The concentration of charge carriers varies with distance in semiconductor called Concentration gradient.
- The motion of charge carriers produce current known as Diffusion current.
- Diffusion current is directly proportional to concentration gradient at point

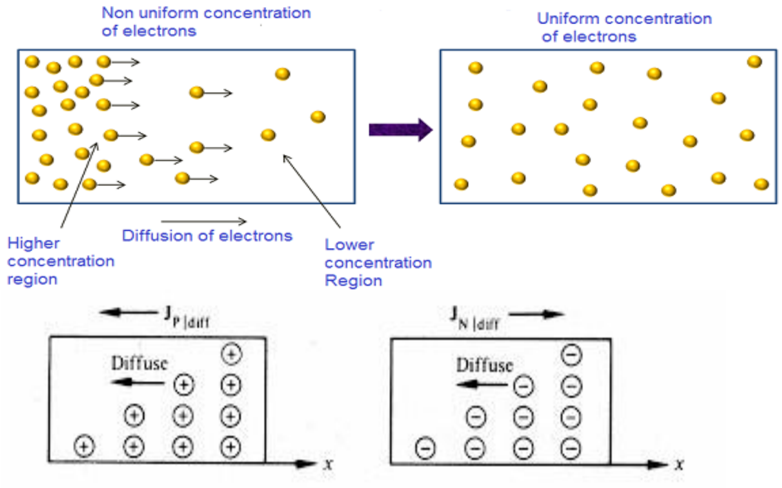
Let $\frac{dn}{dx}$ is concentration gradient in case of electrons

$\frac{dp}{dx}$ is concentration gradient in case of Holes

$\therefore$ Diffusion current(Electron) $\alpha \frac{dn}{dx} \quad = D_n \frac{dn}{dx}$

Diffusion current density for electron is $J_n = eD_n \frac{dn}{dx}$

Diffusion current density for holes is $J_p = -eD_p \frac{dp}{dx}$



$$J = J_n + J_p$$

$$J = J_n[Drift + Diffusion] + J_p[Drift + Diffusion]$$

$$J = \left[ne\mu_e E + eD_e \frac{dn}{dx}\right] + \left[pe\mu_h E - eD_h \frac{dp}{dx}\right]$$

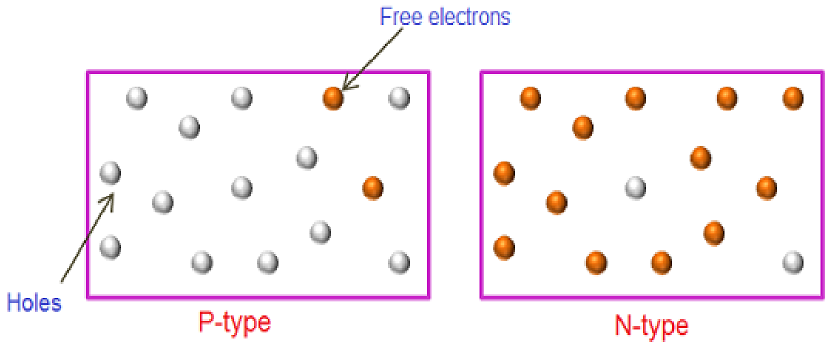
$$J = e\left[n\mu_e E + D_e \frac{dn}{dx}\right] + \left[p\mu_h E - D_h \frac{dp}{dx}\right]$$

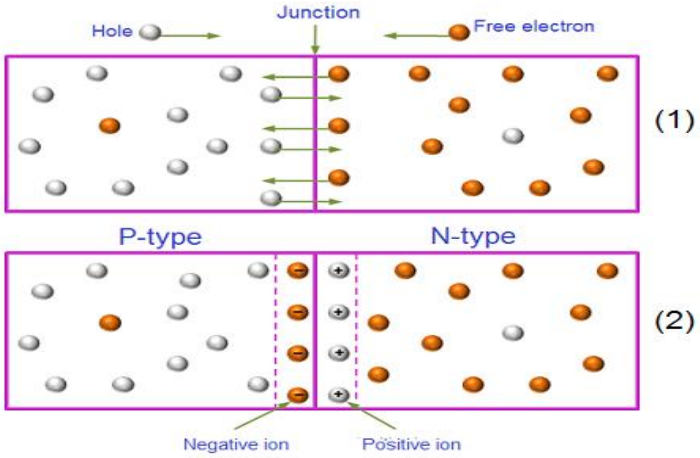
P-N junction

- A single piece of semiconductor is doped with donor impurity at one end & acceptor impurity at other end.
- It's the sharp boundary between P type & N type of semiconductor.

As soon as junction is formed

- The holes from P region diffused in into N region & recombine with free electrons.
- The electrons from N region diffused into P region & recombine with holes.
- During diffusion ,electrons diffused from N to P region leaves behind uncompensated donor ions(positive ions) in N region.
- Holes diffused from P to N region leaves behind uncompensated acceptor ions(negative ions) in P region.

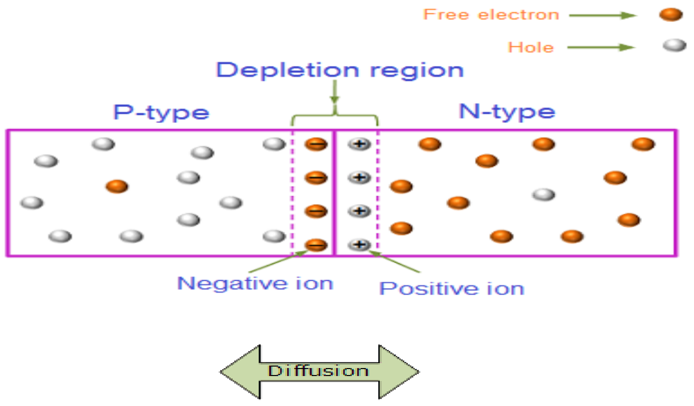


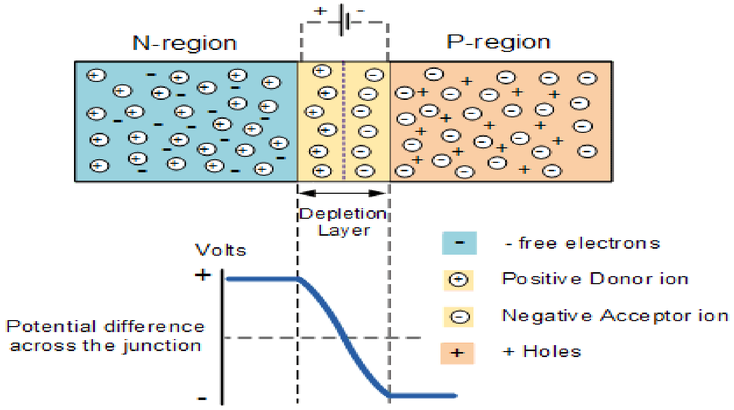


- Near the junction a narrow region is formed due to free charge carriers containing only uncompensated immobile ions called Depletion region.
- Width of depletion region depend on doping level of impurity. It is of the order of 10^{-6}m or 1micron.
- In depletion region the are positive immobile ions in N region & negative immobile ions in P region.
- Due to the charge separation, Voltage V_B is developed across the junction under equilibrium condition known as Potential barrier.

Capacitance of PN junction

- In PN junction two parallel rows of charge impurity ions acts as plates of capacitor while depletion region act as a dielectric between them. The Capacitance formed in the junction known as junction capacitance.

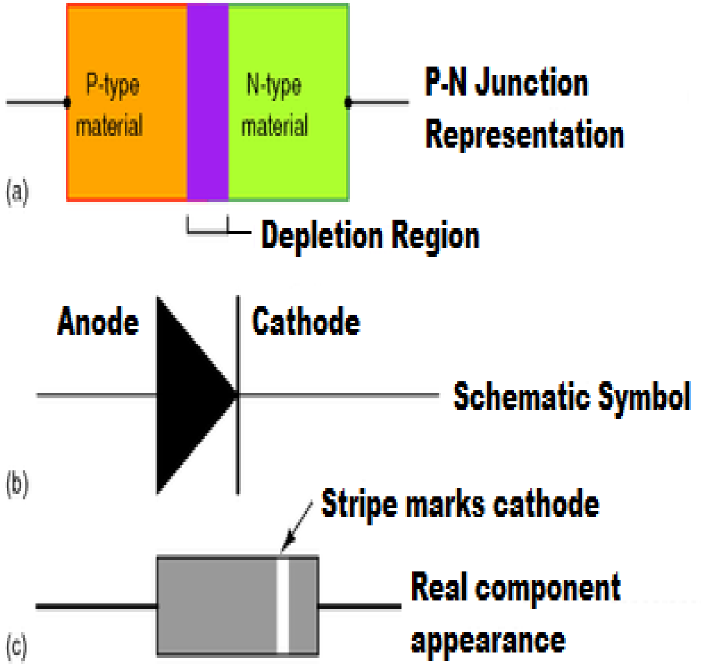




Working of P-N junction Diode

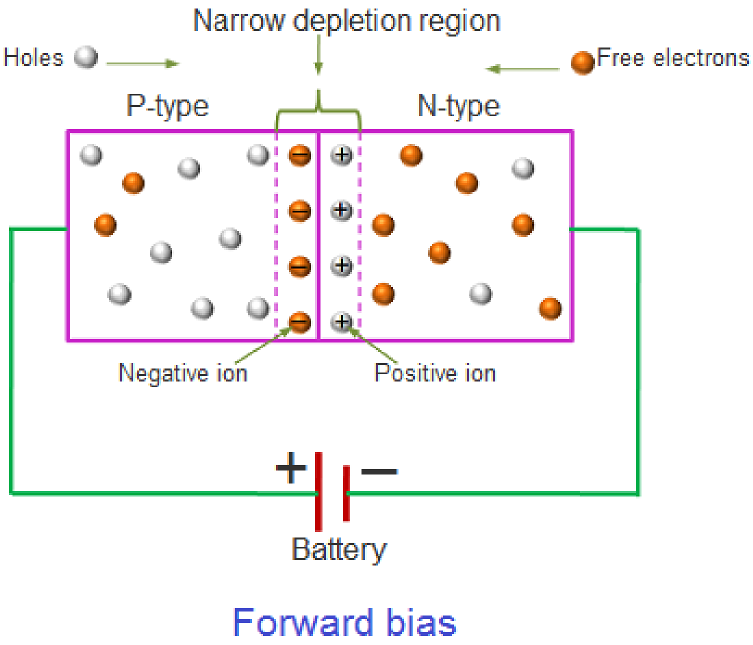
P-N junction Diode

- it consist of P-N junction formed either by Si or Ge.
- Having two terminals one is connected to P-region & other connected to N- region of diode.
- Ckt symbol is as shown in fig b.
- The arrow head represent the direction of flow of current in forward bias.
- Real appearance is shown in fig c.



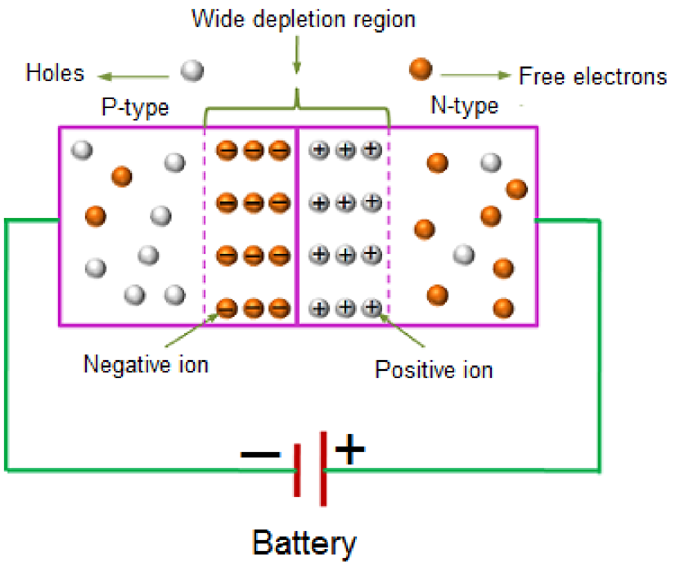
Forward Bias P-N Junction Diode

- Positive terminal of B.T is connected to the P-region & negative terminal of B.T is connected to N-region of Diode.
- The holes from P- region repelled by positive terminal of B.T towards the junction.
- The electrons from N- region repelled by negative terminal of B.T towards the junction.
- Due to this some of the electrons & holes enters in the depletion region & recombine with each other.
- This reduced the barrier potential & large current flow through the junction due to majority charge carriers.
- In F.B junction has low resistance.
- P-N junction is ON in F.B.



Reverse Bias P-N Junction Diode

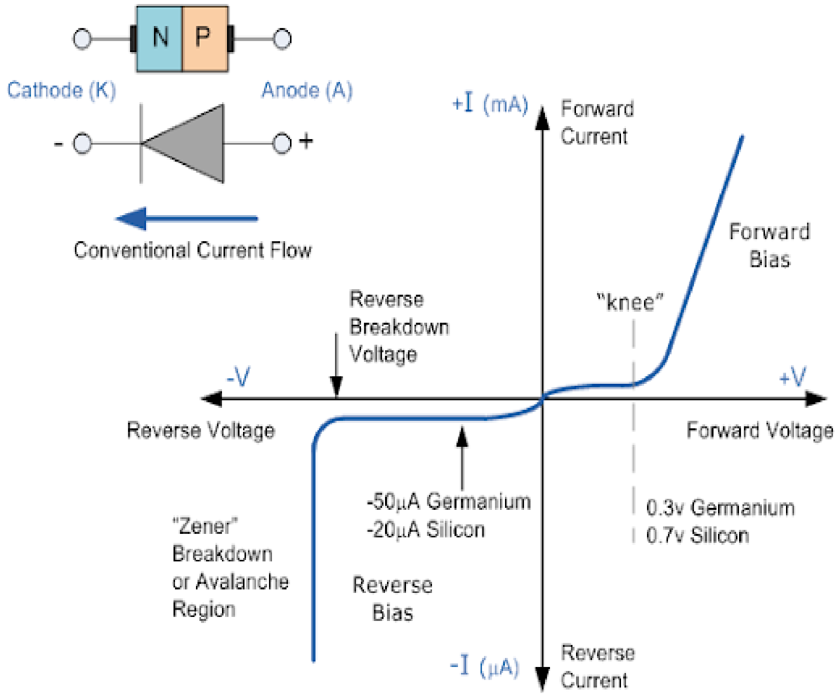
- Positive terminal of B.T is connected to the N-region & negative terminal of B.T is connected to P-region of Diode.
- The holes from P- region are attracted by negative terminal of B.T away from the junction.
- The electrons from N- region are attracted by positive terminal of B.T away from the junction.
- Due to this potential barrier as well as width of depletion region increased.
- Very small current flowing through the diode due to the minority charge carriers & known as Reverse saturation current.
- This current is due to thermally generated electrons & holes.
- In R.B junction has high resistance.



Reverse bias

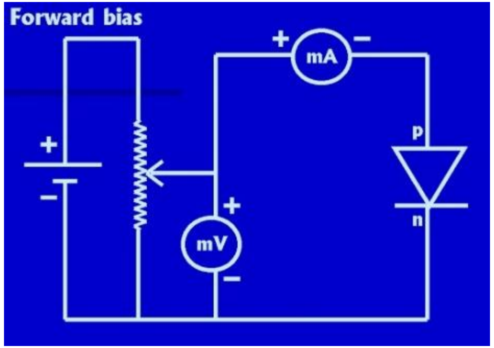
V-I characteristics of P-N junction Diode

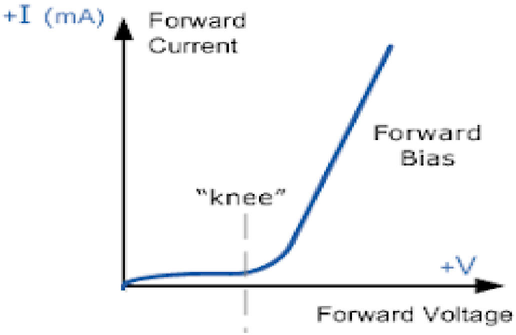
- The graph which shows the variation of current through the diode when voltage is applied across P-N junction diode in F.B & R.B called as V-I characteristics.



Forward Characteristics of P-N Junction Diode

- Characteristics of diode in forward bias
- Initially no current(I) flowing through the diode up to certain value of voltage(V).
- Above the certain value of voltage(V), current(I) increases rapidly.
- This is because the external voltage is initially oppose by barrier potential up to certain point.

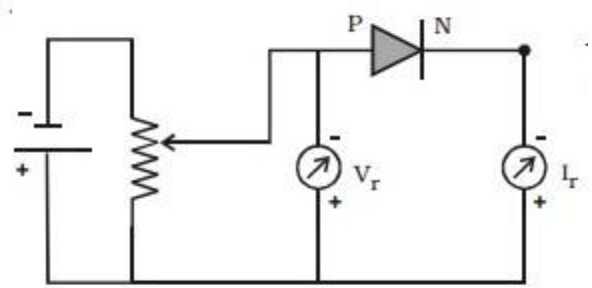


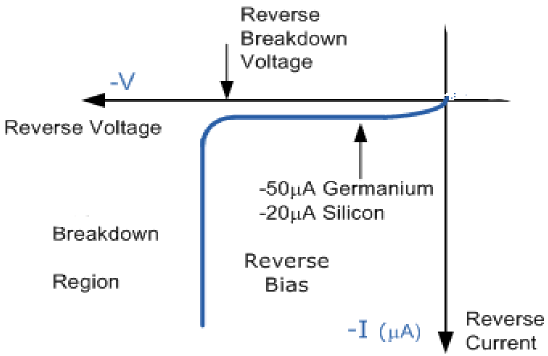


- At certain voltage the barrier potential becomes zero & depletion region breaks.
- Heavy current starts flowing through the diode.
- The forward voltage at which the diode starts conducting is called Knee voltage or Cut in voltage or threshold voltage.
- The cut in voltage for Ge is 0.3 V & Si is 0.7 V.

Reverse Characteristics of P-N junction Diode

- Characteristics of diode in reverse bias.
- Diode current(I_r) is very small even reverse voltage (V_r) is high.
- When reverse voltage increase to sufficient large value , reverse current increase rapidly.

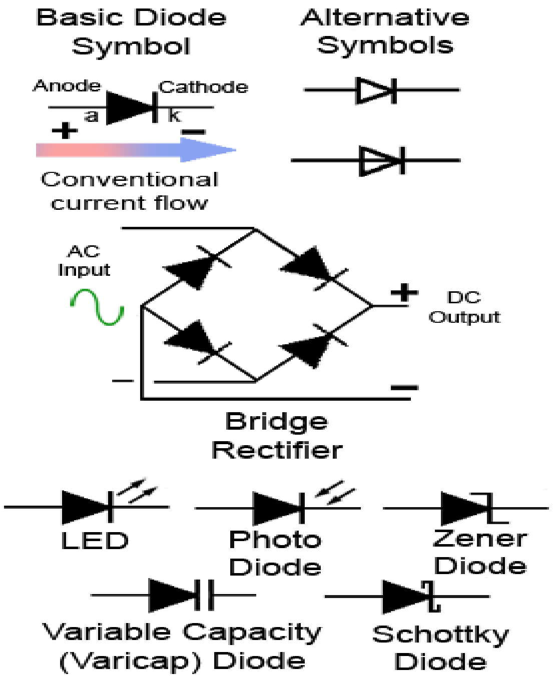




- The reverse voltage at which reverse current increase rapidly known as Break down voltage.
- Reverse current remains constant below break down known as Reverse Saturation current.
- Above the break down voltage diode will not recover to its original form & damage completely.

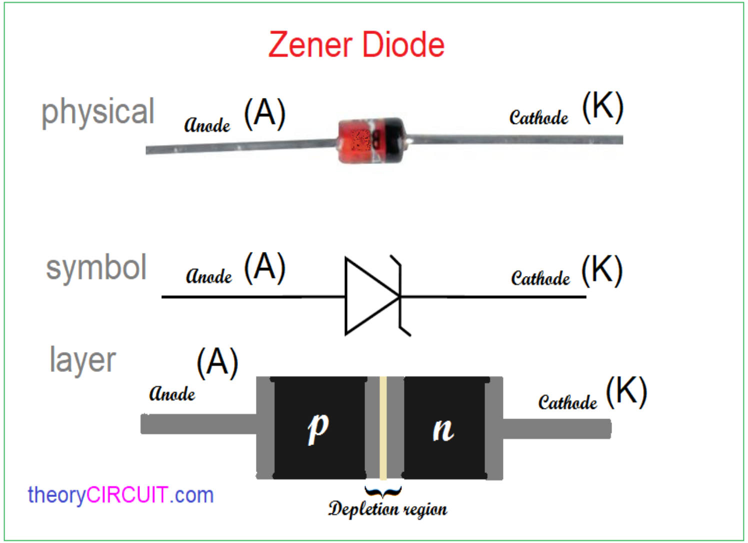
Applications of P-N junction Diode

- Rectifier (Converting AC to DC).
- Signal diode in communication ckt.
- Switch in Logic ckt.
- Varacator Diode in radio , TV receivers.
- Photo diode used in computer hard wears.
- As solar cell in Space application.



Zener Diode

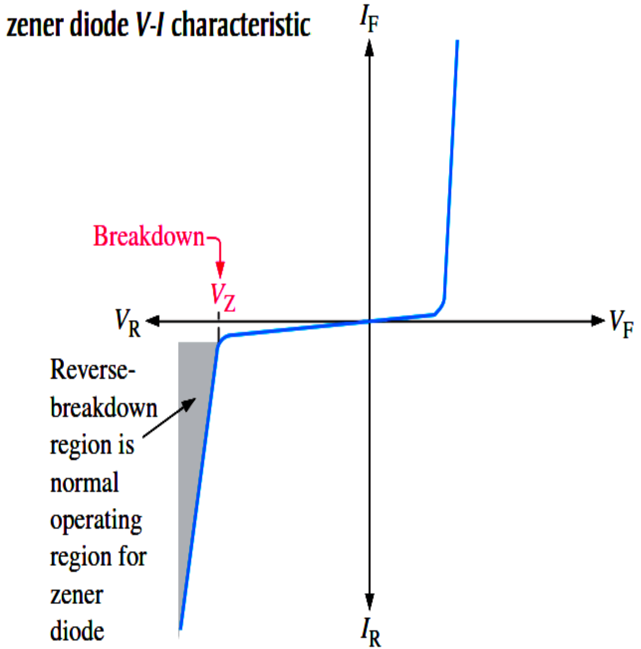
- It is a reverse bias heavily doped P-N junction diode.
- Operated in Break down region.
- Current is limited by external resistance only.
- Also called Voltage regulator, Breakdown or Advance diode.



V-I Characteristics of Zener Diode

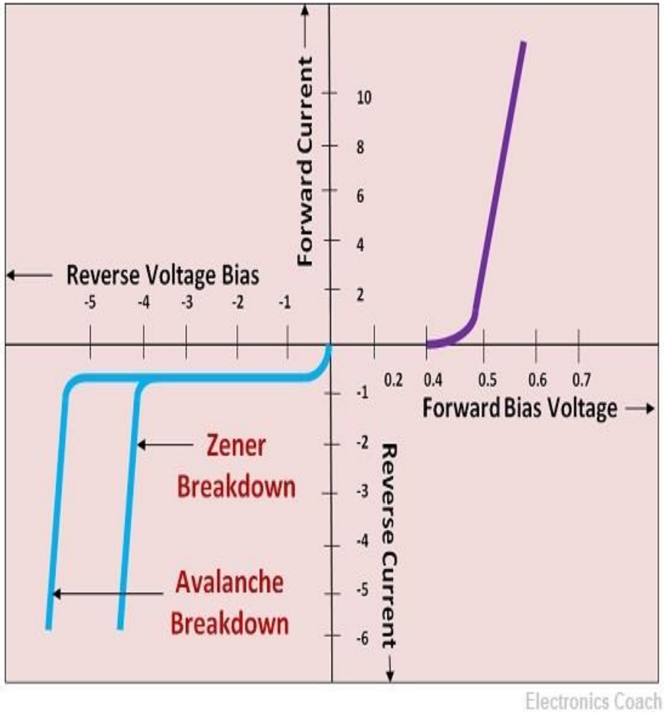
- When the reverse voltage of zener diode increases, initially due to high reverse resistance very small current flow due to minority carriers.
- Further increase in the reverse voltage current increases rapidly.
- The reverse voltage at reverse current increases rapidly called Zener break down voltage or Zener voltage.
- In Zener diode , breakdown voltage is very small.
- Increase in the reverse voltage above the Zener voltage, control breakdown protect the diode from damage.
- After break down voltage, current increases rapidly while voltage remains constant.
- Location of Zener region can be controlled by doping.
- Increase in doping decrease the Zener potential.
- There are two types of Breakdown

  Zener Breakdown & Avalanche Breakdown



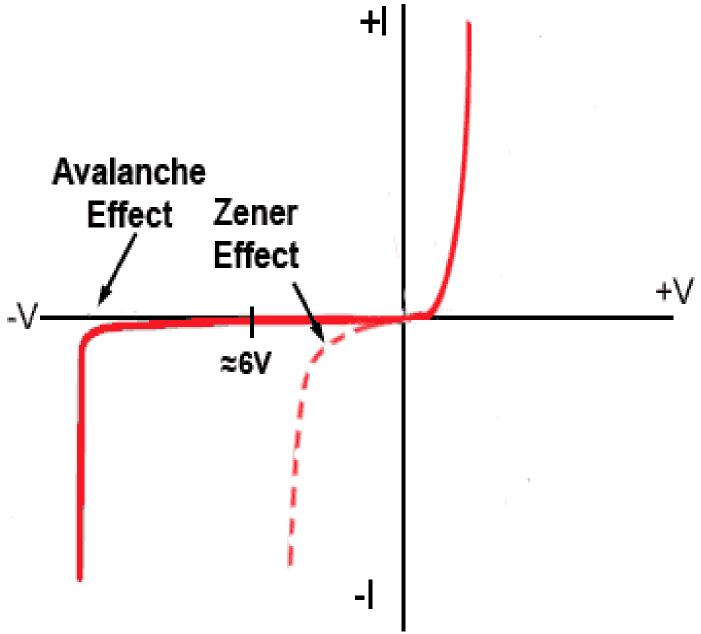
Zener break down.

- Zener Breakdown occurs in heavily doped junction diode
- breaking of covalent bond by strong electric field.
- When reverse voltage of junction increase, strong electric filed set in across narrow depletion region.
- This electric field is strong enough to breaks the covalent bond.
- Generation of electron-hole pairs & accelerating towards the junction.
- Thus large current flow through the diode.
- An internal electric field is developed is of the order of 10^6 V/m for 1 volt of reverse potential.
- This break down observed up to 6 V.
- Explanation was first given by Zener, hence called Zener mechanism.



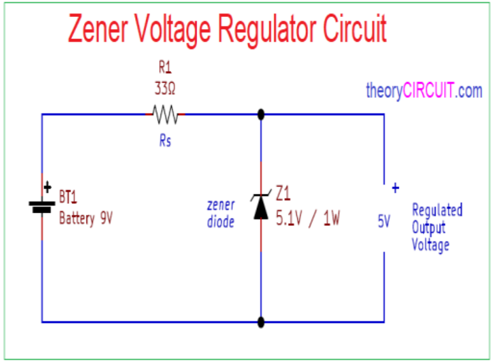
Avalanche Breakdown

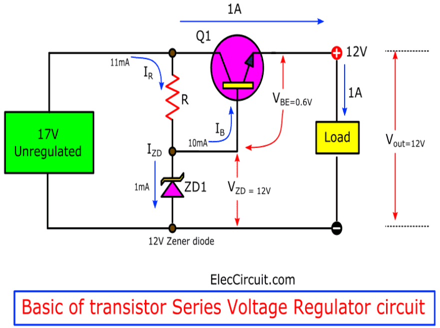
- Zener Breakdown occurs in lightly doped junction diode
- Electric field is not strong enough.
- When reverse voltage of junction increase, the amount of energy imparted to minority charge carriers.
- These minority charge carriers collide with host atom , breaks the covalent bond & generate additional electron-hole pairs.
- These carriers also get energy due to applied voltage & collides another host atoms which gives further charge carriers.
- thus avalanche of carriers takes place & reverse current increase sharply in very short time.
- This mechanism known as Avalanche breakd

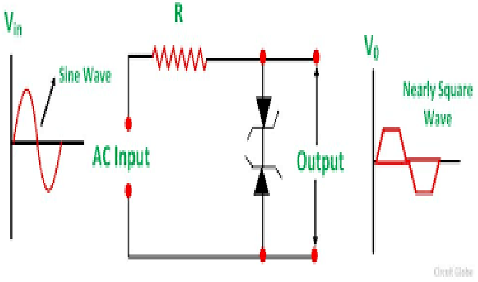


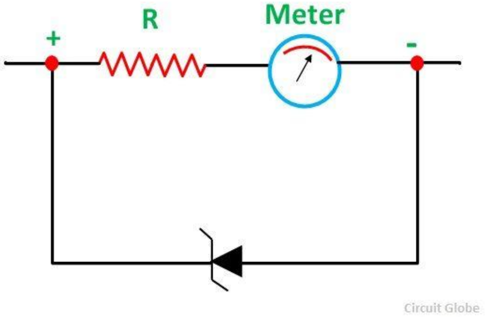
Applications of Zener Diode

- Voltage regulator.
- Reference diode in transistor ckt.
- Peck clipper in wave shaping ckt
- For meter protection.



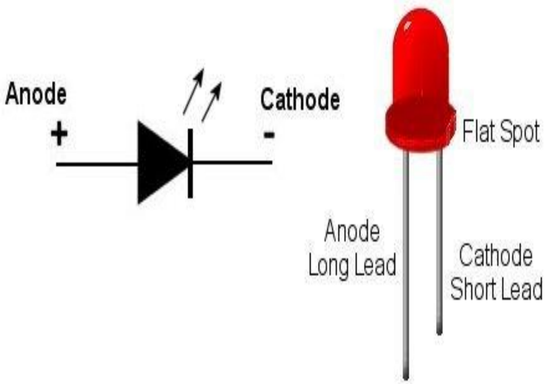






Light Emitting Diode

- LED is optoelectronics device
- Converts electrical energy into light energy.



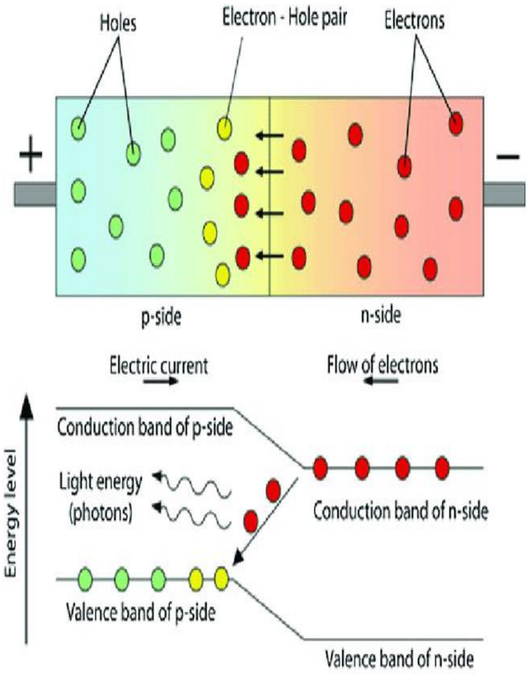
Working of LED

- P-N junction of LED is forward bias.
- The majority of charge carriers moving towards the junction.
- Recombination takes place.
- during recombination, electrons in C.B of N side falls in V.B of P side which is on lower level.
- i.e electrons are jumped from higher energy level to lower energy level.
- Hence difference of energy radiated in the form of heat & light.
- In LED greater percentage of energy is given out in the form of light due to the material used for making LED.
- The energy emitted is given by

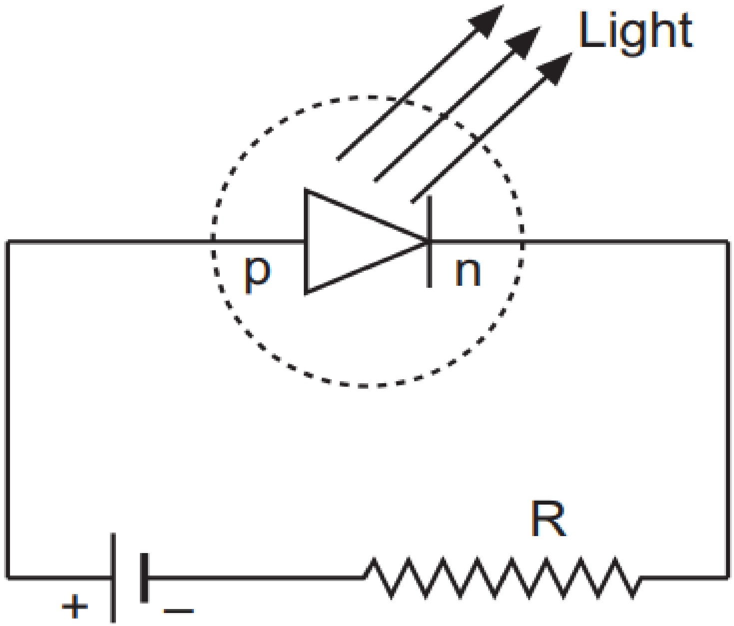
$$E_g = h\upsilon$$

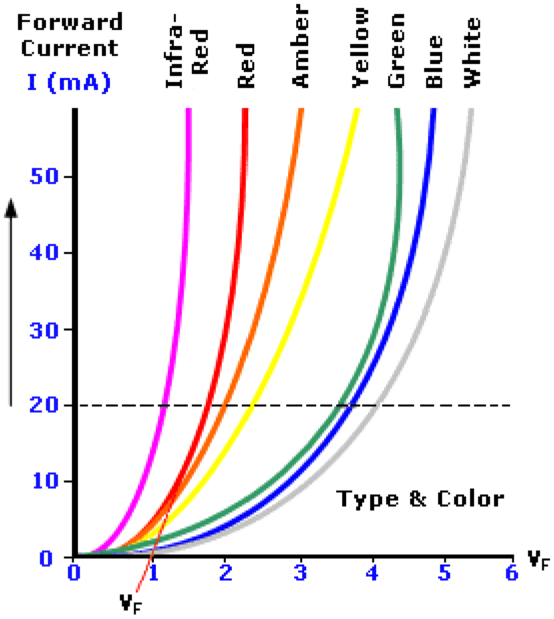
$$E_g = \frac{hc}{\lambda} \qquad \Rightarrow \lambda = \frac{hc}{E_g} \quad \Rightarrow \lambda = \frac{1.24}{E_g}\ \mu\text{m}$$

- the voltage at which LED just glows & current starts increasing rapidly is known as Striking potential.



V-I characteristic of LED





The semiconducting material used for LED

Typical LED Characteristics			
Semiconductor Material	Wavelength	Colour	V_F @ 20mA
GaAs	850-940nm	Infra-Red	1.2v
GaAsP	630-660nm	Red	1.8v
GaAsP	605-620nm	Amber	2.0v
GaAsP:N	585-595nm	Yellow	2.2v
AlGaP	550-570nm	Green	3.5v
SiC	430-505nm	Blue	3.6v
GaInN	450nm	White	4.0v

Applications of LED

- Infrared LED used in Burglar alarm.
- In optical switch application.
- Power ON/OFF condition.
- In 7- segment, 16- segment & dot matrix display.
- In the field of optical communication.
- In image sensing circuit.

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Fermi Function & Fermi Energy

Related Formulae

$$f(E) = \frac{1}{1 + e^{\left[\frac{E-E_f}{kT}\right]}}$$

$$E_f = \frac{1}{2} m v_f^2 = kT$$

$$\Rightarrow F(E_g) = e^{\left[-\frac{E_g}{2kT}\right]}$$

$$k = 1.38 \times 10^{-23} J/K$$

$$m = 9.1 \times 10^{-31} Kg$$

$$e = 1.6 \times 10^{-19} C$$

$$1eV = 1.6 \times 10^{-19} J$$

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- Evaluate the Fermi function as kT above Fermi energy.

Solution-

$$f(E) = \frac{1}{1 + e^{\left[\frac{E-E_f}{kT}\right]}}$$

For energy above Fermi energy

We have

$$\left[\frac{E-E_f}{kT}\right] = 1$$

$$\therefore \; f(E) = \frac{1}{1+e^1}$$

$$\Rightarrow f(E) = \frac{1}{1+2.718}$$

$$\Rightarrow f(E) = 0.2689$$

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- Calculate the Fermi velocity of charge carrier in a metal having Fermi temp.2500ºk.

Solution-we have $$\frac{1}{2}mv_f^2 = kT$$

$$\Rightarrow v_f^2 = \frac{2kT}{m}$$

$$\Rightarrow v_f^2 = \frac{2 \times 1.38 \times 10^{-23} \times 2500}{9.1 \times 10^{-31}}$$

$$\Rightarrow v_f^2 = \frac{2 \times 1.38 \times 10^{-23} \times 2500}{9.1 \times 10^{-31}}$$

$$\Rightarrow v_f^2 = 7.582 \times 10^{10}$$

$$\Rightarrow v_f = 275.35 \times 10^3 m/s$$

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- What is the probability of an electron being thermally promoted to the conduction band in diamond at 27ºC,if band gap is 5.6 eV wide?

Solution-

Given

$$E_g = 5.6\,eV = 5.6 \times 1.6 \times 10^{-19}\,J$$

$$T = 27°C = 27 + 273 = 300°K$$

$$k = 1.38 \times 10^{-23}\,J/K$$

$$F(E_g) = ?$$

$$\Rightarrow \boldsymbol{F(E_g) = e^{\left[-\frac{E_g}{2kT}\right]}}$$

$$\Rightarrow \boldsymbol{F(E_g) = e^{\left[-\frac{5.6 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 300}\right]}}$$

$$\Rightarrow \boldsymbol{F(E_g) = 1.008 \times 10^{-47}}$$

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- The Fermi level for potassium is 2.1 eV. Calculate velocity of the electron at the Fermi level.

Solution-

Given, $E_f = 2.1eV = 2.1 \times 1.6 \times 10^{-19} J$

$$v_f = ?$$

$$Now\ E_f = \frac{1}{2} m v_f^2$$

$$\Rightarrow v_f^2 = \frac{2E_f}{m}$$

$$\Rightarrow v_f = \sqrt{\frac{2 \times 2.1 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}}$$

$$\Rightarrow v_f = 8.6 \times 10^5 m/s$$

N U M E R I C A L S

Electrical Conductivity of Semiconductor

- Calculate the mobility of electron in copper, if the free electrons per unit volume is 8.496×10^{22} cm^{-3} and resistivity of copper is 1.7×10^{-6} ohm-cm .

Solution-

Given

$$n = 8.496\times10^{22}\,cm^{-3} = 8.496\times10^{28}\,m^{-3}$$

$$\rho = 1.7\times10^{-6}\,ohm-cm = 1.7\times10^{-8}\,ohm-m$$

$$\mu_e = ?$$

$$Now,\ \rho = \frac{1}{\sigma}$$

$$\sigma = ne\mu_e$$

$$\Rightarrow \rho = \frac{1}{ne\mu_e}$$

$$\Rightarrow \mu_e = \frac{1}{ne\rho}$$

$$\Rightarrow \mu_e = \frac{1}{8.496\times10^{28}\times1.6\times10^{-19}\times1.7\times10^{-8}}$$

$$\Rightarrow \mu_e = 4.327\times10^{-3}\,m^2/Vs$$

NUMERICALS

- Mobilities of holes & electrons in a sample of intrinsic germanium at room temperature are 1700cm^2/V.s and 3600 cm^2/Vs resp.If the electron & hole densities are each equal to 2.5×10^{13} per cm^3, calculate its conductivity.

Solution-

Given that,

$$\mu_h = 1700cm^2/Vs = 1700 \times 10^{-4} m^2/Vs$$

$$\mu_e = 3600cm^2/Vs = 3600 \times 10^{-4} m^2/Vs$$

$$n = p = n_i = 2.5 \times 10^{13}/cm^3 = 2.5 \times 10^{19}/m^3$$

$$we\ know\ that\ , \sigma = n_i e(\mu_e + \mu_h)$$

$$\Rightarrow \boldsymbol{\sigma = 2.5 \times 10^{19} \times 1.6 \times 10^{-19}(3600 \times 10^{-4} + 1700 \times 10^{-4})}$$

$$\Rightarrow \sigma = 2.12\, ohm^{-1}m^{-1}$$

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- LED is made from GaAs emits yellow light of wavelength 5850Aº.calculate energy band gap of the material.

Solution-

Given that, $\lambda = 5850A^\circ = 5850 \times 10^{-10}m$

$$h = 6.63 \times 10^{-34}Js$$

$$c = 3 \times 10^{8}m/s$$

$E_g = ?$ $\quad$ $E_g = hv$

$$E_g = \frac{hc}{\lambda}$$

$$E_g = \frac{6.63\times10^{-34}\times3\times10^{8}}{5850\times10^{-10}}$$

$$E_g = 3.4 \times 10^{-19}J = 2.12\ eV$$