Semiconductor:

A semiconductor is a material which has electrical conductivity and resistivity in between good conductors and insulators. It partially conducts the current. At low temperature it act as a insulator. At high temperature it act as a conductor.

Properties of a semiconductor:

1. They are formed by covalent bond
2. They have empty conduction band at 0K.
3. They have almost filled valence band at 0K
4. They have small energy gap
5. They have crystalline nature
6. They have negative temperature coefficient of resistance (when temperature increases, conductivity increases, resistivity decrease)
7. By increasing the temperature or by adding impurities to the semiconductor, conductivity increases
   eg: Germanium → $E_g = 0.72\,eV$, Silicon → $E_g = 1.1\,eV$

Elemental and Compound semiconductor:

Based on the composition, semiconductors are classified into Elemental and compound semiconductor.

	Elemental semiconductor	Compound semiconductor
1.	The elemental semiconductors are made from a single element of fourth group in a periodic table	Compound semiconductors are made by the combination of 3rd & 5th group elements or 2nd & 6th group elements in a periodic table
2.	Example: Germanium, Silicon	Example: GaAs & InP
3.	They are called indirect bandgap semiconductors (ie) electron hole recombination takes place through traps in a band gap	They are called direct bandgap semiconductors (i.e) electron hole recombination takes place directly with each other
4.	Heat is produced during recombination	photons are emitted during recombination
5.	Current Amplification is more	Current amplification is less
6.	They are used for making diodes & transistors	They are used for laser diodes, LEDS

Intrinsic and Extrinsic semiconductor:

Based on purity, semiconductors are classified into two types

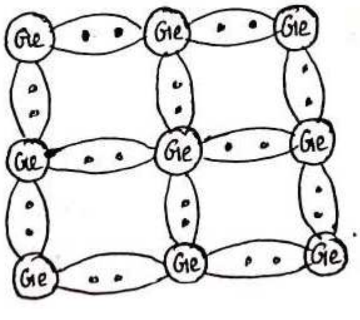
1. Intrinsic semiconductor
2. Extrinsic semiconductor.

Intrinsic semiconductors:

- Extremely pure semiconductors without any impurities are known as Intrinsic semiconductors.
- These semiconductors are free from lattice defects
- Intrinsic semiconductor also called as pure semiconductors.

eg: Pure Germanium, Pure silicon.

* At absolute temperature, the valence band of intrinsic semiconductor is completely filled and the conduction band is completely empty. Therefore at absolute temperature, an intrinsic semiconductor behaves as an insulator and has zero conductivity
* As the temperature is gradually increased, the electron in the valence band get excited to conduction band. The excitation of electrons from the valence band leaves an equal number of holes in the valence band. Both the electrons in the conduction band and holes in the valence band serve as charge carriers and contribute to electrical conductivity.
* Thus intrinsic semiconductor act as insulator at low temperature and conductor at high temperature.



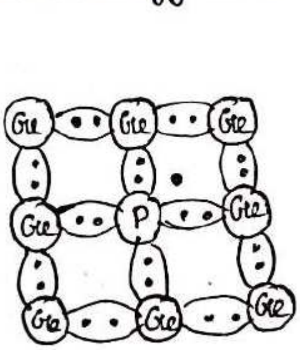
Extrinsic semiconductor:

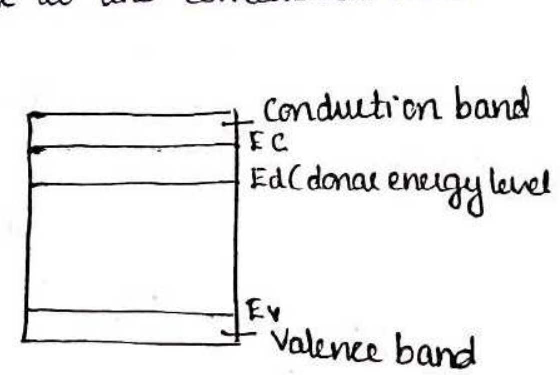
A semiconductor doped with impurities are called Extrinsic semiconductor. The process of adding impurities to a semiconductor is known as doping.

- Arsenic, Antimony, phosphorous, Gallium, Aluminium and Boron are common doping agent.
- Based on the type of impurity added, extrinsic semiconductor are classified into two types
  1) n-type semiconductor
  2) p-type semiconductor

N-type semiconductor:

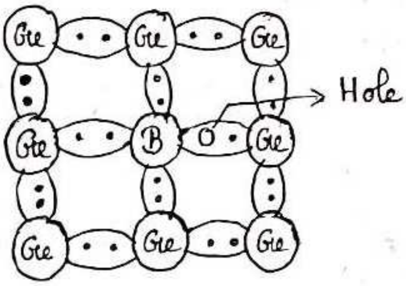
- when pentavalent impurity (arsenic, antimony, phosphorous) is added to a pure semiconductor is called n-type semiconductor.
- They are called donar impurities, because they donate free electrons to the semiconductor.
- when phosphorous is added with pure germanium, the four valence electrons of a pure semiconductor (Si or Ge) form covalent bond with the four valence electrons of pentavalent impurity atom (phosphorous). fifth electron finds no place in the covalent bond and left free. This act as conduction electron.
- By adding pentavalent impurity, large number of free electrons in the semiconductor are produced. Here the majority charge carriers are electrons, minority charge carriers are holes.
- The donated electron form a energy level is called donar energy level (Ed). The donar energy level is very close to the conduction band

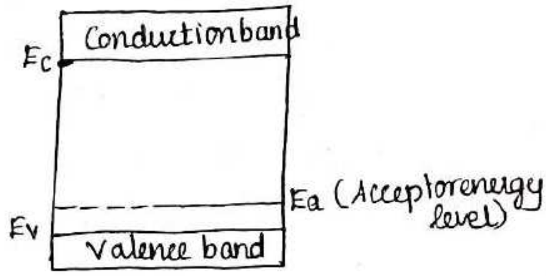




P- Type semiconductor :

- when trivalent impurity (Boron, Gallium, Indium) is added to a Pure semiconductor is called p type semi conductor
- when Boron is added with pure germanium, three valence electrons of the impurity atom form covalent bond of germanium atom. The fourth electron in germanium is unable to form a covalent bond due to lack of electron. Due to incomplete covalent bond, there is a short of one electron, a vacancy is formed and called as hole.
- The addition of trivalent impurity creates a large number of holes in the semiconductor. Here the majority charge carriers are holes and minority charge carriers are electrons
- Trivalent impurity are called acceptor impurity, because the holes can accept the electron. Here acceptor energy level (Ea) is created above the valence band





Fermilevel and its variation in temperature with intrinsic semiconductor

In an intrinsic semiconductor, the density of electron in the conduction band is equal to the density of holes in the valence band.

$$n = p$$

$$2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} e^{(E_F-E_C)/KT} = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} e^{(E_V-E_F)/KT} \quad -(1)$$

$$e^{(E_F-E_C)/KT} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2} e^{(E_V-E_F)/KT}$$

$$e^{(E_F-E_C-E_V+E_F)/KT} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

$$e^{2E_f - E_c - E_v/KT} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

Take log on both sides

$$\log_e e^{(2E_f - E_c - E_v)/KT} = \log_e\left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

$$\frac{2E_f - E_c - E_v}{KT} = \frac{3}{2}\log_e \frac{m_h^*}{m_e^*}$$

$$2E_f - E_c - E_v = \frac{3KT}{2}\log_e \frac{m_h^*}{m_e^*}$$

$$2E_f = (E_c + E_v) + \frac{3KT}{2}\log_e\left(\frac{m_h^*}{m_e^*}\right)$$

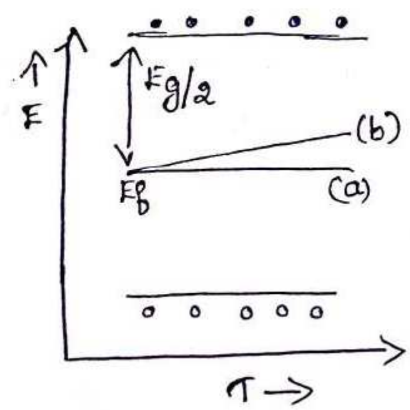
$$\boxed{E_f = \left(\frac{E_c + E_v}{2}\right) + \frac{3KT}{4}\log_e\left(\frac{m_h^*}{m_e^*}\right)} \quad -(2)$$

If $m_h^* = m_e^*$, $\log_e\left(\frac{m_h^*}{m_e^*}\right) = \log_e 1 = 0$

Eqn (2) becomes

$$\boxed{E_f = \frac{E_c + E_v}{2}}$$

Thus the fermilevel is located half way between the top of the valence band and bottom of the conduction band.

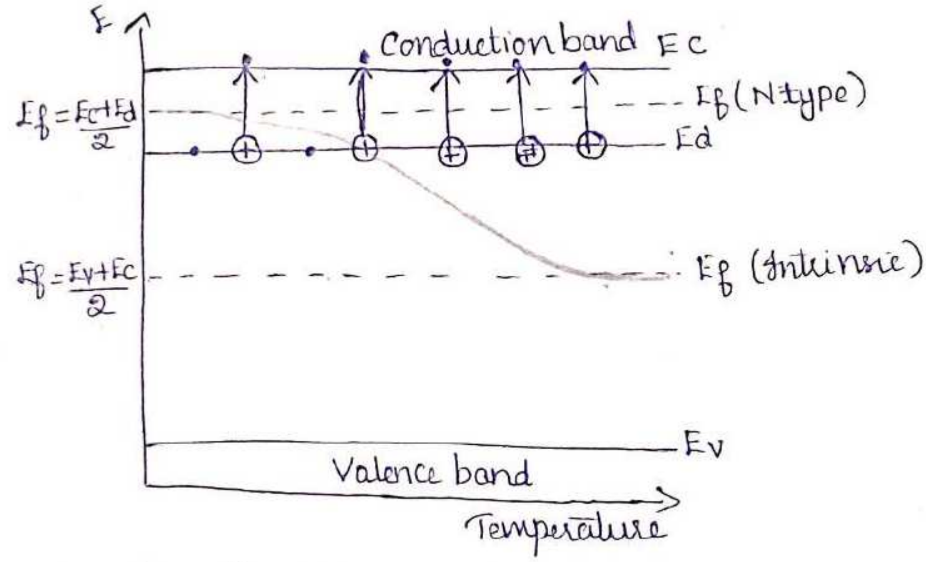


In real, $m_h^* > m_e^*$ the fermi level is just above the middle of energy gap & it rises slightly with increasing temperature.

Variation of fermilevel with temperature and impurity concentration in N-type semiconductor:

Fermi energy, $E_f = \frac{E_d + E_C}{2} + \frac{KT}{2} \log \left[\frac{N_d}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}} \right]$

At $T = 0K$, $\boxed{E_f = \frac{E_d + E_C}{2}}$

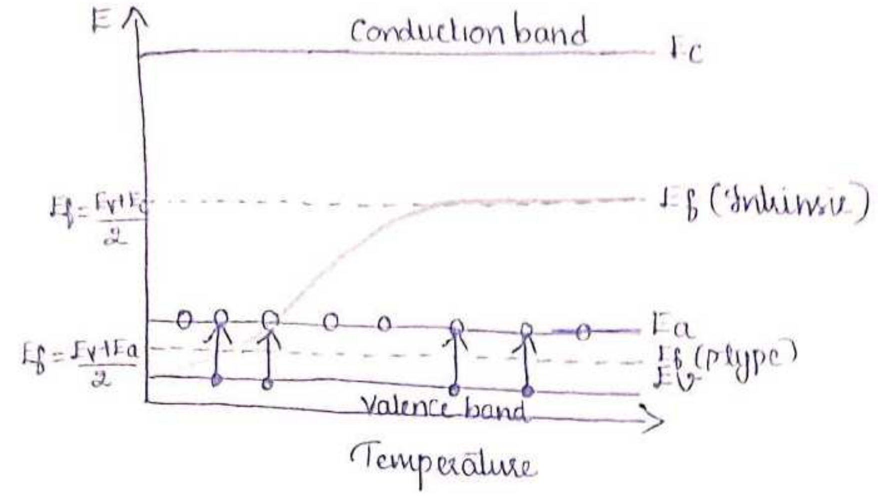


- At $T = 0K$, the fermi energy level lies exactly in the middle of the conduction band and donar level
- when temperature is increased, some electrons in the donar level may be shifted to conduction band and some holes will be created in donar level.
- At a particular temperature, all the electrons in donar level may be shifted to conduction band. The fermi level crosses the donar level and finally reaches the middle of the band gap E_f at higher temperature
- E_f – fermi level in intrinsic semiconductor.
- At higher temperature, n type semiconductor loses its extrinsic character and behaves as intrinsic semiconductor

Variation of fermi level with temperature and impurity concentration in P type semiconductor:

Fermi level $E_f = \frac{E_a + E_v}{2} - \frac{KT}{2} \log \left[\frac{N_a}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}} \right]$

At $T = 0K$, $E_f = \frac{E_a + E_v}{2}$



- At T=0K, fermi energy level lies exactly in the midway between the Valence band and acceptor level.
- when temperature is increased, some of the electrons in the valence band may be shifted to acceptor level by breaking up the covalent bonds and hence the fermilevel is shifted in the upward direction
- when temperature is increased beyond 0K, at a particular temperature, all the acceptor atoms are ionized, the fermi level crosses the acceptor level
- when temperature is increased further, due to generation of electron-hole pair by covalent bond breaking, fermi level moves towards intrinsic level E_f.
- At higher temperature, p type semiconductor loses its extrinsic character and behaves as an intrinsic semiconductor.

Carrier generation and recombination:

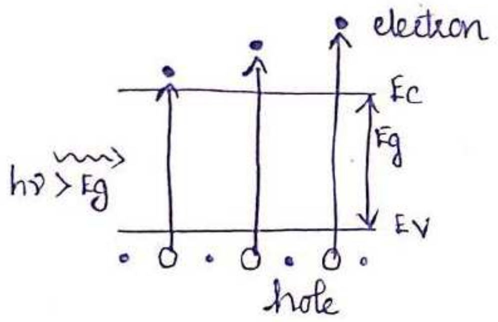
Carrier generation : It is the process in which electrons and holes are created

There are three types of carrier generation

1. Photogeneration
2. Phonon generation
3. Impact Ionisation

1. Photogeneration: • Here light of frequency ν falls on a semiconductor

• when the incident light energy greater than the bandgap of a semiconductor one electron can jump from valence band to the conduction band generating an electron hole pair

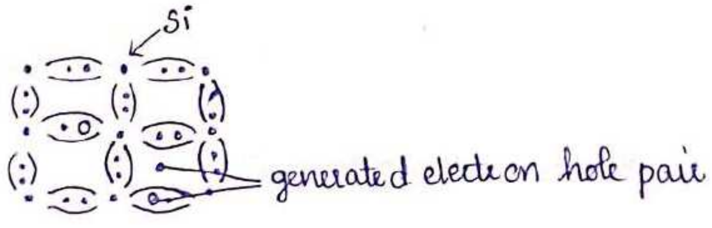


ii) phonon generation:

• It occurs when a semiconductor is under thermal excitation

• with the increase of temperature of a semiconductor, lattice vibrations increase which give rise to more phonons

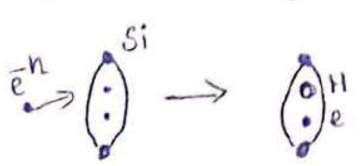
• Due to lattice vibration, covalent bonds in the semiconductor break down and electron hole pairs are generated



iii) Impact Ionization:

• In this process one energetic charge carrier will create another charge carrier

• when a semiconductor is under electric field, electrons gain energy from the applied electric field and hit other Si-atoms



• In this process, covalent bond breaks generating more carriers.

Recombination:

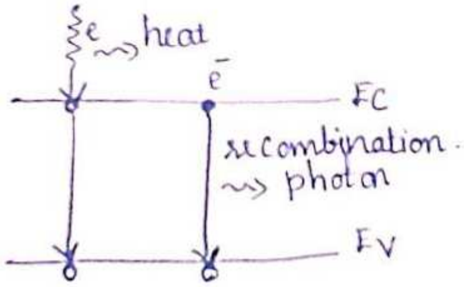
- In recombination, a pair of electron and hole gets recombined.
- when a free electron in the conduction band falls to valence band and recombines with a hole, it becomes a bound electron in the valence band

$$\text{Free } \bar{e}^n \text{ in Conduction band} + \text{hole} \xrightarrow[\text{recombination}]{} \text{Bound } \bar{e}^n \text{ in Valence band}$$

There are three types of recombination

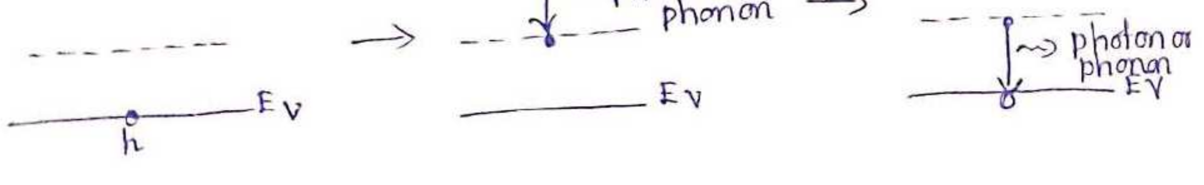
1. Radiative recombination:

- It takes place in direct band gap semiconductor (GaAs)
- In this process, electron from conduction band minimum falls to valence band maximum without changing its momentum, emitting photon (light). This is called direct recombination.
- Electrons from higher energy state of conduction band will come to the conduction band minimum releasing energy as heat



2. Schockley - Read Hall recombination:

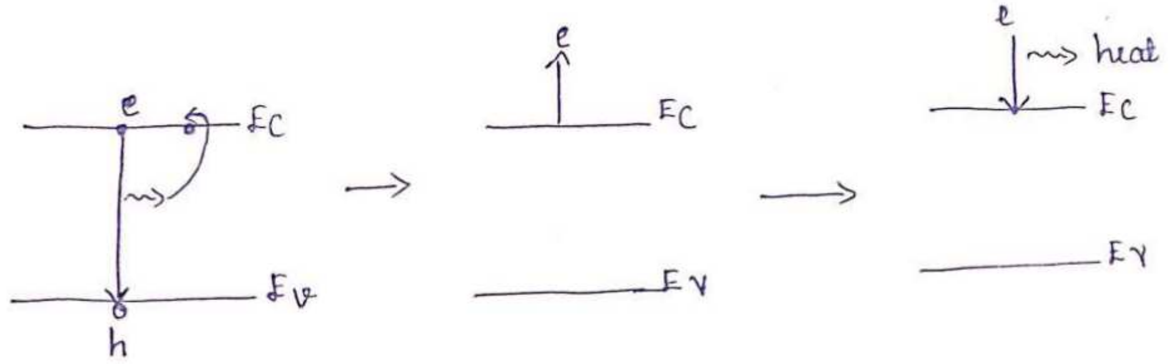
- This type of recombination takes place in impure semiconductor which has defect level.
- The defect level lies in the middle of the forbidden gap
- In this recombination, electron from conduction band minimum come to a defect level and release energy as photons or phonons. Then electron turns from defect level to valence band.



3. Auger recombination:

- Here three carriers are involved

- In this process, electron and hole recombine and energy is given to the third free electron in the conduction band
- Then the third excited electron comes back to conduction band minimum emitting energy as heat.
- It occurs for a heavily doped material.



Carrier transport

Mobility

- when an electrical field is applied in a semiconducting material, the charge carriers such as free electrons and holes attain drift velocity V_d.
- Drift velocity is proportional to the electric field strength

$$V_d \propto E$$
$$V_d = \mu E$$

$\mu \Rightarrow$ proportionality constant (Mobility)

Electrical conductivity:

- In semiconductors, electrons and holes are charge carriers.
- when electric field is applied, the electrons move with drift velocity V_{dn}

$$V_{dn} = \mu_n E$$

$\mu_n \Rightarrow$ Mobility of electron.

Drift current density $J_n = neV_{dn}$

$$J_n = \sigma_n E$$

$\sigma_n \Rightarrow$ conductivity of electron

$$\sigma_n = \frac{J_n}{E} = \frac{neV_{dn}}{E}$$

$$\sigma_n = \frac{ne\mu_n E}{E}$$

$$\boxed{\sigma_n = ne\mu_n}$$

similarly for holes $\boxed{\sigma_p = pe\mu_p}$ $\mu_p \rightarrow$ Mobility of holes

Total conductivity σ due to free electrons and holes

$$\begin{aligned} \sigma &= \sigma_n + \sigma_p \\ &= ne\mu_n + pe\mu_p \\ &= e(n\mu_n + p\mu_p) \end{aligned}$$

In intrinsic semiconductor, which contains same number of free electrons and holes, $n = p = n_i$

$$\begin{aligned} \sigma_i &= e(n_i\mu_n + n_i\mu_p) \\ &= en_i(\mu_n + \mu_p) \end{aligned}$$

Drift and Diffusion Current:

The net current flows across a semiconductor has two components:

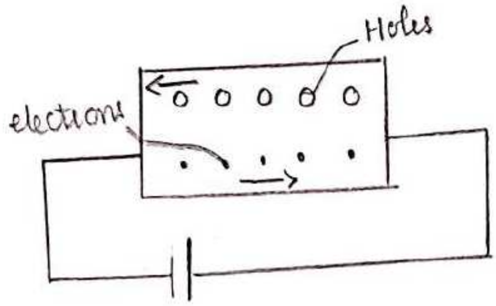
i) Drift Current

ii) Diffusion Current.

Drift Current:

Definition: The electric current produced due to the motion of charge carriers under the influence of an external electric field is known as drift current.

The charges carriers are forced to move in a particular direction due to the electric field. This is known as drift motion and the current is called drift current.



Force $F = eE$ — ① (E - Electric field)

$F = ma$ — ② (m - mass, a - acceleration)

acceleration $a = \frac{V_d}{\tau}$

$F = \frac{mV_d}{\tau}$ — ③

$\frac{mV_d}{\tau} = eE$

Drift Velocity $V_d = \frac{eE\tau}{m}$

$$\boxed{\mu = \frac{e\tau}{m}}$$ $\mu \Rightarrow$ Mobility

Current density $J = \sigma E$

Electrical conductivity $\sigma = \frac{ne^2\tau}{m}$

$J = \frac{ne^2\tau}{m} E$

$= \frac{n\,e\,e\tau E}{m}$

$J = ne\mu E$

For electrons , $J_n(\text{drift}) = ne\mu_n E$

For holes , $J_p(\text{drift}) = pe\mu_p E$

$n, p \rightarrow$ number of electrons and holes per unit volume

$\mu_n, \mu_p \rightarrow$ Mobility of electrons and holes

Total drift current density

$$J = J_n(\text{drift}) + J_p(\text{drift})$$

$$= ne\mu_n E + pe\mu_p E$$

$$= eE(n\mu_n + p\mu_p)$$

For intrinsic semiconductor, $n = p = n_i$

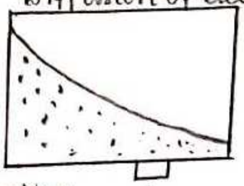
$$\boxed{J = eEn_i(\mu_n + \mu_p)}$$

Diffusion Current:

Definition: The non-uniform distribution of charge carriers creates a region of uneven concentration in the semiconductor

- The charge carriers move from the regions of higher concentration to the regions of lower concentration. This process is known as diffusion. The current is known as diffusion current.
- consider a semiconductor having concentration gradient of electrons $\left(\frac{dn}{dx}\right)$ within the semiconductor.
- The electrons diffuse from high concentration to low concentration due to concentration gradient.

Diffusion of electrons $\rightarrow$



Concentration gradient of e^-ns $\left(\frac{dn}{dx}\right)$

- Rate of flow of electrons through unit area $\propto -\left(\frac{dn}{dx}\right)$

$$= -D_n \frac{dn}{dx}$$

$D_n \rightarrow$ proportionality constant and it is known as diffusion coefficient of electrons

- $\left.\begin{array}{r}\text{Rate of flow of electrons through}\\ \text{unit area}\end{array}\right\} = -e \times -D_n \frac{dn}{dx}$

$$J_n(\text{diffusion}) = eD_n\left(\frac{dn}{dx}\right)$$

Similarly, the diffusion current density of holes is given by

$$J_p(\text{diffusion}) = -eD_p\left(\frac{dP}{dx}\right)$$

where $D_p \rightarrow$ diffusion coefficient of holes

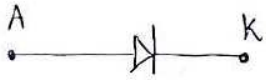
Total diffusion current density $= eD_n \frac{dn}{dx} - eD_p \frac{dP}{dx}$

P-N junction diode :

- A PN junction is formed from a piece of semiconductor (Germanium or Silicon) by doping P-type material (acceptor impurity) to one half and N type material (donar impurity) on other half side
- The plane dividing the two zones is called as junction (PN junction diod
- The immobile positive and negative ions set up the potential across the junction. This is called barrier potential (V_b)

symbol of P-N junction diode

- The ptype and N type regions are known as anode and cathode.



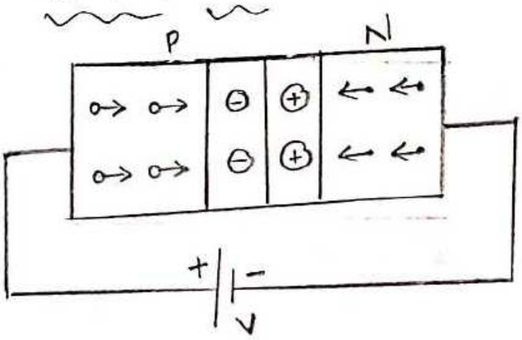
A - Anode
K - Cathode

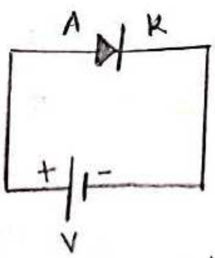
Working of P-N junction diode:

The behaviour of P-N junction diode is studied by applying a bias. The voltage is applied in two ways

(i) forward bias.
(ii) Reverse bias

forward bias



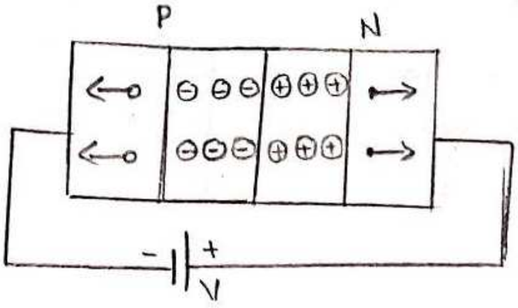


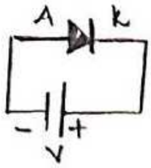
PN junction under forward bias

- when a positive terminal of a battery is connected to P-region and a negative terminal to N region, the PN junction is said to be forward biased
- when the junction is forward biased, the holes in the P-region are repelled by the negative terminal of the battery and they are forced to move towards the junction.
- This reduces the width of the ~~potential barrier~~ depletion region and barrier potential.
- when the applied voltage is greater than potential barrier V_B, then the majority carriers (holes in P-region and electrons in N region) cross the barrier
- Now, the current flow in the forward direction. The PN junction offers very low resistance under forward biased condition.

Reverse bias:

when the positive terminal of the battery is connected to N-region and negative terminal to the P-region, PN junction is said to be reverse biased



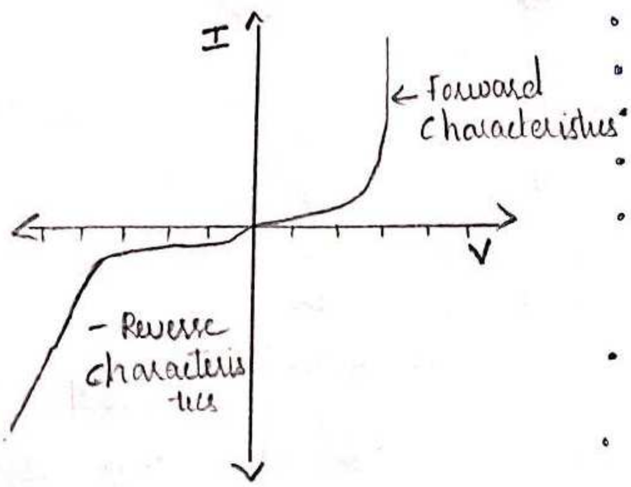


PN junction under reverse bias

- when the junction is reverse biased, the holes in the P region are attracted by the negative terminal of the battery
- Similarly the electrons in the N region are attracted by the positive terminal of a battery. This increases the width of the depletion region and barrier potential (V_B).
- The increased barrier potential makes it very difficult for the majority carriers to diffuse across the junction. Thus there is no current due to majority carriers.
- PN junction offers very high resistance under reverse biased condition
- In a reverse biased PN junction, a small amount of current flows through the junction due to minority carriers.

V-I characteristics of PN junction diode

- A graph is drawn between voltage applied across its terminals and the current flows through it.
- The complete graph consists of forward and reverse characteristics. The V-I characteristics of PN junction diode



Advantages:

- They are light in weight
- They are smaller in size and occupy less space
- They have longer life
- They are mechanically strong
- Their operating efficiency is very high.

Applications:

- They are used as rectifier elements in DC Power supplies
- They are used as signal diodes in communicatio circuits for modulation and demodulation
- They are used in clipper and clapper circuits.
- They are used as a switch in logic circuits and in computers.

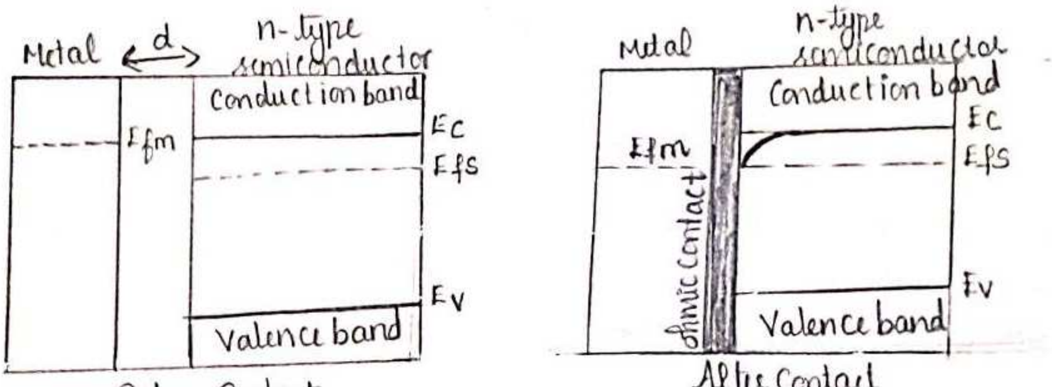
Ohmic Contact:

Definition: An ohmic contact is a non-rectifying contact which obeys ohm's law (ie) $V = IR$. The resistance of the ohmic contact should be low (ie) conductivity should be large.

Explanation:

Before Contact:

Let us consider a metal of fermi energy E_{fm} and n type semiconductor of fermi energy E_{fs} and they are seperated by a distance (d), The fermi energy (E_{fm}) of metal lies above that of the fermi energy of the semiconductor (E_{FS}).



Before Contact   After Contact

After Contact:

Now when the metal and n-type semiconductor are made in contact with each other, then the energy bands of n type semiconductor bend downwards near the contact. The magnitude of the band bending and its extension is very small.

As a result there is no potential barrier between the metal and the semiconductor and the resistivity becomes very low (or) almost zero. Therefore the electrons can flow freely throughout the contact and the current increases at the ohmic contact.

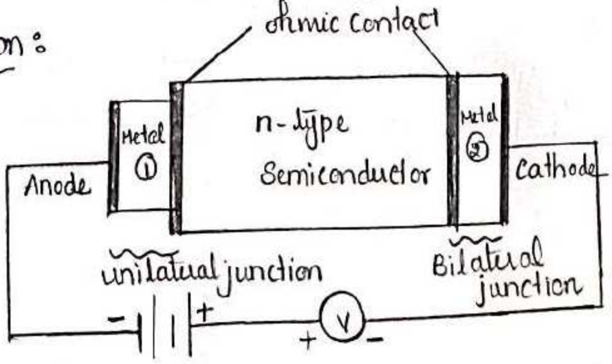
Example: Schottky diode is a example, which behaves as a ohmic contact if the impurity concentration is very high.

Schottky diode:

Principle: Schottky diode is a unilateral device, in which current flows from metal to semiconductor (n-type) in one direction.

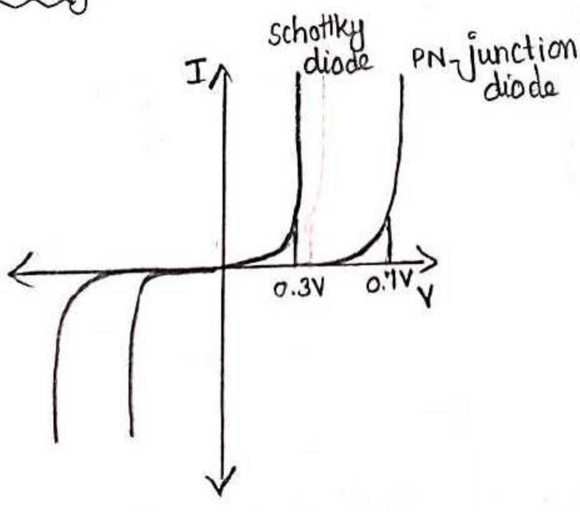
Symbol: The symbol of schottky diode is

Construction:



- Schottky diode also called as schottky barrier diode (or) hot carrier diode is formed by metals such as Chromium, Aluminium Molybdenum, platinum gold etc and n type semiconductor (silicon).
- It is made of two junctions
  1. A unilateral metal-semiconductor junction
  2. A bilateral metal - semiconductor junction
- Schottky diode act as a terminal device in which metal (1) and the semiconductor, formed at one end act as Anode with unilateral junction and metal (2) and semiconductor formed at the other end act as Cathode with bilateral junction.
- At the ohmic contact, the potential barrier is almost zero. The potential decrease with increase in temperature (or) doping of a semiconductor.

Working:



- The diode is forward biased
- The voltage applied to the diode, is slowly increased in steps of 0.1V, 0.2V etc and current is measured
- The V-I characteristics of schottky diode is shown in figure along with the V-I characteristics curve for p-n junction diode for comparison.

- In schottky diode, forward Voltage drop [0.3V] is Very less, when compared to p-n junction diode the forward voltage drop [0.7V].
- For a schottky diode, the current increases enormously even for a small applied Voltage
- The current in the schottky diode is due to 3 Components
  (I) Diffusion Current (I_D)
  (II) Tunneling Current (I_T)
  (III) Thermoionic emission Current (I_{TE})

$$\therefore \text{Total Current } I_{Total} = I_D + I_T + I_{TE}$$

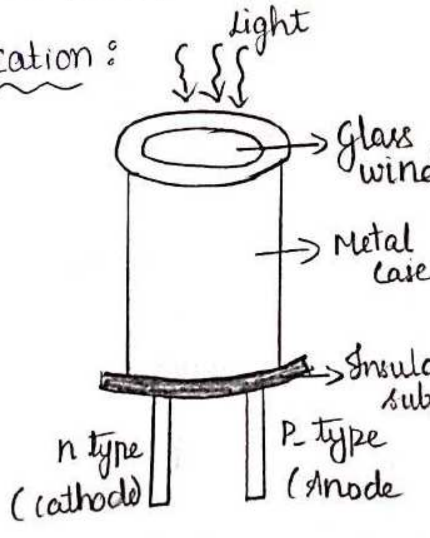
Applications

- It have low voltage drop, they are used in high switching system efficiency Component
- They are used in Bipolar Junction Transistor (BJT)
- They are also used in Voltage clamping and voltage rectifying applications
- schottky diode play a Vital role in GaAs circuits and high power applications

Photo current in PN Junction diode: (Photodiode)

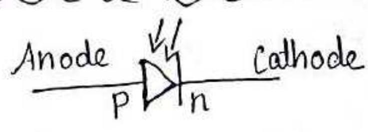
Principle: when a p-n junction diode is exposed to light (photons), under reverse bias, it produces electron and hole pairs. Due to the flow of these charge carriers, it produces a reverse current.

Fabrication:



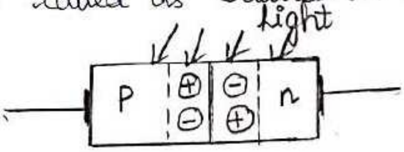
- The photodiode is made up of p and n type materials with a small glass window on the top for the light to pass through it and strike the p-n junction
- The p-n junction mounted on the insulated substrate is sealed inside the metal case for safety.

Symbol of photodiode:



Operation:

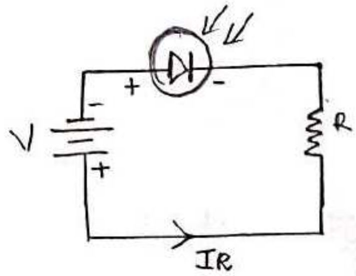
- The photodiode is reverse biased
- when no light is incident on the pn junction of the photodiode, then no charges are created and therefore no current (or) a very little reverse current (I_R) flows through the circuit. This current is called dark current.
- Now, when light is made to incident on the p-n junction, then each photon creates an electronhole pair at the junction
- These photo-generated charge carries move towards the potential and constitute a current known as photocurrent
- The photo current increases with the increase in intensity of light falling on the p-n junction
- The current reaches a maximum and is called as Saturation current.



Modes of operation:

The photodiode operates in 3 Modes

1. Photo voltaic Mode
2. Photo conductive Mode
3. Avalanche diode Mode.



Types

Based on the modes of operation, there are different types of photodiode

1. PIN [P type - Intrinsic - n type] photodiode
2. APD [Avalanche pin photodiode]
3. Schottky photodiode
4. Solar cell etc.

Advantages

1. They have a long life period
2. It is light in weight
3. It is very compact (small in size)
4. Noise of the photodiode is very less
5. The response of the photodiode is wide spectral.

Disadvantage:
1. Dark Current is temperature dependent
2. Thermal stability is very poor
3. Amplification is compulsorily required for better performance
4. Efficiency is poor in rainy / winter season

Applications:

1. They are used in charge-Couple devices (CCD), photoconductors and Photomultiplier tubes.
2. They have wide applications in clocks, radio, camera, street lights etc
3. They are used in optical communication systems
4. In medicine, they are used in Computed tomography (CT) instrument.

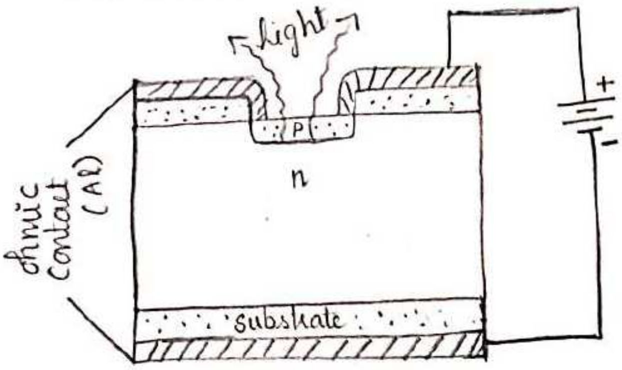
Light Emitting Diode (LED)

Definition: LED is a semiconductor p-n junction diode which converts electrical energy to light energy under forward biasing. It emits light in both visible and IR region.

Types of LED: There are two types of LED
1) Planar (or) surface emitting LED
2) Dome shaped LED.

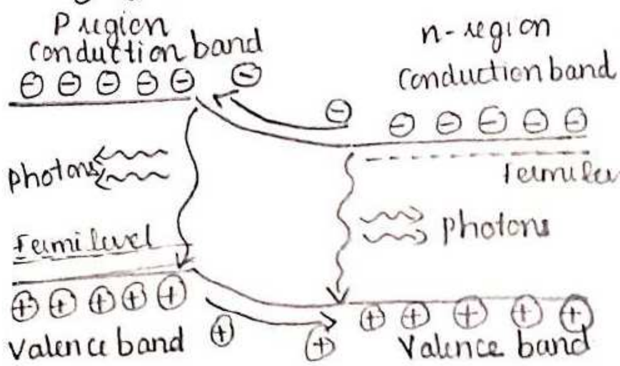
Principle:
- Injection luminescence is the principle used in LED's
- when LED is forward biased, the majority charge carriers moves from p to n and similarly from n to p region and becomes excess minority carriers.
- Then these minority charge carriers diffuse through the junction and recombines with the majority charge carriers in n and p region respectively to produce light.

Construction:



- The surface emitting LED is shown in figure
- Here p-n junction is formed by diffusion or epitaxial techniques
- The p-n junction is made by doping silicon with GaAs crystal. Since silicon can act both as donor (when it replaces Gallium) and acceptor (when it replaces arsenide)
- A p-n junction is formed on GaAs substrate such that p layer is formed by diffusion on n layer.
- In order to increase the probability of radiative recombination, the thickness of n layer is higher than the thickness of p layer
- ohmic Contacts are made with the help of Aluminium
- Top layer of p material is left uncovered, for the emission of light
- proper biasing can be applied at the ohmic contact.
- The whole p-n junction is surrounded by plastic material, so that the losses due to reflection can be minimized.

Working



- The diode is forward biased
- Due to forward bias, the majority charge carriers from n and p regions cross the junction and become minority charge carrier (ie) Electron which are majority charge carriers in n region cross the junction and go to p region and become minority carriers in p region
- similarly, holes which are majority charge carrier in 'p' region cross the junction and go to 'n' region and become minority charge carrier in n region

- By the similar process, excess of minority carriers are injected in both p and n region s is called minority carrier injection.
- Now if the biasing voltage is further increased, these excess minority carriers diffuse away from the junction and they directly recombine with the majority (ie) the electrons, which are excess minority carriers in 'p' region recombines with the holes which are the majority carriers in 'p' regions and emit light
- similarly holes which are the excess minority carriers in n region recombine with the electrons which are majority carriers in 'n' region and emits light.
- Therefore electron hole recombination process occur more and more and thereby light is emitted through the top layer of p material which is left uncovered.

Advantages:
1. They are smaller in size
2. The cost is very low
3. It has long life time
4. LED's are available in different colours at low cost
5. It operates at very low voltage.
6. Its intensity can be controlled easily
7. It can be operated at wide range of temperature (0 – 70°C)
8. Dome shaped LED has less scattering loss

Disadvantage:

1. power output is low
2. Intensity is less than laser
3. The light cannot control through longer distance.
4. The light output is incoherent and are not in phase.
5. The light will not have directionality.

Dome shaped LED

- In planar LED, the reflection loss is more because most of the emitted light strikes the material interface at an angle greater than the critical angle. So light gets totally internally reflected will not come out of the interface Thus the light is lost.
- This loss of light due to internal reflection can be minimized in two ways

(i) By making p material in the shape of hemispherical dome. So angle at which the light strikes the interface can be made less than critical angle and hence the light will not lost by total internal reflection.

(ii) By covering the p-n junction by a plastic medium of higher refractive index in the shape of hemispherical dome, total internal reflection can be reduced. This LED is used for commercial purpose. Hence, usually dome shaped hemispherical LED is preferable than planar LED.

Classification of LED :

LED materials are classified into

i) Inorganic LED

ii) Organic LED

Inorganic materials: (group III or V compound semiconductors). Mostly made up of direct bandgap semiconductors (Eg: GaAs)

- AlGaAs : Indirect bandgap semiconductor directly grown on GaAs substrates in which Al < 0.45. used in the IR region or red region of the spectrum
- InAlGaP : Covers the wider region in the visible spectrum from red to green
- InGaN : Covers blue, green and violet region
- GaAsP : Covers middle region of the visible region to the IR region of the spectrum

Different types of LED :

Based on wavelength, LED is classified as

a) Ultraviolet LED (240 nm to 360 nm)

b) Near ultraviolet to green (395 nm to 530 nm)

c) yellow green to red (565 nm to 645 nm)

d) Deep red to near Infrared (660 nm to 900 nm)

a) Ultraviolet LED : output power is 100mW and mainly used in water disinfection and Bio/medical application. The wavelength is as short as 280 nm.
For eg: GaN or AlGaN with wavelengths 360 nm or longer.

b) Near ultraviolet to green blue LEDs : → (450 to 475 nm), green LEDs (520 to 530 nm)
eg: InGaN

c) yellow green to red (565 nm to 645 nm), predominately used in traffic light (yellow) - 590 nm, red light used in traffic light (625 nm) eg: Aluminium Indium Gallium Phosphate

d) Deep red to near red (660 nm to 900nm) Infrared remote control Night Vision illumination (660 - 680 nm) eg: Aluminium Gallium Arsenide

Organic LED : (OLED)

- Organic LED (Organic Light Emitting Diode) is a new type of electronic device which emits light, consuming less energy.
- Organic LEDs are generally made up of many layers with organic molecules of different conductivity levels, ranging from insulators to conductors.

Principle :

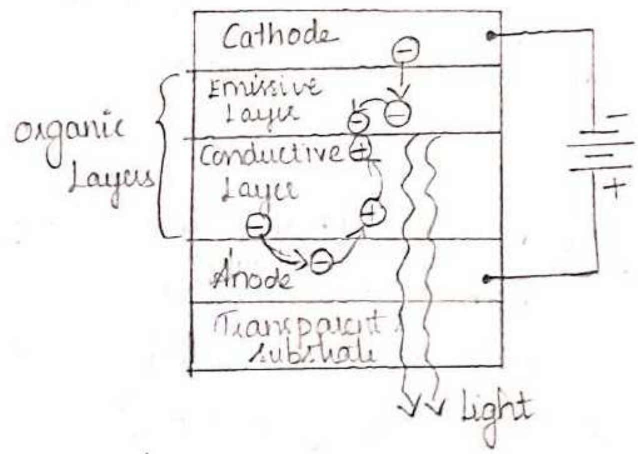
An electron moves from the cathode to the emissive layer and the hole moves from the anode to the conductive layer and they recombine to produce photons. This is the principle used to emit light in OLED

Fabrication :

The two layer OLED consists of a cathode and an anode, in between we have two organic layers

1. Emissive layer
2. Conductive layer, made up of different conductivities

- All the layers are grown over a transparent substrate, through which the light has to be emitted.
- Necessary biasing is given for the OLED.



Working :

- Voltage is applied across the OLED
- Due to the applied voltage, the cathode gives electrons to the emissive layer
- The anode withdraws an electron from the conductive layer and creates a hole in the conductive layer.
- Soon, the emissive layer becomes rich in negatively charged particles (electrons) and the conductive layer becomes rich in positively charged particles (holes)

- Now, due to the electrostatic forces between these electrons and holes, they come closer and recombine with each other
- In OLED, the recombination occurs closer to the emissive layer, because in Organic semiconductors, holes moves faster than electrons.
- Thus, the recombination of electrons and holes produce light and is emitted through the transparent substrate.

Advantages:

OLED's have more advantages, when compared to CRT, LCD and LEDS. Some of them are as follows,

1. OLED is very thin and more flexible
2. They are light in weight
3. Light emission is brighter than normal LED's.
4. The conductive & emissive layers can be increased to increase the efficiency of OLED
5. OLED's do not require backlighting like LCD's
6. They have large field view [About 170°]

Disadvantages:

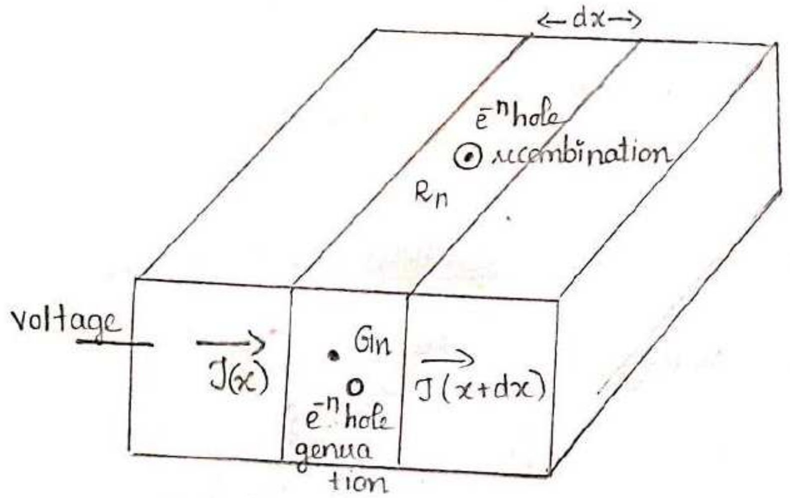
1. Cost of manufacturing is high
2. OLED's can be easily damaged when water falls on it.
3. Blue OLED have less lifetime, when compared to Red OLED.
4. Maintenance cost also increases due to different life time.

Applications:

1. OLED's are widely used in cell phones, digital cameras etc.
2. They are used in TV screens, computer monitors.
3. They are nowadays used in Automotive dash boards, backlight in cars
4. OLEDs are used in flexible display boards, for displaying video's in real time
5. In future, news papers also may have OLED displays to refresh us with the latest or breaking news.

Continuity Equation:

- Continuity equation is defined as the change in carrier density over a period of time that can be expressed as the difference between the Incoming and outgoing flux of carriers plus carrier (electron-hole) generation and minus electron hole recombination.



- Let us consider a block of semiconductor material with the cross sectional area A. Let $J(x)$ be the current density flowing along the x direction.
- Now consider a small elemental box of thickness dx, through this current density $J(x)$ enters and current density $J(x+dx)$ leaves
- Now in the region dx, due to flow of current, electron hole generation (G_n) and electron hole recombination (R_n) takes place.

This can be expressed in mathematical terms

$$\left(\frac{dn}{dt}\right) A\,dx = \left[\frac{J_n(x)}{-q} - \frac{J_n(x+dx)}{-q}\right] + (G_n - R_n) A\,dx \quad \text{— (1)}$$

where,

$\frac{dn}{dt}$ → rate of change of electron concentration over a period of time

$\frac{J_n(x)}{-q}$ → Current density per unit area (or) the number of electrons flowing in the box of Area A.

$\frac{J_n(x+dx)}{-q}$ → The number of electrons flowing out of the box of area A.

G_n → The number of electrons generated within the Volume $A\,dx$

R_n → The number of electrons recombined within the Volume $A\,dx$

Divide equation (1) by $A\,dx$

$$\frac{dn}{dt} = \frac{1}{q}\left[\frac{J_n(x+dx) - J_n(x)}{A\,dx}\right] + (G_n - R_n) \quad -(2)$$

where, $\dfrac{J_n(x+dx) - J_n(x)}{A\,dx} = \dfrac{dJ_n}{dt}$

$$\frac{dn}{dt} = \frac{1}{q}\left[\frac{dJ_n}{dt}\right] + (G_n - R_n) \quad -(3)$$

for electons

$$\frac{dp}{dt} = -\frac{1}{q}\left[\frac{dJ_p}{dt}\right] + (G_p - R_p) \quad -(4)$$

for holes

The total current density is the sum of drift current & diffusion current

$$J_n = qn\mu_n E + qD_n\frac{dn}{d\cancel{t}} \quad -(5) \quad \text{for electons}$$

$$J_p = qp\mu_p E - qD_p\frac{dp}{d\cancel{t}} \quad -(6) \quad \text{for holes}$$

Differentiate eqn (5) & (6) wrt time

$$\frac{dJ_n}{dt} = q\left[\mu_n n\frac{dE}{dt} + \mu_n E\frac{dn}{dt} + D_n\frac{d^2n}{dt^2}\right] \quad -(7)$$

$$\frac{dJ_p}{dt} = -q\left[-\mu_p p\frac{dE}{dt} - \mu_p E\frac{dp}{dt} + D_p\frac{d^2p}{dt^2}\right] \quad -(8)$$

Substitute eqn (7) & (8) in (3) & (4).

$$\frac{dn}{dt} = \left[\mu_n n\frac{dE}{dt} + \mu_n E\frac{dn}{dt} + D_n\frac{d^2n}{dt^2}\right] + (G_n - R_n)$$

$$\frac{dp}{dt} = \left[-\mu_p p\frac{dE}{dt} - \mu_p E\frac{dp}{dt} + D_p\frac{d^2p}{dt^2}\right] + (G_p - R_p)$$

The above equations are called called continiuty equations for electons and holes.