Intrinsic Semiconductors

- In semiconductors and insulators, when an external electric field is applied the conduction is not possible as there is a forbidden gap, which is absent in metals.

- In order to conduct, the electrons from the top of the full valence band have to move into the conduction band, by *crossing the forbidden gap*.

- The field that needs to be applied to do this work will be extremely large.

Eg: Silicon where the forbidden gap is about 1 eV.
The distance between these two locations is about 1 Å (10^{-10} m).

➢ A field gradient of approximately 1V/ (10^{-10} m) = 10^{10}Vm^{-1} is necessary to move an electron from the top of the valence band to the bottom of the conduction band.

✓ The other possibility by which this transition can be brought about is by *thermal excitation*.

✓ At room temperature, the thermal energy that is available can excite a limited number of electrons across the energy gap. This limited number accounts for semi-conduction.

✓ When the energy gap is large as in diamond, the number of electrons that can be excited across the gap is extremely small.

✓ In intrinsic semiconductors, the conduction is due to the intrinsic processes (*without the influence of impurities)*.

✓ A pure crystal of silicon or germanium is an intrinsic semiconductor. The electrons that are excited from the top of the valence band to the bottom of the conduction band by thermal energy are responsible for conduction.

✓ The number of electrons excited across the gap can be calculated from the Fermi-Dirac probability distribution.

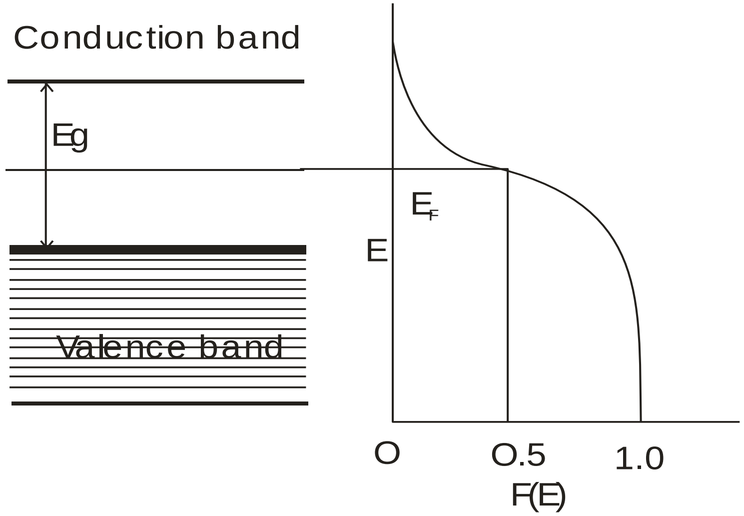
$$f(E) = \frac{1}{1+\{exp[E - E_F)/k_B T]\}}$$

- The Fermi level E_F for an intrinsic semiconductor lies midway in the forbidden gap.

- The probability of finding an electron here is 50%, even though energy levels at this point are forbidden.

- Then $(E-E_F)$ is equal to $E_g/2$, where E_g is the magnitude of the energy gap.

➢For a typical semiconductor like silicon, Eg = 1.1 eV, so that $(E–E_F)$ is 0.55 eV, which is more than twenty times larger than the thermal energy k_BT at room temperature (=0.026 eV).



The Fermi level in an intrinsic semiconductor lies in the middle of the energy gap.

- The probability $f(E)$ of an electron occupying energy level E becomes $f(E) = \exp(-E_g / 2k_BT)$.

- The fraction of electrons at energy E is equal to the probability $f(E)$. The number n of electrons promoted across the gap, $n = N \exp(-E_g / 2k_BT)$

where N is the number of electrons available for excitation from the top of the valence band.

- The promotion of some of the electrons across the gap leaves some vacant electron sites in the valence band. These are called *holes*.

- *An intrinsic semiconductor contains an equal number of holes in the valence band and electrons in the conduction band*, that is $n_e = n_h$.

- Under an externally applied field, the electrons, which are excited into the conduction band by thermal means, can accelerate using the vacant states available in the conduction band.

- At the same time, the holes in the valence band also move, but in a direction *opposite* to that of electrons.
- The conductivity of the intrinsic semiconductor depends on the concentration of these charge carriers, n_e and n_h.
- In the case of metals, the drift velocity acquired by the free electrons in an applied field.
- The mobility of conduction electrons and holes, μ_e and μ_h, as the drift velocity acquired by them under unit field gradient.

The conductivity σ of an intrinsic semiconductor as

$$\sigma_i = n_e e \mu_e + n_h e \mu_h$$

where e is the electronic charge, n_e and n_h are concentrations of electrons and holes per unit volume.

Fermi level

The number of free electrons per unit volume in an intrinsic semiconductor is

$$n = 2\left(\frac{2\pi m_e^* kT}{\mathrm{h}^2}\right)^{3/2} \exp\left(\frac{E_F - E_c}{kT}\right)$$

The number of holes per unit volume in an intrinsic semiconductor is

$$p = 2\left[\frac{2m_h^* \pi kT}{h^2}\right]^{3/2} .\exp\left(\frac{E_V - E_F}{KT}\right)$$

Since n = p in intrinsic semiconductors.

$$2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}\exp\left(\frac{E_F - E_c}{kT}\right) = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}\exp\left(\frac{Ev - E_F}{kT}\right)$$

$$\left(\boldsymbol{m_e^*}\right)^{3/2}\exp\frac{\left(\boldsymbol{E_F - E_C}\right)}{\boldsymbol{kT}} = \left(\boldsymbol{m_h^{*3/2}}\right)\exp\left[\frac{\boldsymbol{Ev - E_F}}{\boldsymbol{KT}}\right]$$

$$\boldsymbol{e}^{2\boldsymbol{E_F}/\boldsymbol{kT}} = \left(\frac{\boldsymbol{m_h^*}}{\boldsymbol{m_e^*}}\right)^{3/2}\exp\left(\frac{\boldsymbol{E_v + E_c}}{\boldsymbol{kT}}\right)$$

Taking log on both sides,

$$\frac{2E_F}{kT} = \frac{3}{2}log_e\left(\frac{m_h^*}{m_e^*}\right) + log_e\left[exp\left(\frac{E_v + E_c}{kT}\right)\right]$$

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

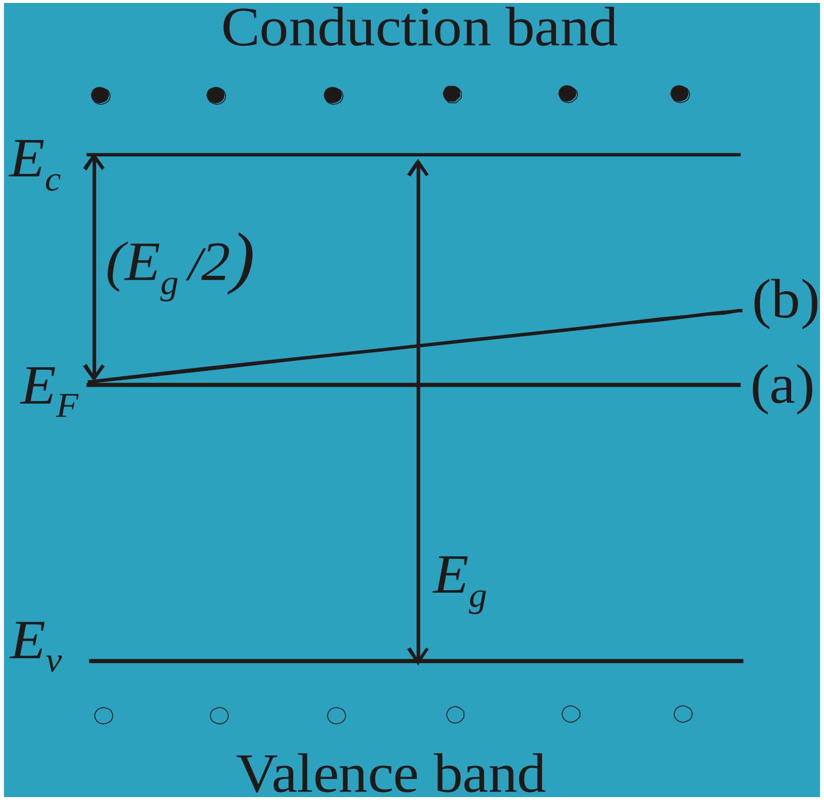
or $E_f = \frac{3kT}{4}\log_e\left(\frac{m_h^*}{m_e^*}\right) + \left(\frac{E_v + E_c}{2}\right)$

If we assume that, $\boxed{m_e^* = m_h^*}$

$$\boxed{E_F = \left(\frac{E_v + E_c}{2}\right)}$$

[since $\log_e 1 = 0$]

Thus, the Fermi level is located half way between the valence and conduction band and its position is independent of temperature. Since $m_h{}^*$ is greater than $m_e{}^*$, E_F is just above the middle, and rises slightly with increase in temperature



Position of Fermi level in an intrinsic semiconductor at various temperatures

(a) at T = 0 K, the Fermi level in the middle of the forbidden gap

(b) as temperature increases, E_F shifts upwards

EXTRINSIC SEMICONDUCTOR

In an extrinsic semiconducting material, the charge carriers originate from impurity atoms added to the original material is called impurity [or] extrinsic semiconductor.

- This Semiconductor obtained by doping TRIVALENT and PENTAVALENT impurites in a TETRAVALENT semiconductor. The electrical conductivity of pure semiconductors may be changed even with the addition of few amount of impurities.

DOPING

The method of adding impurities to a pure semiconductor is known as DOPING, and the impurity added is called the dopping agent(Ex-Ar,Sb,P,Ge and Al).

The addition of impurity would increases the no. of free electrons and holes in a semiconductor and hence increases its conductivity.

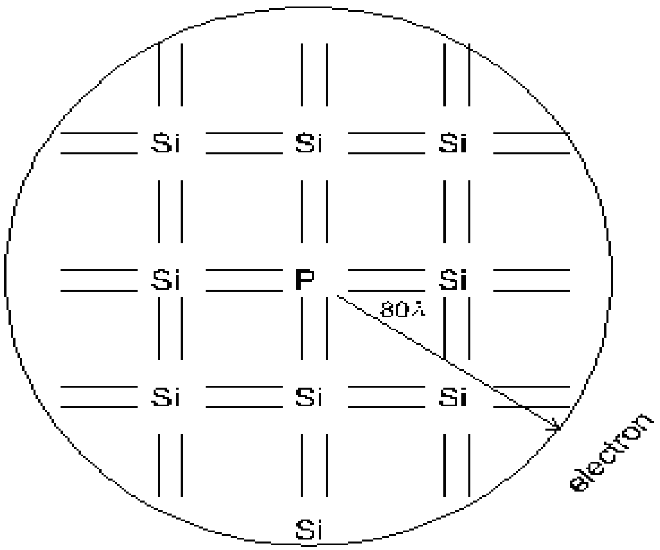
SORTS OF SEMICONDUCTOR according to ADDITION OF IMPURITIES

n-type semiconductor

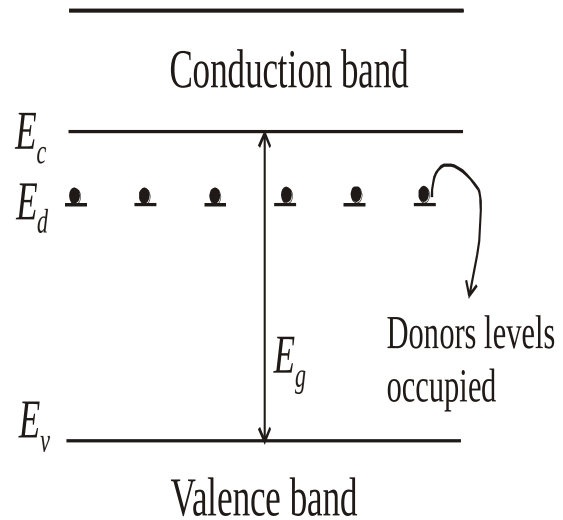
p-type semiconductor

N – type semiconductor

When pentavalent impurity is added to the intrinsic semiconductors, n type semi conductors are formed.



n - type semiconductor



At T = 0K

❖When small amounts of pentavalent impurity such as phosphorous are added during crystal formation, the impurity atoms lock into the crystal lattice[see above Fig).

❖ Consider a silicon crystal which is doped with a fifth column element such as P, As or Sb.

❖ Four of the five electrons in the outermost orbital of the phosphorus atom take part in the tetrahedral bonding with the four silicon neighbours.

❖ The *fifth electron* cannot take part in the discrete covalent bonding. It is *loosely* bound to the parent atom.

❖It is possible to calculate an orbit for the fifth electron assuming that it revolves around the positively charged phosphorus ion, in the same way as for the "1s" electron around the hydrogen nucleus.

❖ The electron of the phosphorus atom is moving in *the electric field of the silicon crystal* and not in free space, as is the case in the hydrogen atom.

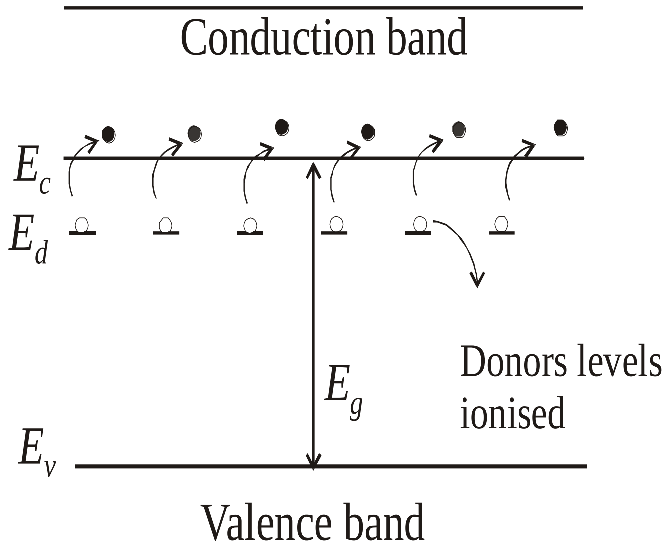
❖ This brings in the dielectric constant of the crystal into the orbital calculations, and the radius of the electron orbit here turns out to be very large, about 80 Å, as against 0.5 Å for the hydrogen orbit. Such a large orbit evidently means that the fifth electron is almost free and is at an energy level close to the conduction band.

❖At OK, the electronic system is in its lowest energy state, all the valence electron will be in the valence band and all the phosphorous atoms will be un-ionised.

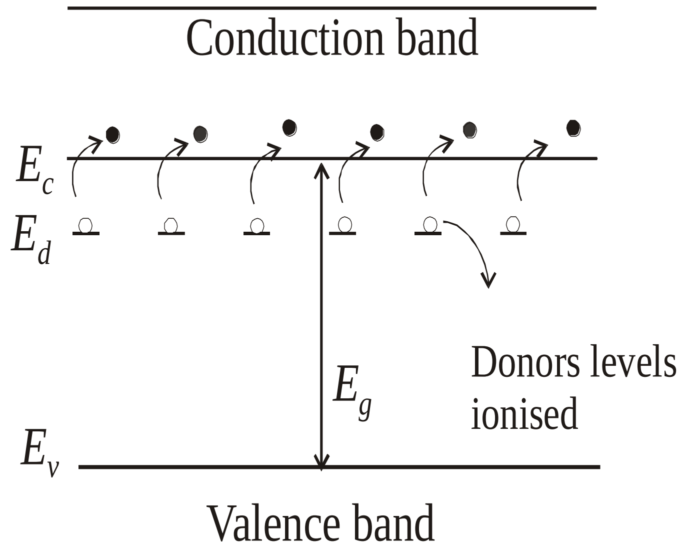
❖ The energy levels of the donor atoms are very close to the conduction band.

❖ In the energy level diagram, the energy level of the fifth electron is called donor level. The donor level is so close to the bottom of the conduction band.

❖ Most of the donor level electrons are excited into the conduction band at room temperature and become majority charge carriers.



At T > 0K



At T = 300K

If the thermal energy is sufficiently high, in addition to the ionization of donor impurity atoms, breaking of covalent bonds may also occur thereby giving rise to generation of electron hole pair.

Fermi energy

The Fermi energy for n – type semiconductor is given by

$$E_F = \frac{(E_c + E_d)}{2} + \frac{kT}{2}\ln\left[\frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}}\right]$$

At 0 K,

$$E_F = \frac{(E_c + E_d)}{2}$$

Variation of Fermi level with temperature

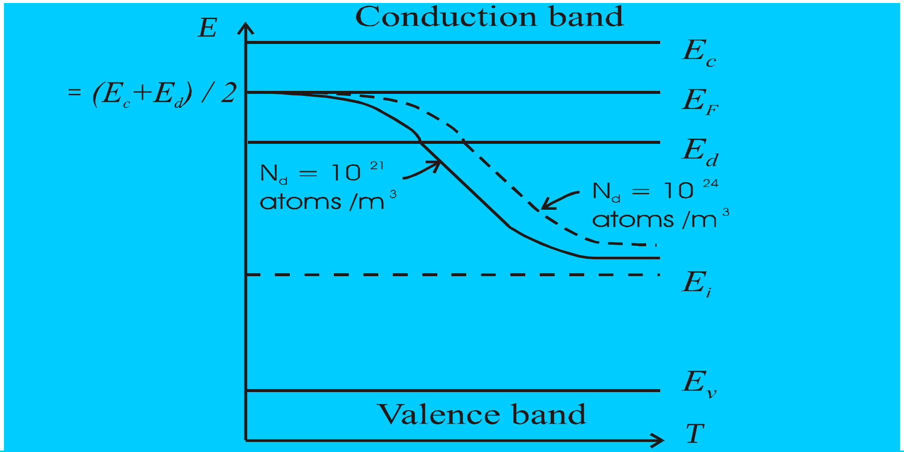
The Fermi energy is given by,

$$\boldsymbol{E_F = \left(\frac{E_d + E_c}{2}\right) + \frac{kT}{2}\ln\frac{N_d}{2\left[\frac{2\pi m_e * kT}{h^2}\right]^{3/2}}}$$

Let

$$2\left[\frac{2\pi m_e * kT}{h^2}\right]^{3/2} = N_x$$

$$= \left(\frac{E_d + E_c}{2}\right) - \frac{kT}{2} ln\left(\frac{N_d}{N_x}\right)^{-1}$$



Variation of Fermi level with donor concentration with temperature

As T increases, Fermi level drops. Also for a given temperature the Fermi level shift upward as the concentration increases.

We can say that E_F decreases slightly with increase in temperature.

As the temperature is increased, more and more donor atoms are ionized. For a particular temperature all the donor, atoms are ionized.

Further increase in temperature results in generation of electron-hole pairs due to the breaking of covalence bonds and the material tends to behave in intrinsic manner. The Fermi level gradually moves towards the intrinsic Fermi level E_i .

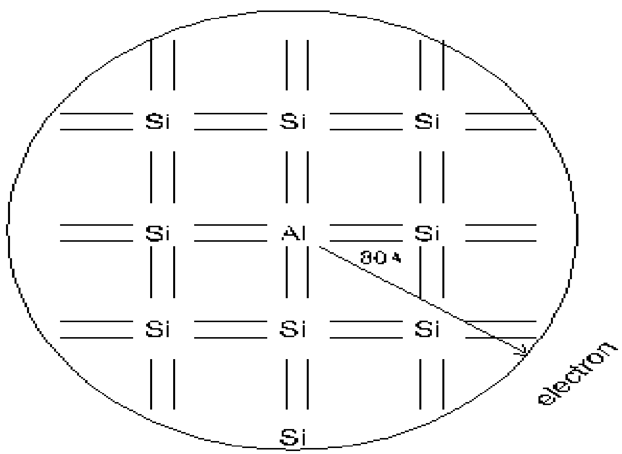
P -Type Semiconductor

When trivalent impurity is added to intrinsic semiconductor, P type semi conductors are formed.

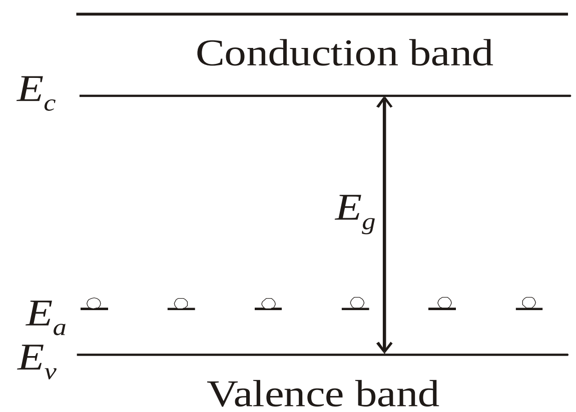
Al has three electrons in the outer orbital. While substituting for silicon in the crystal, it *needs an extra- electron* to complete the tetrahedral arrangement of bonds around it.

➢The extra electron can come only from one of the neighbouring silicon atoms, thereby creating a vacant electron site (hole) on the silicon.

➢ The aluminium atom with the extra electron becomes a negative charge and the hole with a positive charge can be considered to resolve around the aluminium atom, leading to the same orbital calculations as above T.



p - type semiconductor



At T = 0K

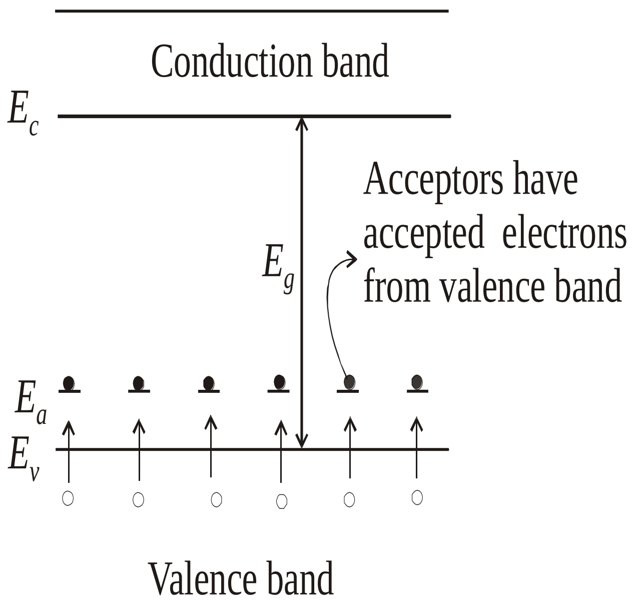
- Since the trivalent impurity accepts an electron, the energy level of this impurity atom is called acceptor level. This acceptor level lies just above the valence bond.

- Even at relatively low temperatures, these acceptor atoms get ionized taking electrons from valence bond and thus giving to holes in the valence bond for conduction.

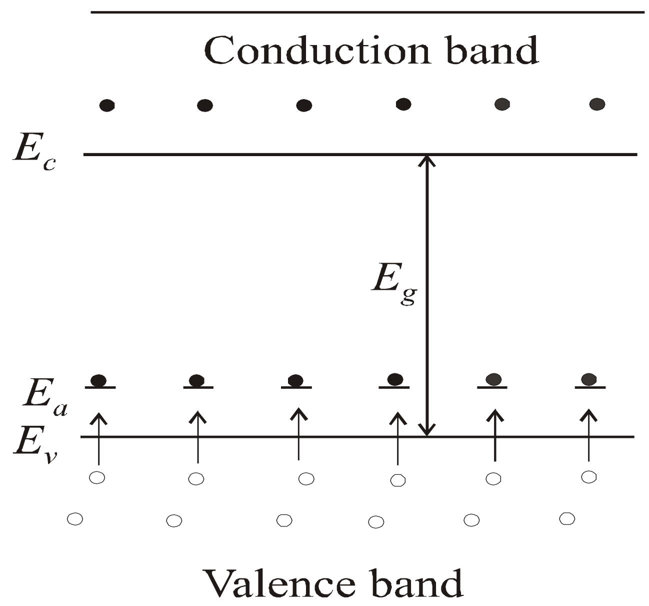
- Due to ionization of acceptor atoms, only holes and no electrons are created.

If the temperature is sufficiently high, in addition to the above process, electron-hole pairs are generated due to the breaking of covalent bonds.

Thus holes are more in number than electrons and hence holes are majority carriers and electrons are minority carriers



(a) At T > 0K



(b) At T = 300K

Fermi Energy

The Fermi energy for p – type semiconductor is given by

$$E_F = \left(\frac{E_v + E_a}{2}\right) - \frac{kT}{2} ln\left[\frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}}\right]$$

At 0 K,

$$E_F = \frac{E_v + E_a}{kT}$$

At 0K, Fermi level is exactly at the middle of the acceptor level on the top of the valence band.

VARIATION OF FERMI LEVEL WITH TEMPERATURE

$$E_F = \left(\frac{E_v + E_a}{2}\right) - \frac{kT}{2} ln \left(\frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}} \right) = \left(\frac{E_v + E_a}{2}\right) - \frac{kT}{2} ln \left(\frac{N_a}{N_y}\right)$$

where $N_y = 2 \left(\frac{2\pi m_h * kT}{h^2}\right)^{3/2}$

and therefore $E_F = \left(\frac{E_v + E_a}{2}\right) + \frac{kT}{2} ln \left(\frac{N_a}{N_y}\right)$

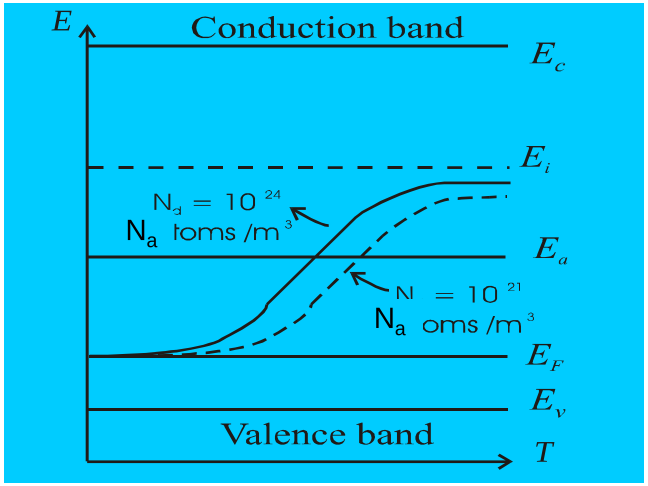
From the above eqn, it is seen that E_F increases slightly as the temperature increases.

As the temperature increases, more and more acceptor atoms are ionised.

➢ For a particular temperature all the acceptor atoms are ionized.

➢ Further increase in temperature results in generation of electron-hole pair due to the breaking of covalent bonds and the material tend to behave in intrinsic manner.

➢ The Fermi level gradually moves towards the intrinsic Fermi level.



Variation of Fermi level with acceptor concentration and temperature

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18PYB103J –Semiconductor Physics

Module-II Lecture-III

Carrier Generation & Carrier Recombination

Carrier Generation & Recombination

Carrier **generation** describes processes by which electrons gain energy and move from the valence band to the conduction band, producing two mobile carriers; while **recombination** describes processes by which a conduction band electron loses energy and re-occupies the energy state of an electron hole in the valence band.

Semiconductors are characterized by two types of mobile carriers, electrons in the conduction band and holes in the valence band. The **generation rate** gives the number of electrons generated at each point in the device due to the absorption of photons..

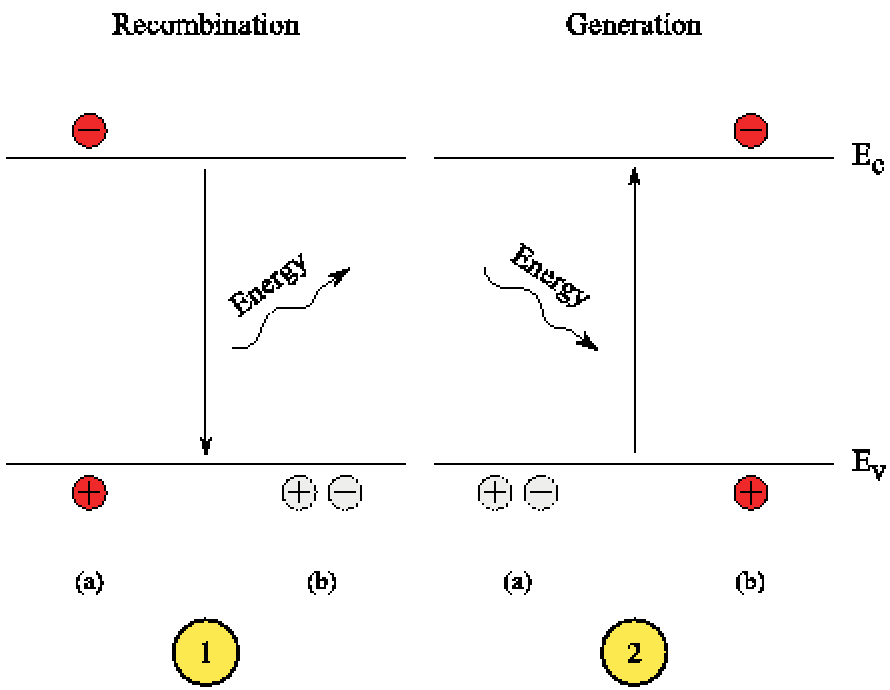
Excess carriers, essential for device operation, are created by optical excitation, electron. bombardment, or injected across a forward-biased p-n junction. • These **excess carriers** can dominate the conduction process in semiconductor materials.

In semiconductors several different processes exist which lead to generation or recombination, the most important ones are:

- **Photon transition (or) Optical generation/recombination**
- **Phonon transition (or) Shockley-Read-Hall generation/recombination**
- **Auger generation/recombination (or) Three particle transitions**
- **Impact ionization**

In thermal equilibrium the generation and recombination processes are in dynamic equilibrium. When the system is supplied with additional energy, for example through the absorption of photons or the influence of temperature, additional carriers are generated. The most important generation/recombination processes for the simulation of semiconductor devices are summarized in the following.

1. Photon Transition

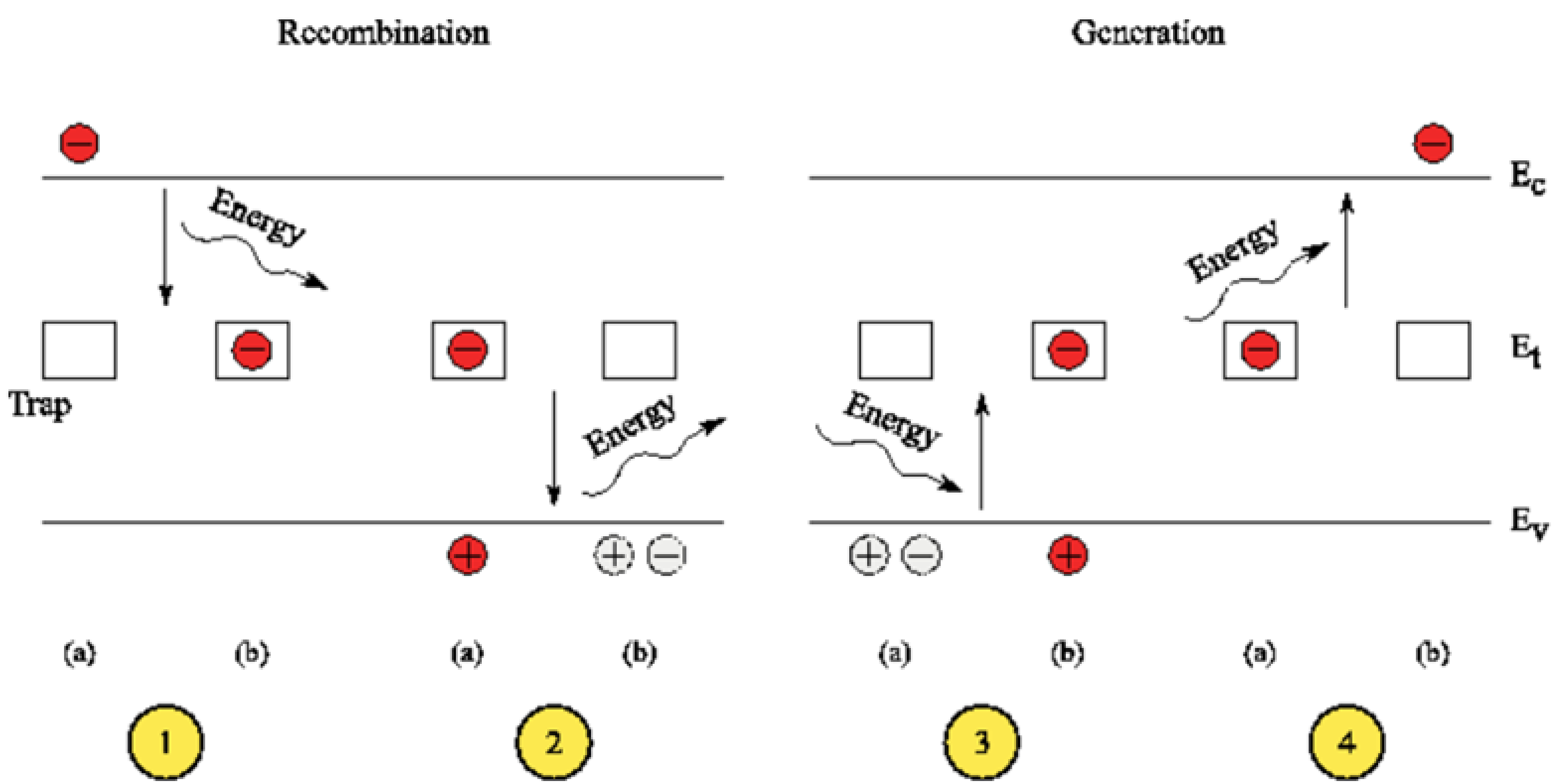


Direct generation/recombination process. During photon assisted recombination an electron from the conduction band re-combines with a hole in the valence band. The excess energy is transferred to a photon. The reverse process obtains its energy from radiation and generates an electron hole pair.

The photon transition is a direct, band-to-band, generation/recombination process. An electron from the conduction band falls back to the valence-band and releases its energy in the form of a photon (light).

The reverse process, the generation of an electron-hole pair, is triggered by a sufficiently energetic photon which transfers its energy to a valence band electron which is excited to the conduction band leaving a hole behind. The photon energy for this process has to be at least of the magnitude of the band-gap energy.

2. Phonon Transition (OR) Shockley-Read-Hall generation/recombination



Four sub-processes in the Shockley-Read-Hall generation/recombination process. 1. electron capture, 2. hole capture, 3. hole emission, and 4. electron emission.

Another process is the generation/recombination by phonon emission. This process is trap-assisted utilizing a lattice defect at the energy level E_t within the semiconductor band-gap. The excess energy during recombination and the necessary energy for generation is transferred to and from the crystal lattice (phonon). A theory describing this effect has been established by Shockley, Read, and Hall. Therefore, the effect is throughout the literature referenced as Shockley-Read-Hall (SRH) generation/recombination. Four sub-processes are possible:

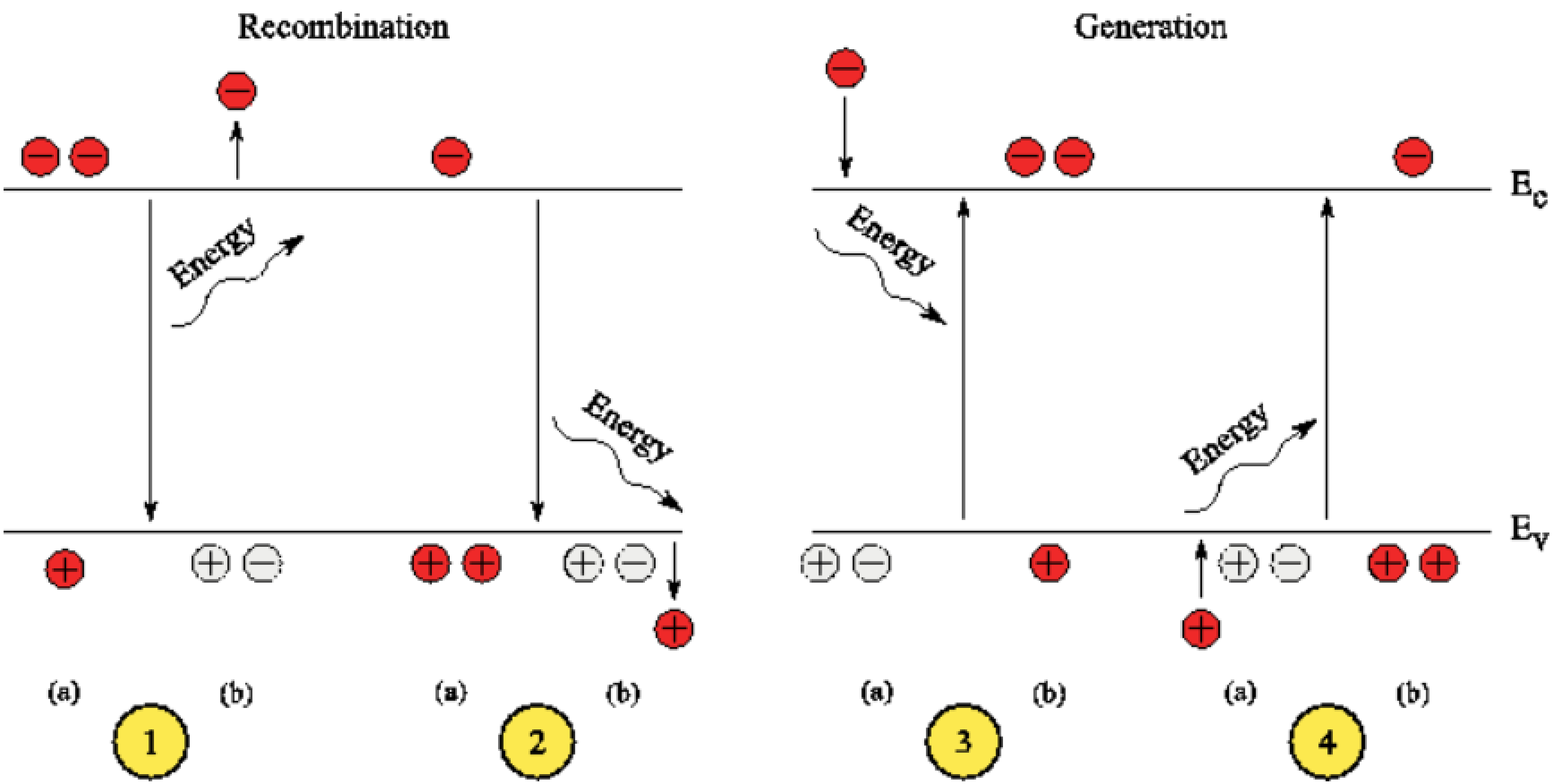
Electron capture. An electron from the conduction band is captured by an empty trap in the band-gap of the semiconductor. The excess energy of E_c - E_t is transferred to the crystal lattice (phonon emission).

Hole capture. The trapped electron moves to the valence band and neutralizes a hole (the hole is captured by the occupied trap). A phonon with the energy E_t -E_v is generated.

Hole emission. An electron from the valence band is trapped leaving a hole in the valence band (the hole is emitted from the empty trap to the valence band). The energy necessary for this process is E_t - E_v.

Electron emission. A trapped electron moves from the trap energy level to the conduction band. For this process additional energy of the magnitude E_c - E_t has to be supplied.

3. Auger generation/recombination (or) Three particle transitions



Four sub-processes in the Auger generation/recombination mechanism. 1. electron capture, 2. hole capture, 3. electron emission, and 4. hole emission.

In the direct band-to-band Auger mechanism three particles are involved. During generation an electron hole pair is generated consuming the energy of a highly energetic particle. In the opposite process, when an electron hole pair recombines, the excess energy is transferred to a third particle. In detail the four possible processes are as follows:

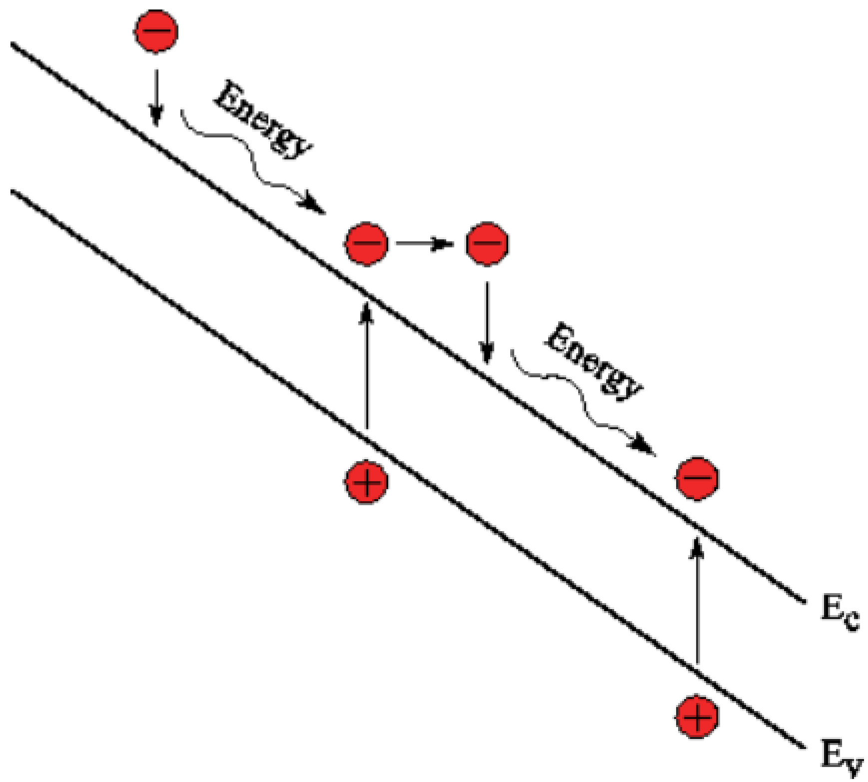
Electron capture. An electron from the conduction band moves to the valence band neutralizing a hole in the valence band. The excess energy is transferred to an electron in the conduction band.

Hole capture. Again, an electron from the conduction band moves to the valence band and recombines with a valence hole. The excess energy is, in contrast to Process 1, transferred to another hole in the valence band.

Electron emission. A highly energetic electron from the conduction band transfers its energy to an electron in the valence band. The valence electron moves to the conduction band generating an electron hole pair.

Hole emission. A highly energetic hole from the valence band transfers its energy to an electron in the valence band which is then excited to the conduction band generating an electron hole pair.

4. Impact ionization



Impact ionization and avalanche multiplication. An energetic electron donates its energy to the generation of an electron hole pair. The newly generated electron can, due to the high electric field, obtain high energy and generate further carriers, leading to avalanche multiplication.

Impact ionization is a pure generation process. Microscopically it is exactly the same mechanism as the generation part of the Auger process: a highly energetic carrier moves to the conduction or valence band, depending on the carrier type, and the excess energy is used to excite an electron from the valence band to the conduction band generating another electron hole pair. The major difference is the cause of the effect. While it is purely the carrier concentration in the Auger mechanism, for impact ionization it is the current density.

Two partial processes can be distinguished:

Electron emission. A highly energetic electron from the conduction band transfers its energy to an electron in the valence band. The valence electron moves to the conduction band generating an electron hole pair.

Hole emission. A highly energetic hole from the valence band transfers its energy to an electron in the valence band which is then excited to the conduction band generating an electron hole pair.

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18PYB103J –Semiconduuctor Physics

1. Calculate the conductivity of intrinsic germanium at 300K using the following data:

Given data

$n_i = 2.4 \times 10^{19}\ \mathrm{m}^{-3}$; $\mu_e = 0.39\ \mathrm{m}^2 V^{-1} s^{-1}$; $\mu_h = 0.19\ \mathrm{m}^2 V^{-1} s^{-1}$

Solution:

$$\sigma_i = n_i e(\mu_e + \mu_h) = 2.4 \times 10^{19} \times 1.6 \times 10^{-19} (0.39 + 0.19)$$

$$= 2.2272\ (\text{ohm metre})^{-1}$$

2. At what temperature we can expect a 10% probability that electrons in silver have an 0.055 energy which is 1% above the Fermi energy? The Fermi energy of silver is 5.5eV.

Given Data

$F(E) = 10\% = 0.1$

$E_F = 5.5\text{eV}$

$E = E_F + = (5.5 + 0.055) = 5.555\ \text{eV}$

Hence $E - E_F = 0.055\ \text{eV} = 0.055 \times 1.6 \times 10^{-19}\ \text{J}$

Solution:-

We know the probability function is given by

$$F(E) = \frac{1}{1 + \exp(E - E_F / kT)}, or, \qquad 0.1 = \frac{1}{1 + \exp\left(\dfrac{0.055 \times 1.6 \times 10^{-19}}{1.38 \times 10^{-23} \times T}\right)}$$

$$= \frac{1}{\exp\left(\dfrac{637.7}{T}\right) + 1}$$

$$Hence, T = \frac{637.7}{\ln 9} = \frac{637.7}{2.197}$$

3. A cadmium sulphide *(Eg* = 2.4eV) photodetector is illuminated with light of wavelength 3000Å. The intensity of radiation falling on the detector is 30 W/m². The area of the detector is 9 mm². Assuming that each quantum generates an electron-hole pair, calculate the number of pairs generated per second.

Given data

wavelength= 3000 Å

Solution:-

$$E = \frac{hc}{\lambda} = \frac{6.625 \times 10^{-34} \times 3 \times 10^{2}}{3000 \times 10^{-10}}$$

$$= \frac{6.625 \times 10^{-19}}{1.602 \times 10^{-19}} eV = 4.13 eV$$

Since this energy is higher than E_g (=2.4eV) electron-hole pairs will be generated.

Number of photons falling

$$= \frac{30 \times 9 \times 10^{-6}}{6.625 \times 10^{-19}} = 4.075 \times 10^{14}$$

Since each photon produces an electron-hole pair, the number of pairs generated per sec = 4.075×10^{14}

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18PYB103J –Semiconduuctor Physics

Carrier Transport

The net flow of the ‘**electron and holes’** in a semiconductor generates the current.

The process through which these charged particles move is called transport.

Two basic transport namely : **Drift & Diffusion.**

The carrier transport phenomena are the foundation for finally determining the current-voltage characteristics of semiconductor devices.

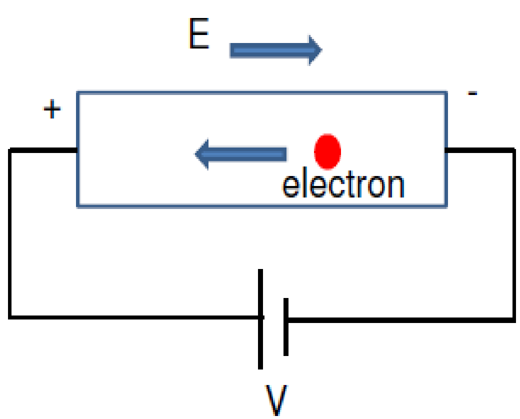
Subtopic :

I. Carrier Drift
II. Carrier Diffusion

Carrier Transport

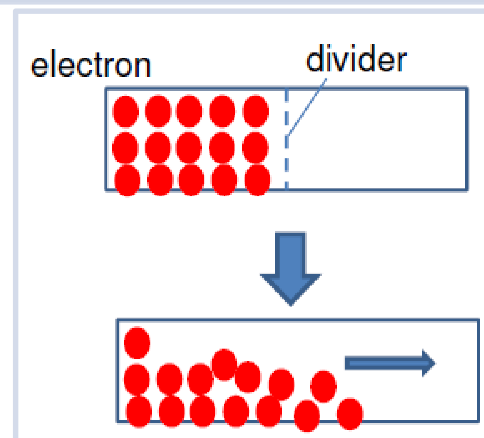
Drift

The electric field (E) is involved in the movement of the charge carrier.

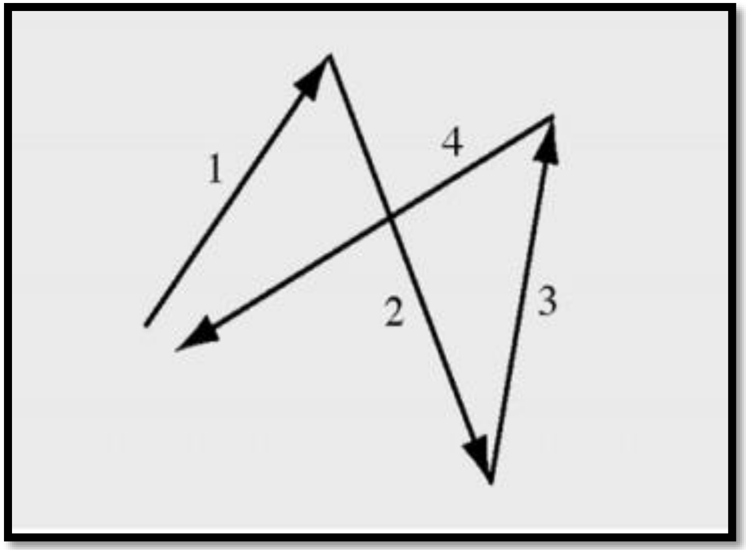


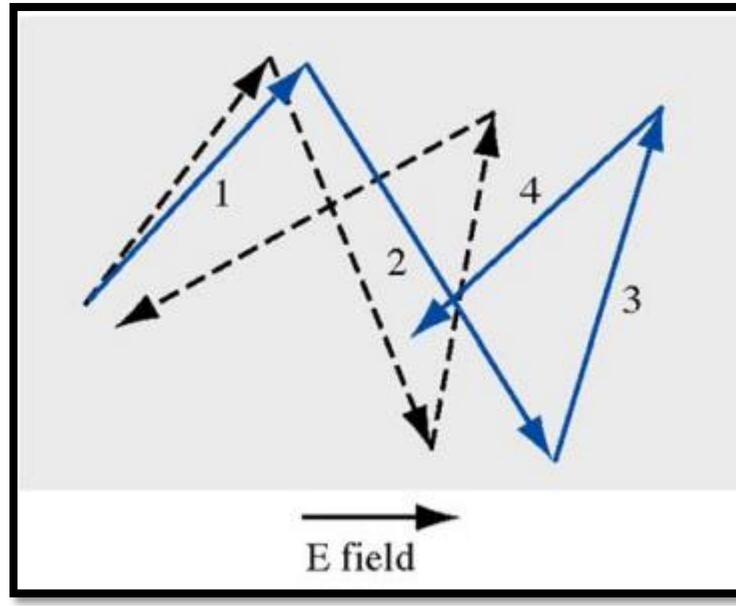
Diffusion

The movement or flow of the charge carrier due to density gradient (dn/dx)



Carrier Transport Phenomena





Random motion of carriers without applied field

No net carrier displacement

Random motion and net movement along the direction of field

Net carrier **displacement** and thus a net velocity along the field.

This velocity is called the **drift velocity,** which gives drift current.

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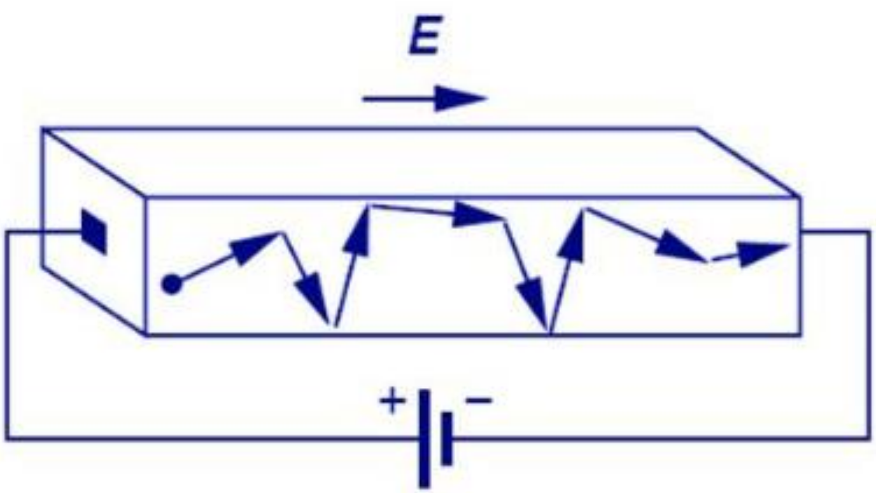
Carrier Drift

- The process in which charged particles move because of an electric field is called ***drift***.
- Charged particles within a semiconductor move with an average velocity proportional to the electric field.
  - The proportionality constant is the carrier ***mobility***.



Hole velocity $\vec{v}_h = \mu_p \vec{E}$

Electron velocity $\vec{v}_e = -\mu_n \vec{E}$

Notation:

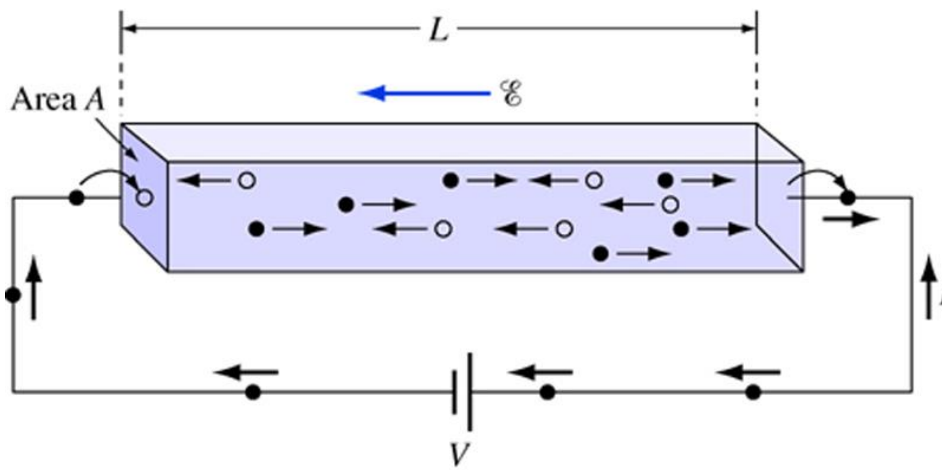
$\mu_p \equiv$ hole mobility ($cm^2/V \cdot s$)

$\mu_n \equiv$ electron mobility ($cm^2/V \cdot s$)

Current density

- In semiconductors, It is useful to compare current density ‘*J*’ rather than current ‘*I*’

$$J = \frac{I}{area}$$



- Ohm’s Law:

$$R = \frac{V}{I} = \frac{r L}{A}$$

- Where ρ is resistivity (in ohm-cm), *L* is length and *A* is cross-sectional area

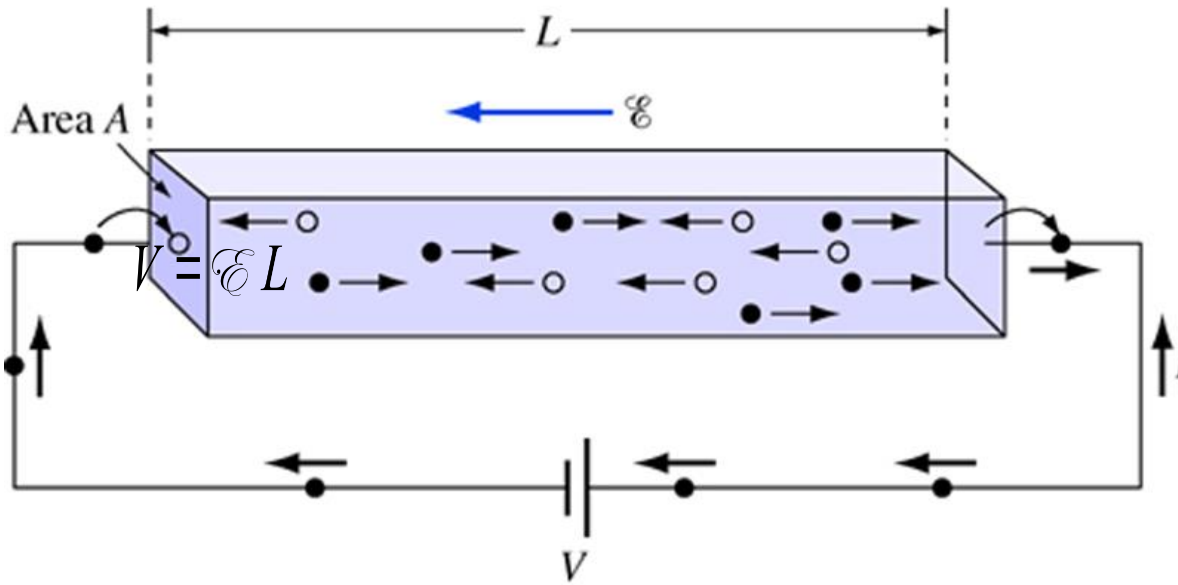
- Let electric field be $\mathscr{E}$
- *I=JA* and $V = \mathscr{E} L$

Therefore

$$\frac{\mathscr{E} L}{JA} = \frac{r L}{A}$$

Or

$$J_{(drift)} = \frac{\mathscr{E}}{r} = s \mathscr{E}$$



$V = \mathscr{E} L$

Where $s = 1/r$ is the conductivity (in ohm-cm^{-1})

Note we added subscript *"drift"* to *J*

The **electric current density** is given by

$J = nev_d$; v_d *is the drift velocity*

The conductivity is $\sigma = J/E = (nev_d/E)$

$\sigma = (ne/E)(eE\tau/m)$ with $v_d = (eE\tau/m)$

$\sigma = (ne^2\tau/m)$, τ is the relaxation time between collisions

Again $v_d = \mu E$, μ is the mobility of charge carrier within the crystal.

Thus, $\mathbf{J = nev_d = ne\,\mu\,E}$

$\sigma = J/E = ne\,\mu$

or in terms of resistivity ρ

$\rho = 1/\sigma = 1/ne\,\mu$

If the material is a semiconductor, the current flow would be due to electron and hole movement.

Correspondingly the current densities due to electron drift and hole are:

J_n (drift) $= n\,\mu_n\, eE$

J_p (drift) $= p\,\mu_p\, eE$

J (drift) = J_n (drift) + J_p (drift)

J (drift) $= n\,\mu_n\, eE + p\,\mu_p\, eE$

Comparison with $J = \sigma E$

$$\boldsymbol{\sigma = n\,\mu_n e + p\,\mu_p e}$$

For an intrinsic semiconductor $n = p = n_p$

$\sigma_i = n_i e(\mu_n + \mu_p)$

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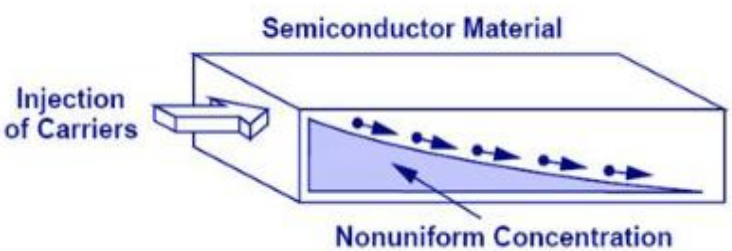
Carrier Diffusion

- Due to thermally induced random motion, mobile particles tend to move from a region of high concentration to a region of low concentration.
  - Analogy: ink droplet in water
- Current flow due to mobile charge diffusion is proportional to the carrier concentration gradient.
  - The proportionality constant is the ***diffusion constant***.



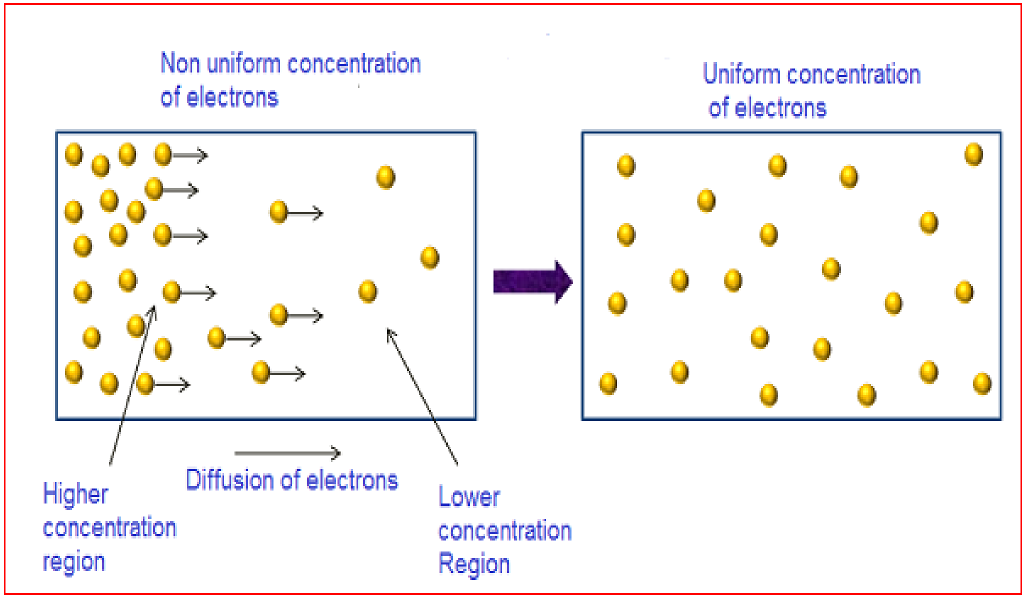
$$J_p = -qD_p \frac{dp}{dx}$$

Notation:

$D_p \equiv$ hole diffusion constant (cm^2/s)

$D_n \equiv$ electron diffusion constant (cm^2/s)

Diffusion Current



•In p-type semiconductor, the diffusion process occurs in the similar manner.

The electrons present at left side of the semiconductor material that moves to right side, to reach the uniform concentration of electrons.

The semiconductor material achieves equal concentration of electrons. Electrons that moves from left side to right side will constitute current. This current is called diffusion current.

Let us suppose that the concentration Δn of electrons varies wit
In the semiconductor, the concentration of gradient being

$d(\Delta n)/dx$

Fick’s law states that the rate at which carriers diffuse is proportional to the density gradient and the movement is in the direction of negative Gradient, the rate of flow of electrons is proportional to

$-d(\Delta n)/dx$

From which the rate of flow across unit area is got, equal to

$-D_n \, d(\Delta n)/dx$, Where D_n is the diffusion coefficient for electron

$$J_n(\text{diffusion}) = -(e)\,(\text{rate of flow across unit area})$$
$$= eD_n \, d(\Delta n)/dx$$

If an excess hole concentration is created in the same region, hole Diffusion takes place in the same direction at a rate per unit area

$$= - D_p \, d(\Delta p) /dx$$

Resulting in a hole diffusion current density.

J_p(diffusion) = +(e) (rate of flow across unit area)

$= - eD_p \, d(\Delta p) /dx$. Where D_p is the hole diffusion coefficient

If there is an electric field E and a concentration gradient in the x-direction, the total hole current is the sum of the drift current.

$$J_p = J_p \text{ (drift)} + J_p \text{ (diffusion)}$$

$$J_p = pe\mu_p - eD_p \, d(\Delta p) /dx$$

Similarly for electrons, the total current density

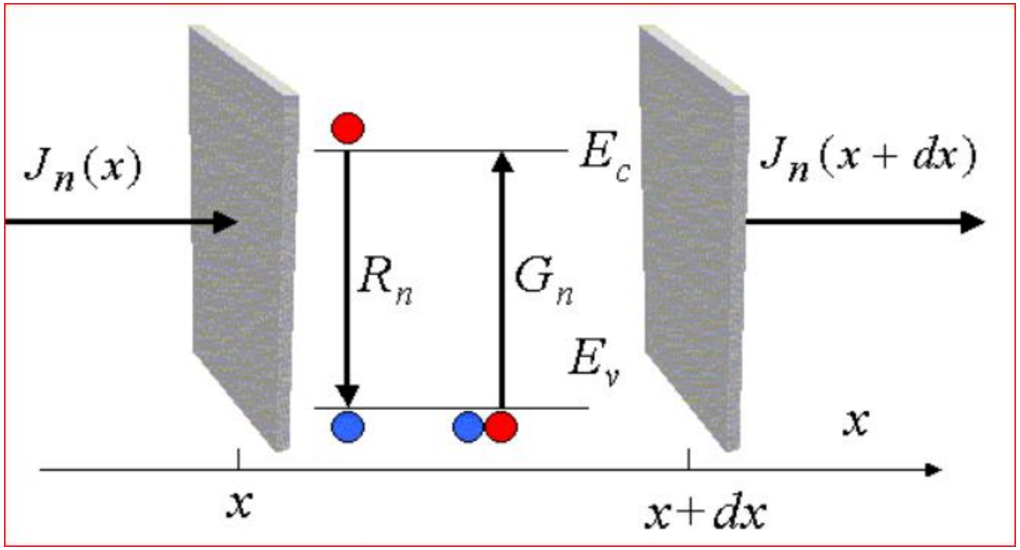
$$J_n = ne\mu_n + eD_n \, d(\Delta n) /dx$$

CONTINUITY EQUATION

- **In the previous sections, we have understood the following concepts.**

- **Drift due to an electric field.**
- **Diffusion due to a concentration gradient.**
- **Recombination of carriers through intermediate-level recombination centers.**

- **The contribution of the overall effect when drift, diffusion, and recombination occur simultaneously in a semiconductor material. The governing equation is called the *continuity equation*.**



Electron currents and possible recombination and generation processes

- The continuity equation describes a basic concept, namely that a **change in carrier density over time is due to the difference between the incoming and outgoing flux of carriers plus the generation and minus the recombination.**

The flow of carriers and recombination and generation rates are illustrated with Figure

One-dimensional continuity equation for electrons

- Consider an infinitesimal slice with thickness **dx located at x.** The number of electrons in the slice may increase due to the net current flow into the slice and the net carrier generation in the slice (mainly four components contribution). {Law of conservation of charges}

- **The number of electrons flowing into the slice at x, minus the number of electrons flowing out at x + dx, plus the rate at which electrons are generated, minus the rate at which they are recombined with holes in the slice.**

- The first two components are found by dividing the currents at each side of the slice by the charge of an electron.

- The **generation and recombination rates are designated by G_n and R_n** , respectively.

- The overall rate of change in the number of electrons in the slice is given as below

$$\frac{\partial n}{\partial t} A dx = \left[\frac{J_n(x) A}{-q} - \frac{J_n(x+dx) A}{-q} \right] + (G_n - R_n) A dx ,$$

where A is the cross-sectional area and Adx is the volume of the slice where A is the cross-sectional area and Adx is the volume of the slice

Expanding the expression for the current at x + dx in Taylor series yields

$$J_n(x+dx) \quad J_n(x) + \frac{\partial J_n}{\partial x} dx + \dots .$$

We thus obtain the basic continuity equation for electrons:

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + (G_n - R_n) .$$

A similar continuity equation can be derived for holes, except that the sign of the first term on the right-hand side of Eq is changed because of the positive charge associated with a hole.

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + (G_p - R_p) .$$

G_n = e- generation rate
R_n = e- recombination rate
G_p = hole generation rate
R_p = hole recombination rate

For the one-dimensional case under low-injection condition, small electric field, uniform doping etc.

The continuity equations for minority carriers :

(i.e., *np in a p-type semiconductor or pn in an n-type semiconductor)*

When an electric field is present in addition to a concentration gradient, both drift current and diffusion current will flow. The total current density at any point is the sum of the drift and diffusion components:

$$\boxed{J_n = q\mu_n n\mathscr{E} + qD_n \frac{dn}{dx},}$$

where $\mathscr{E}$ is the electric field in the x-direction.

A similar expression can be obtained for the hole current:

$$\boxed{J_p = q\mu_p p\mathscr{E} - qD_p \frac{dp}{dx}.}$$

Using the drift and diffusion current density of electrons and holes, we obtain the continuity equation for electrons and holes respectively

$$\boxed{\frac{\partial n_p}{\partial t} = n_p \mu_n \frac{\partial \mathcal{E}}{\partial x} + \mu_n \mathcal{E} \frac{\partial n_p}{\partial x} + D_n \frac{\partial^2 n_p}{\partial x^2} + G_n - R_n}$$

$$\boxed{\frac{\partial p_n}{\partial t} = p_n \mu_p \frac{\partial \mathcal{E}}{\partial x} + \mu_p \mathcal{E} \frac{\partial p_n}{\partial x} + D_p \frac{\partial^2 p_n}{\partial x^2} + G_p - R_n}$$

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18PYB103J -SEMICONDUCTOR PHYSICS
Module-II
Lecture-VIII- SLO1,SLO2

Basic Structure of p-n Junction, Band Diagram of p-n Junction in Thermal Equilibrium

Basic Structure of p-n Junction, Band Diagram of p-n Junction in Thermal Equilibrium

- p-n junction is one of the basic building blocks of integrated circuits. Such a junction can be formed by selective diffusion or ion implantation of n-type or p-type dopant to the p-type or n-type semiconductor.

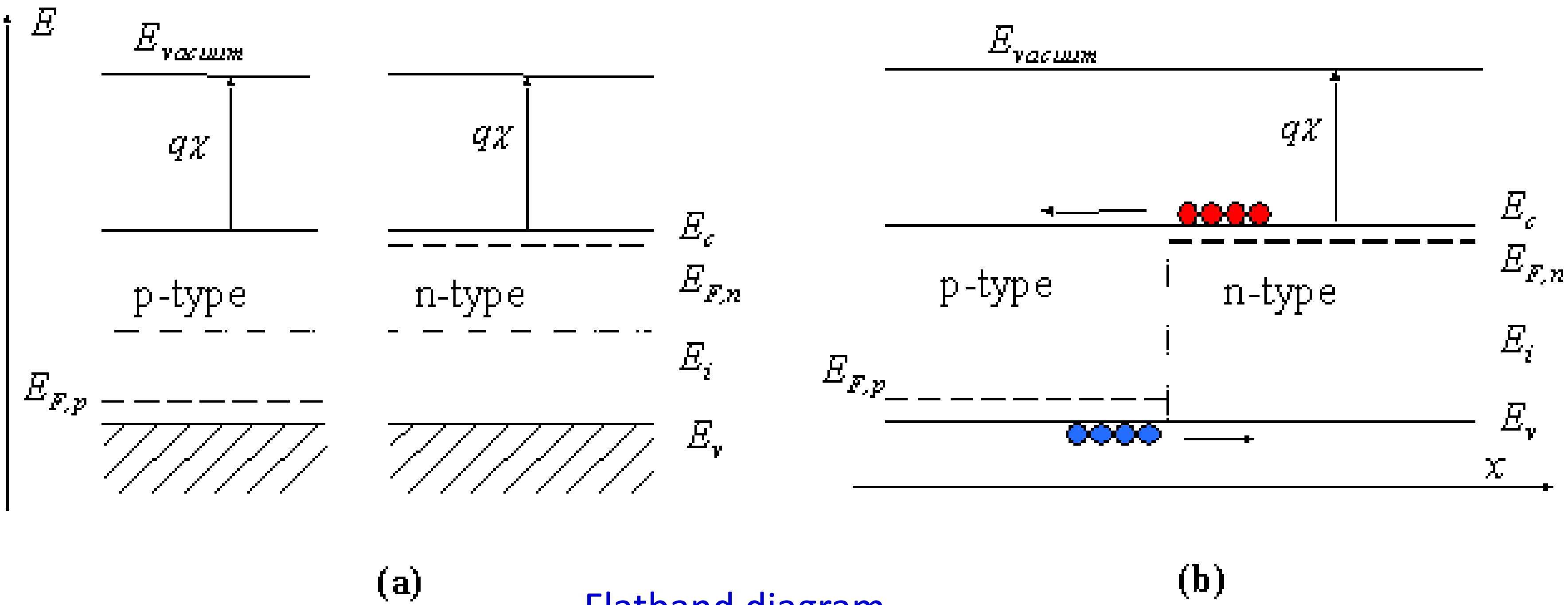
- When p-region and n-region are brought in close contact a p-n junction forms due to the diffusion of charge carriers. While, holes diffuse from p region to n region, electrons diffuse from n region to p region.

- Under thermal equilibrium a built in electric field directed from positive to negative charge which gives rise to drift current and no net transport of carriers due to diffusion is observed across the potential barrier(also called as depletion region).

- At thermal equilibrium, drift and diffusion component of current must cancel each other, J_n and J_p is zero. Hence the Fermi level must be constant throughout and the electron and hole concentrations on both sides remain same.

- While in thermal equilibrium no external voltage is applied between the *n*-type and *p*-type material, there is an internal potential, ϕ_i, which is caused by the work function difference between the *n*-type and *p*-type semiconductors. This potential equals the *built-in* potential.

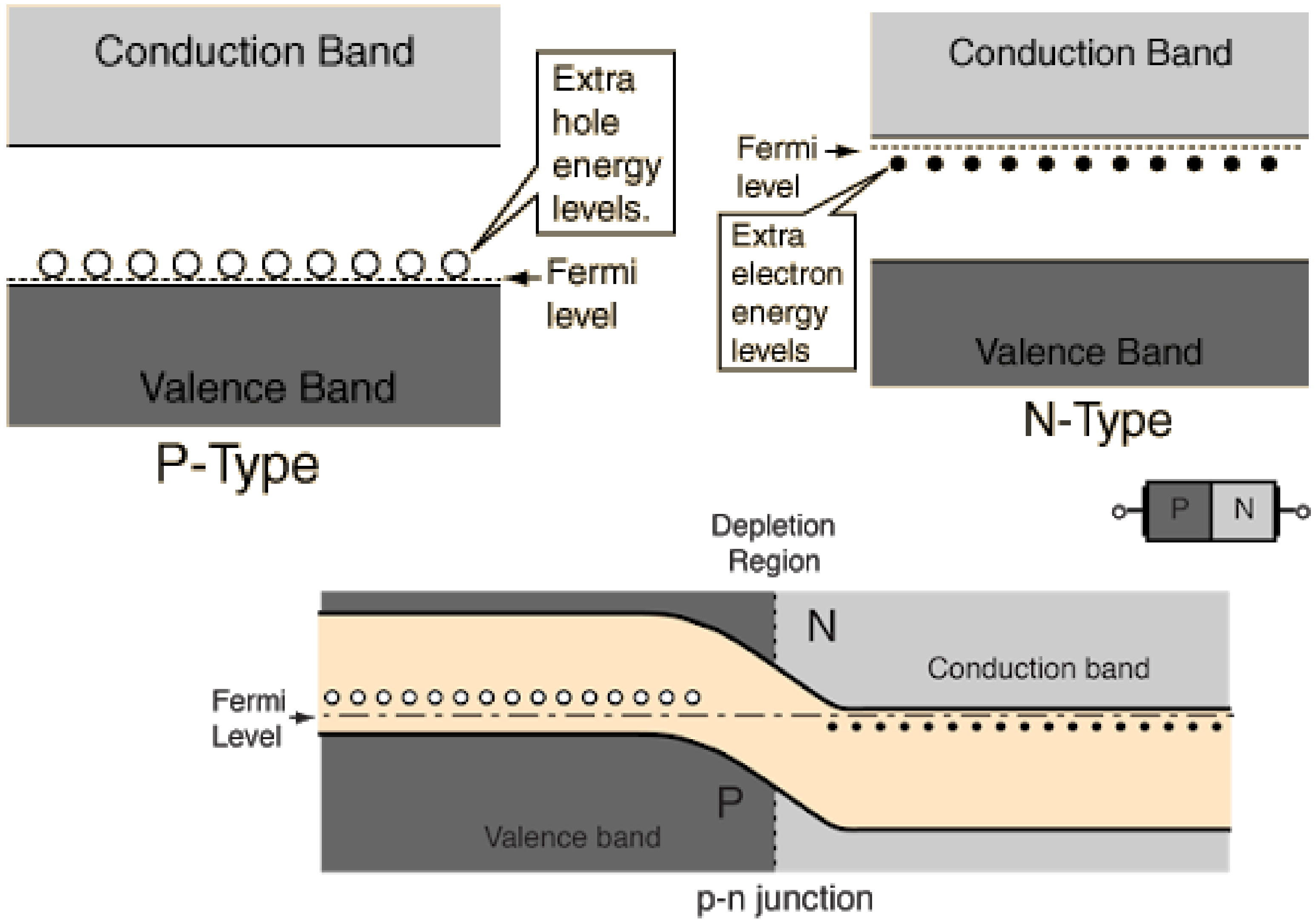
Basic Structure of p-n Junction, Band Diagram of p-n Junction in Thermal Equilibrium



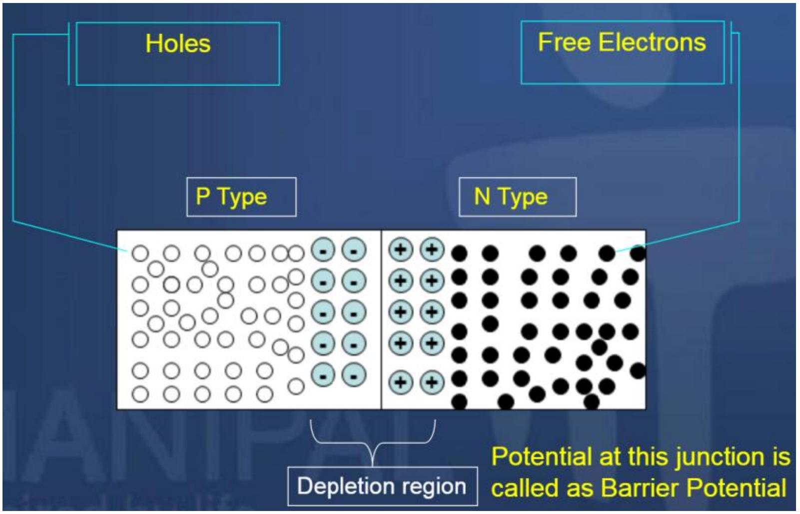
Flatband diagram

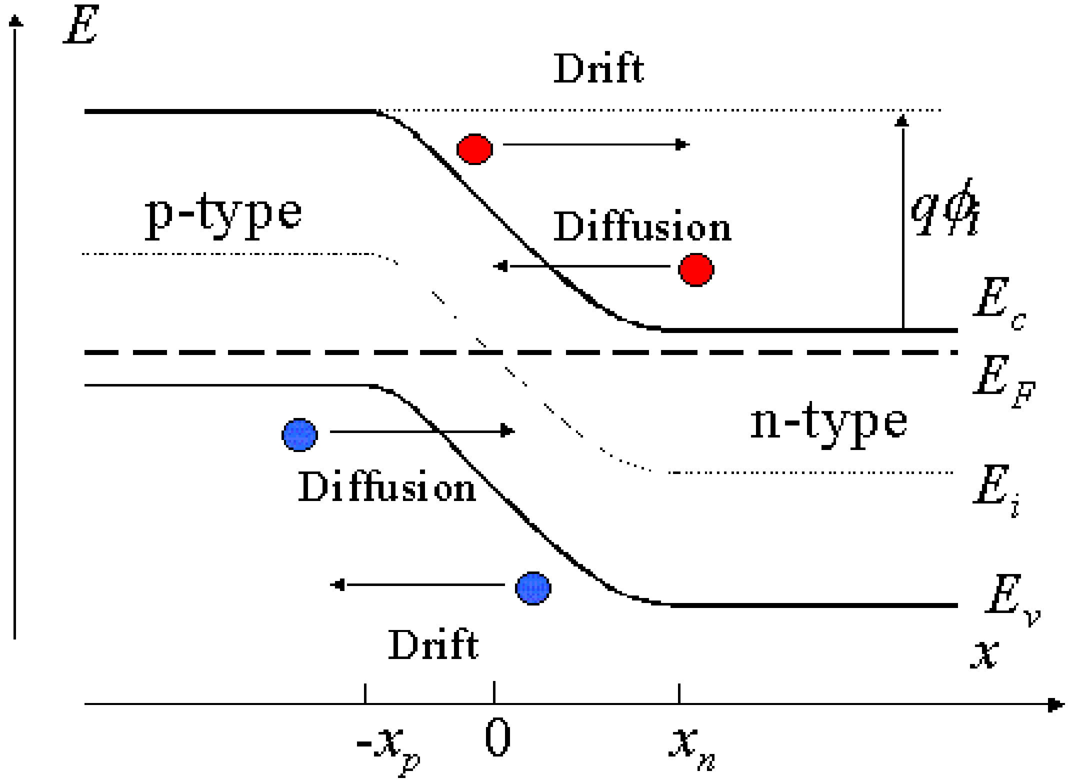
Energy band diagram of a p-n junction (a) before and (b) after merging the n-type and p-type regions

Basic Structure of p-n Junction, Band Diagram of p-n Junction in Thermal Equilibrium



Basic Structure of p-n Junction, Band Diagram of p-n Junction in Thermal Equilibrium





Energy band diagram of a p-n junction in thermal equilibrium

- Fermi level on p-region and n-region is given by

$E_F = E_{ip} - kT\ln(N_a/n_i)$ for p-region

$E_F = E_{in} - kT\ln(N_d/n_i)$ for n-region

E_F(p-region) = E_F(n-region)

$E_{ip} - E_{in} = kT\ln(N_aN_d/n_i^2)$

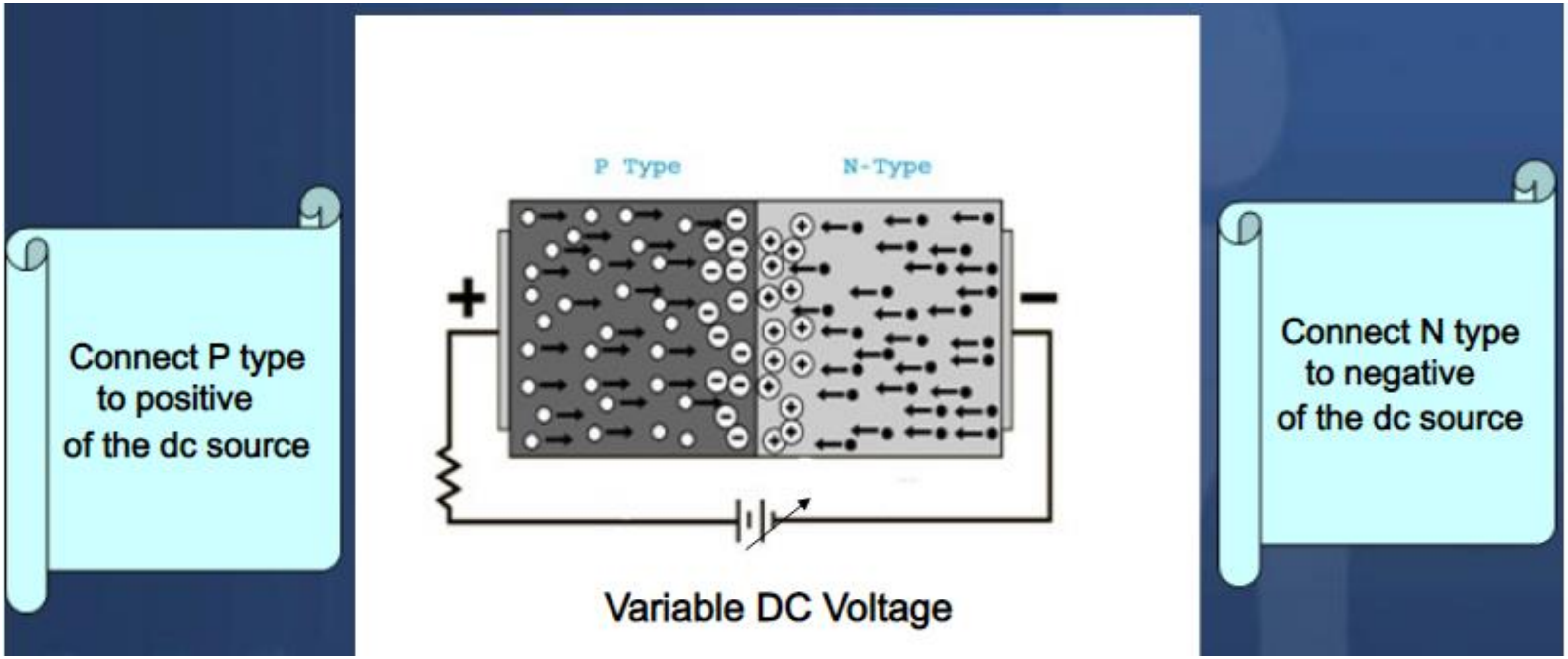
If $E_{ip} - E_{in} = V_{bi}$, Built in Potential, then $V_{bi} = kT\ln(N_aN_d/n_i^2)$

p-n junction under forward biasing

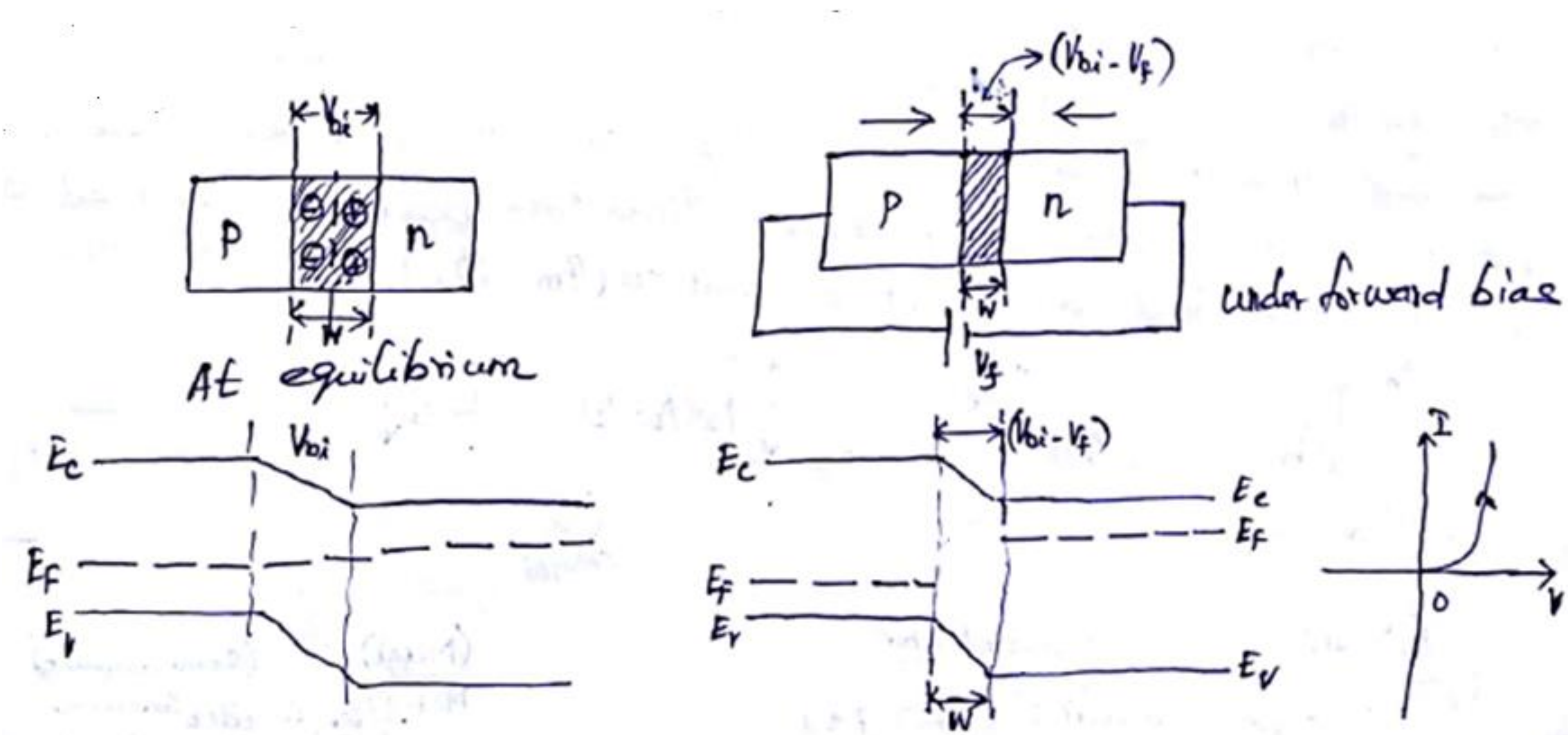
When the p-n junction is applied with external voltage both electrons and hole concentrations deviates from their equilibrium values. Also potential difference across depletion region deviates from its equilibrium value V_{bi} by an amount of applied bias.

When the p-n junction is forward biased by V_f ,ie., positive terminal of the battery is connected to the p-region and the negative terminal of the battery is connected to the n-region, the potential difference across the depletion region decreases by $V_{bi} - V_f$ .The width of depletion region decreases. Thus more electrons move from n region to p region and increase the diffusion current.

Basic Structure of p-n Junction, Band Diagram of p-n Junction in Thermal Equilibrium



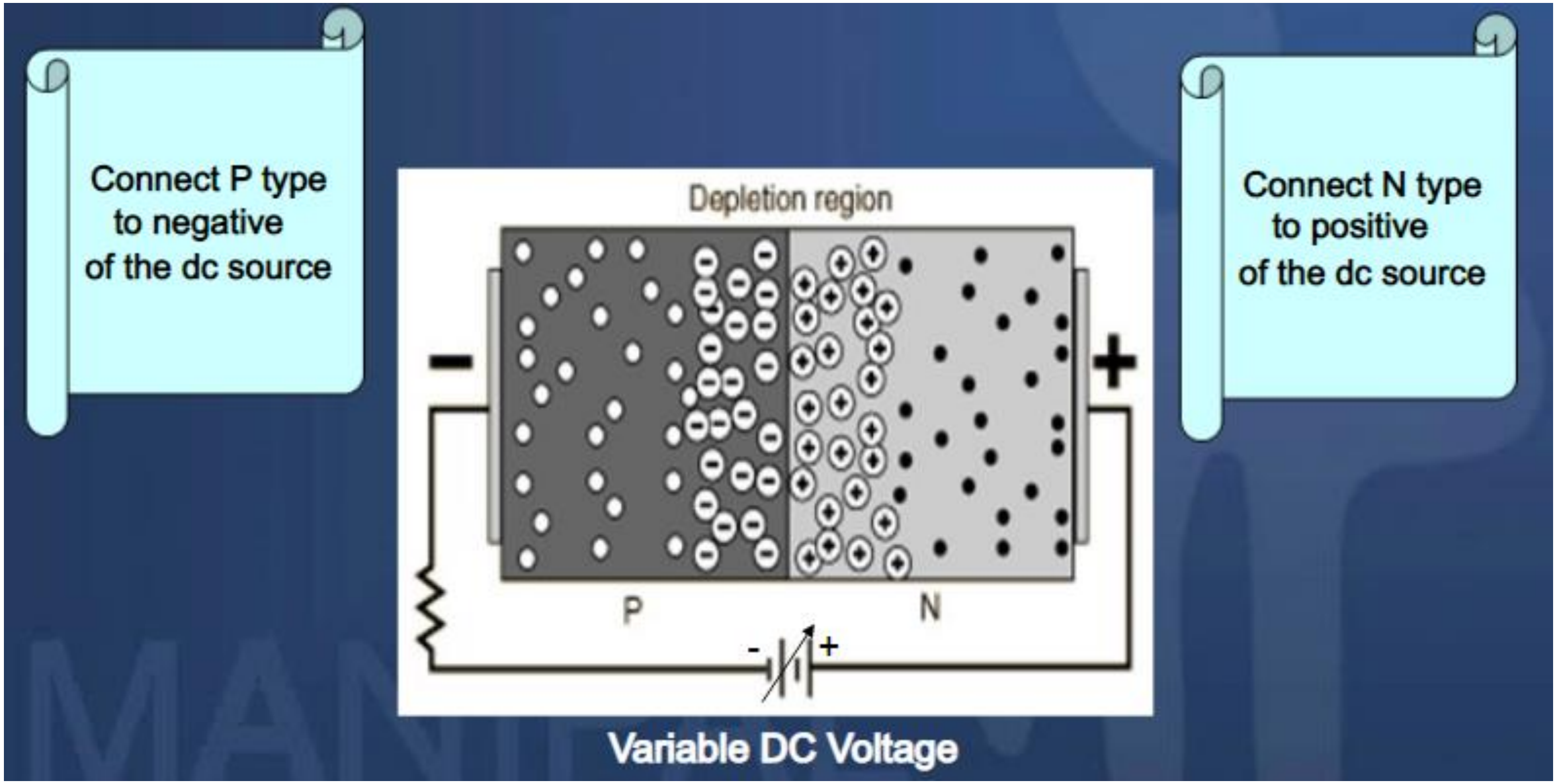
Basic Structure of p-n Junction, Band Diagram of p-n Junction in Thermal Equilibrium



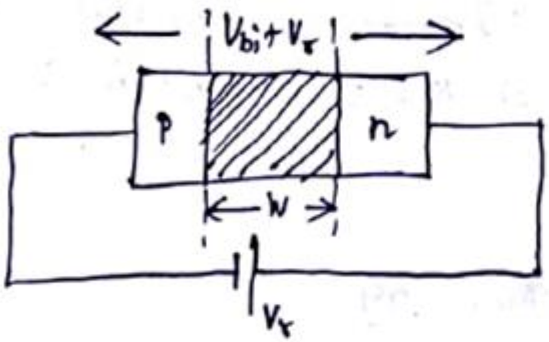
p-n junction under reverse biasing

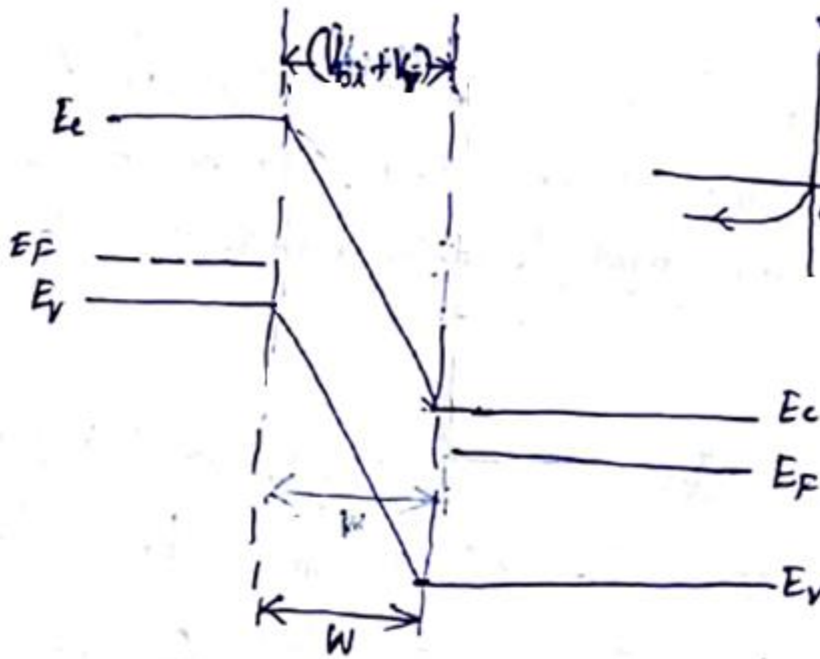
When the p-n junction is reverse biased by V_r ,ie., positive terminal of the battery is connected to the n-region and the negative terminal of the battery is connected to the p-region, the potential difference across the depletion region increases by $V_{bi} + V_r$. The width of depletion region increases. Thus no electrons from n region and no holes from p region diffuse across the junction. Now the current is due to the diffusion of minority charge carriers in the p and n region which is extremely small.

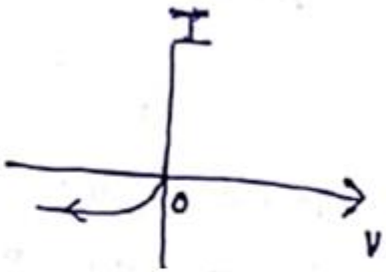
Basic Structure of p-n Junction, Band Diagram of p-n Junction in Thermal Equilibrium



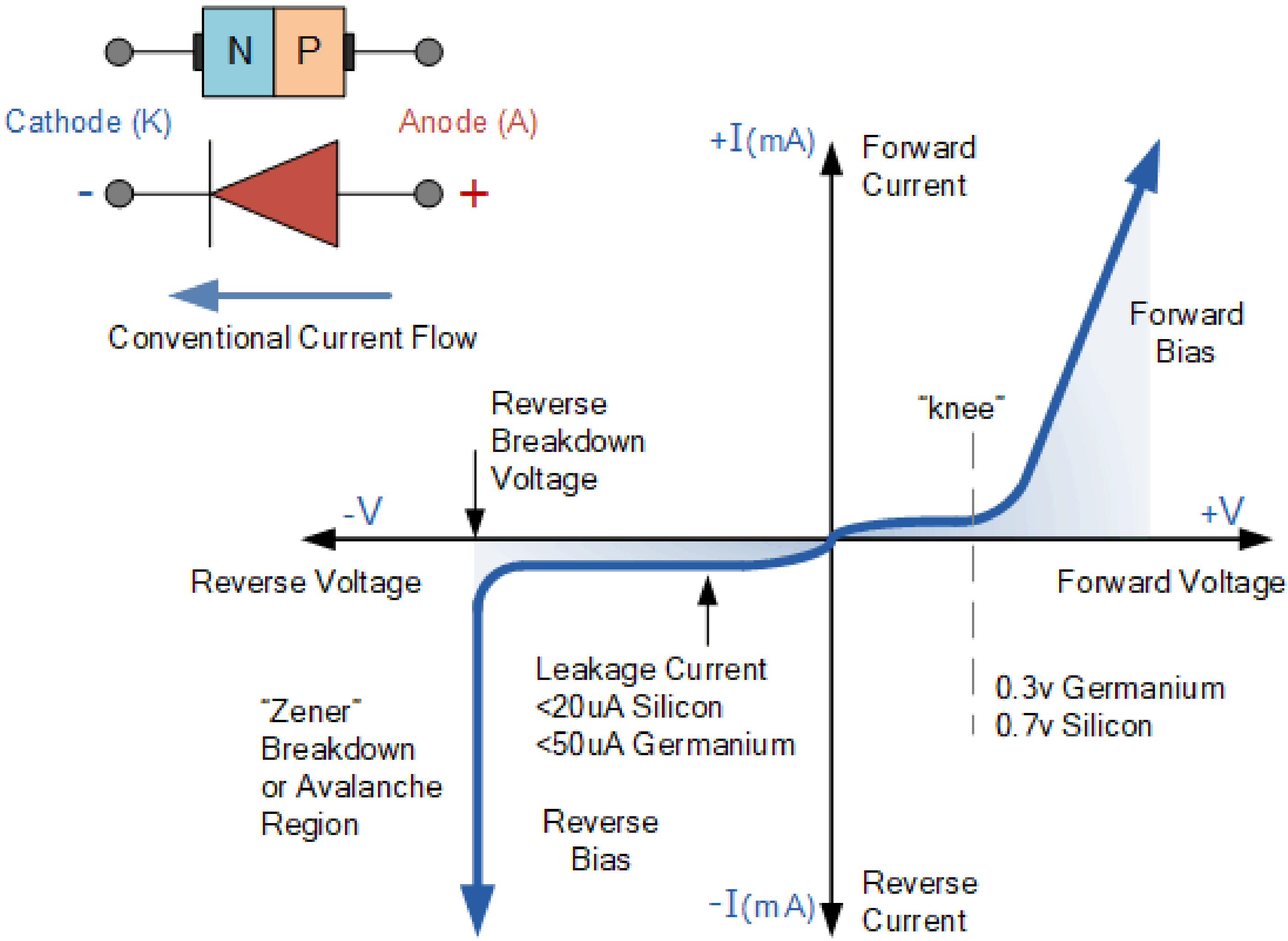
Basic Structure of p-n Junction, Band Diagram of p-n Junction in Thermal Equilibrium







Basic Structure of p-n Junction, Band Diagram of p-n Junction in Thermal Equilibrium



Junction Diode Symbol and Static I-V Characteristics

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18PYB103J -SEMICONDUCTOR PHYSICS
Module-II
Lecture-IX- SLO1,SLO2

Metal-semiconductor junction
Ohmic Contact and Schottky Junction

Metal-semiconductor junction
Ohmic Contact and Schottky Junction

- The metal semiconductor junction is the oldest practical semiconductor device.
- It can be either rectifying or non-rectifying.
- The rectifying semiconductor junction is called as Schottky diode and the non-rectifying junction is called as ohmic contact.

Rectifying Junction or Schottky Junction

Whenever, the work function of n type semiconductor is smaller than that of metal or the work function of p type semiconductor is greater than that of metal, it forms rectifying or Schottky junction.

Let ϕ_m and ϕ_s be the work function of metal and n type semiconductor , respectively where $\phi_m > \phi_s$.

When metal semiconductor contact is made, the conduction electrons begin to flow from the semiconductor in to the metal until the Fermi energies on both sides of the junction becomes equal. Therefore, metal becomes negative charged and the n-type semiconductor becomes positive charged. As a result potential barrier is formed at the metal semiconductor junction equal to $\phi_m - \phi_S = eV$.

When potential is applied to the system after contact such that

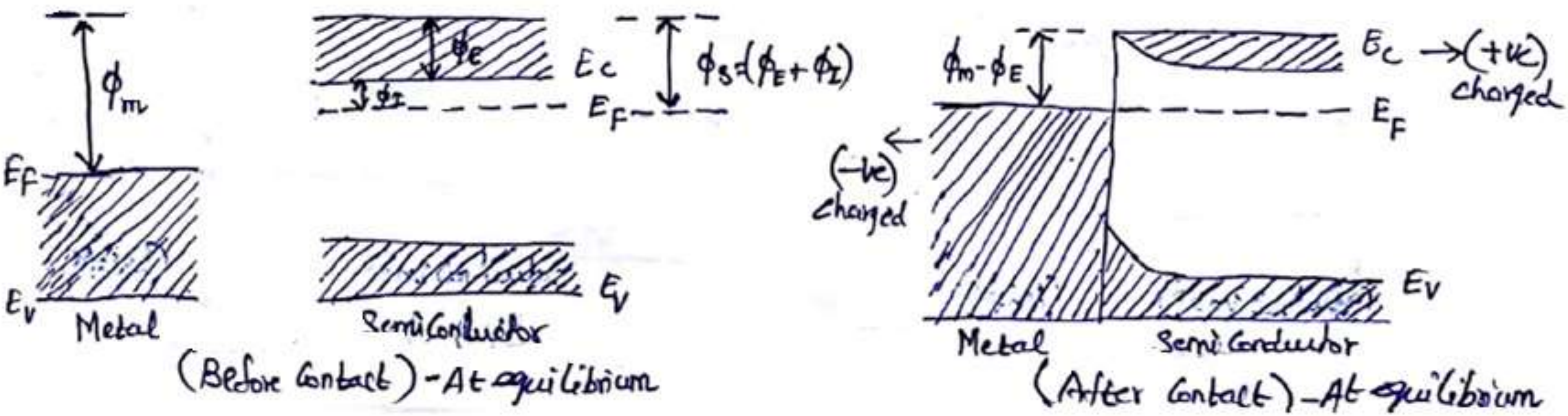
N-type is connected to positive charge and metal to negative charge, **the height of the barrier on the semiconductor side increases by (V_s +V)** and the metal remains unchanged. Therefore the junction is said to be **reverse biased** and the current flows from metal to semiconductor.

Rectifying Junction or Schottky Junction

Conversely if the voltage is reversed, so as to make semiconductor negative charge and metal positive charge, the **height of the barrier on the semiconductor side decreases by (V_s –V)** and the metal remains unchanged. Therefore the junction is said to be **forward biased** and the current flows from semiconductor to metal.

For forward bias the net current increases exponentially with applied voltage and for reverse bias, the net current is constant. Hence, the metal semiconductor contact acts like a rectifier i.e. it conducts in forward bias but not in reverse bias and hence called as rectifying contact.

Rectifying Junction or Schottky Junction



Rectifying Junction or Schottky Junction

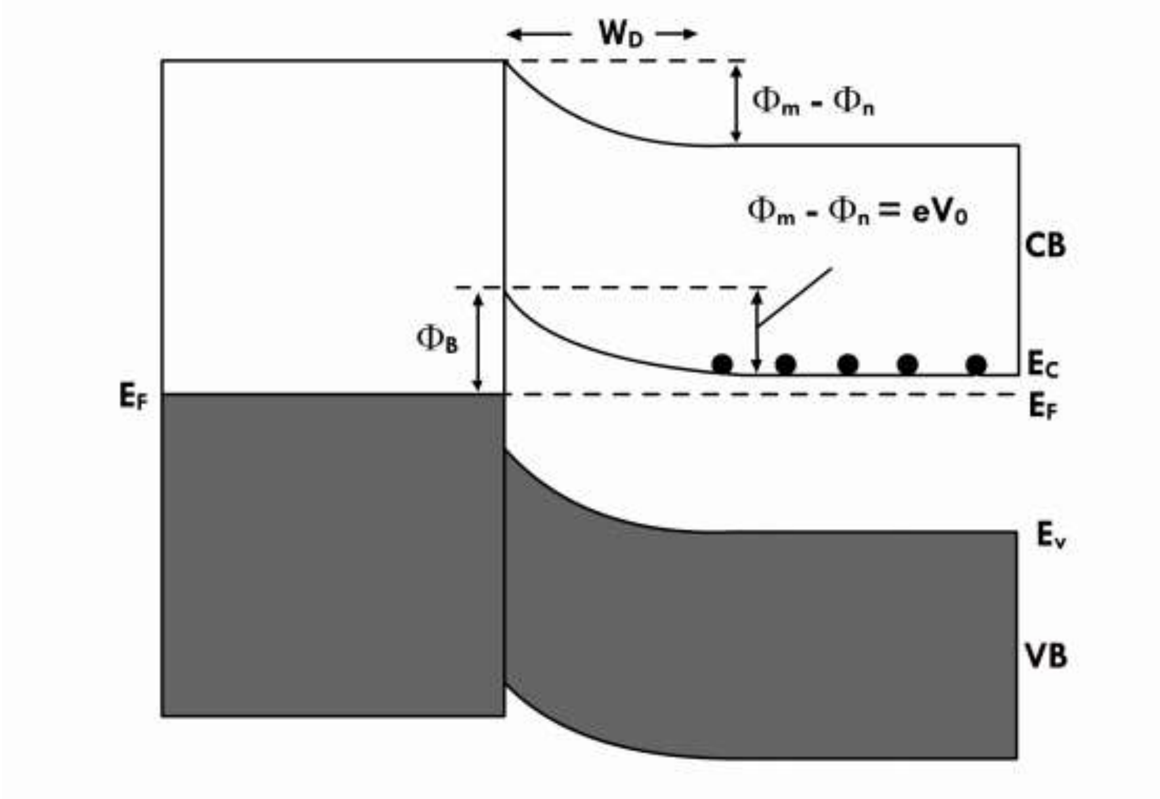


Figure 8: Schottky junction showing the band bending on the semiconductor side. Semiconductor bands bend up going from the semiconductor (positive) to metal (negative) since this is the same direction as the electric field. Adapted from *Principles of Electronic Materials - S.O. Kasap*.

Rectifying Junction or Schottky Junction

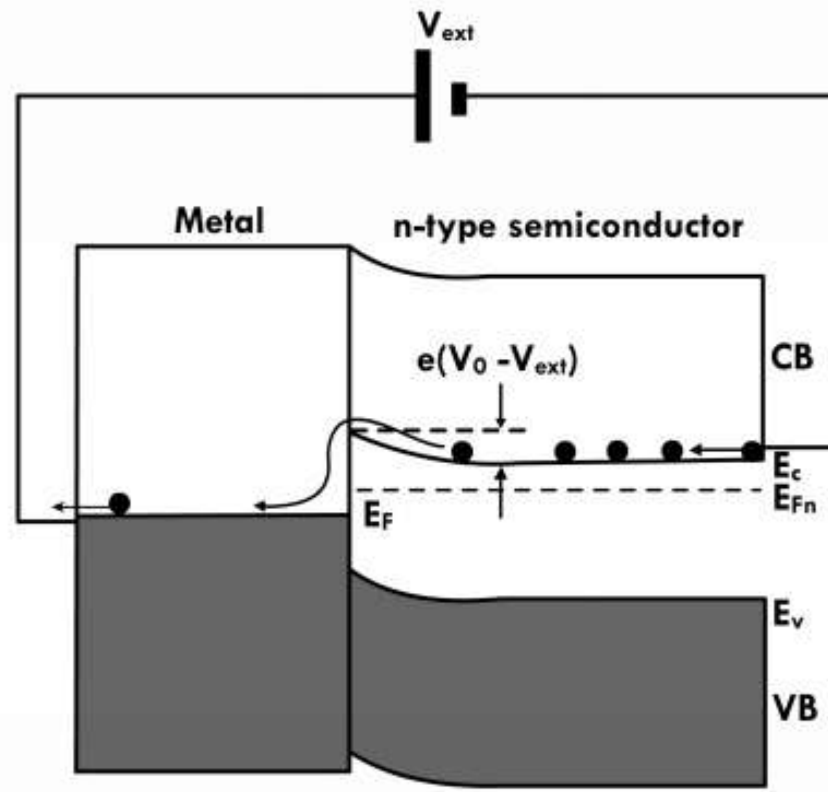


Figure 9: Schottky junction under forward bias. Adapted from *Principles of Electronic Materials - S.O. Kasap.*

Rectifying Junction or Schottky Junction

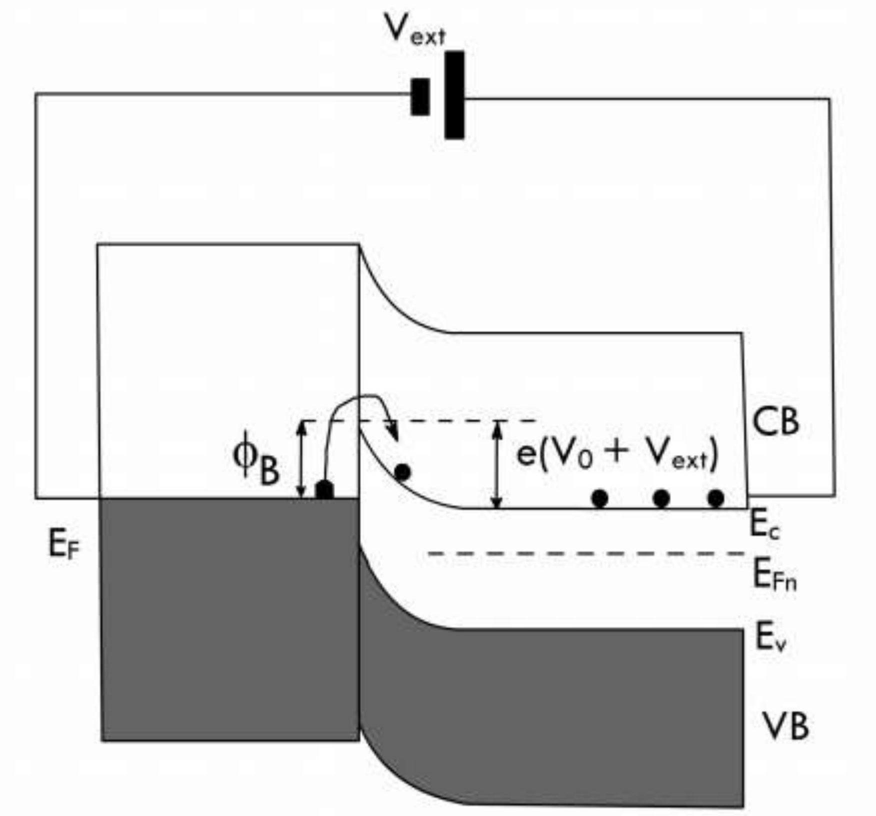


Figure 10: Schottky junction under reverse bias. Adapted from *Principles of Electronic Materials - S.O. Kasap.*

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Rectifying Junction or Schottky Junction

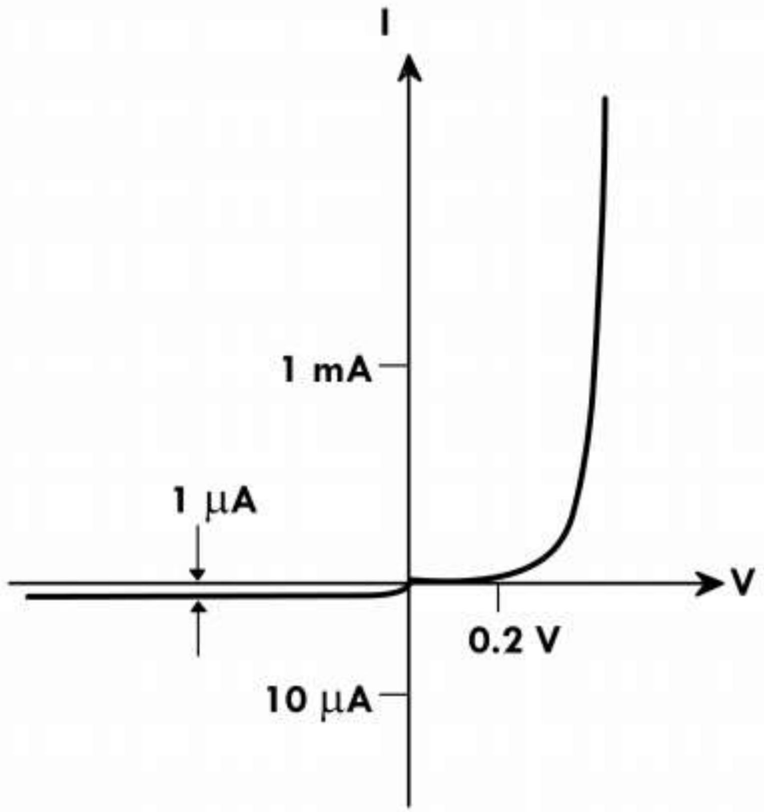


Figure 11: $I - V$ characteristics of a Schottky junction showing rectifying properties. Adapted from *Principles of Electronic Materials - S.O. Kasap.*

Non-Rectifying Junction or Ohmic Junction

Whenever, the work function of metal is smaller than that of n type semiconductor it forms non rectifying or ohmic junction.

Let ϕ_m and ϕ_s be the work function of metal and n type semiconductor , respectively where $\phi_m < \phi_s$.

When metal semiconductor contact is made, the conduction electrons begin to flow from the metal to semiconductor until the Fermi energies on both sides of the junction becomes equal. Therefore, metal becomes positive charged and the n-type semiconductor becomes negative charged. As a result potential barrier is formed at the metal semiconductor junction equal to $\phi_S - \phi_m$ =eV.

When potential is applied to the system after contact such that

N-type is connected to positive charge and metal to negative charge, the electrons flow from semiconductor to metal without encountering an appreciable barrier.

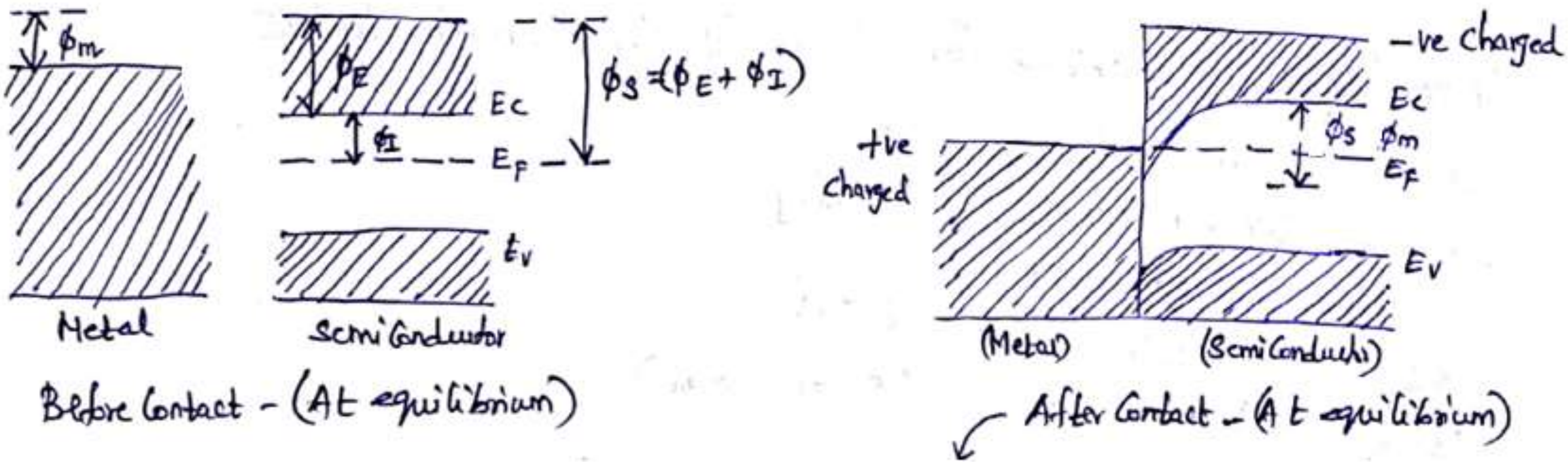
Non-Rectifying Junction or Ohmic Junction

Conversely if the voltage is reversed, so as to make semiconductor negative charge and metal positive charge, the electrons flow from metal to semiconductor without any change in barrier.

Thus in both the cases the current is directly proportional to the applied voltage in accordance with ohms law. Such contacts are called as ohmic contacts.

Thus, a Ohmic junction behaves as a resistor conducting in both forward and reverse bias. The resistivity is determined by the bulk resistivity of the semiconductor.

Non-Rectifying Junction or Ohmic Junction



Non-Rectifying Junction or Ohmic Junction

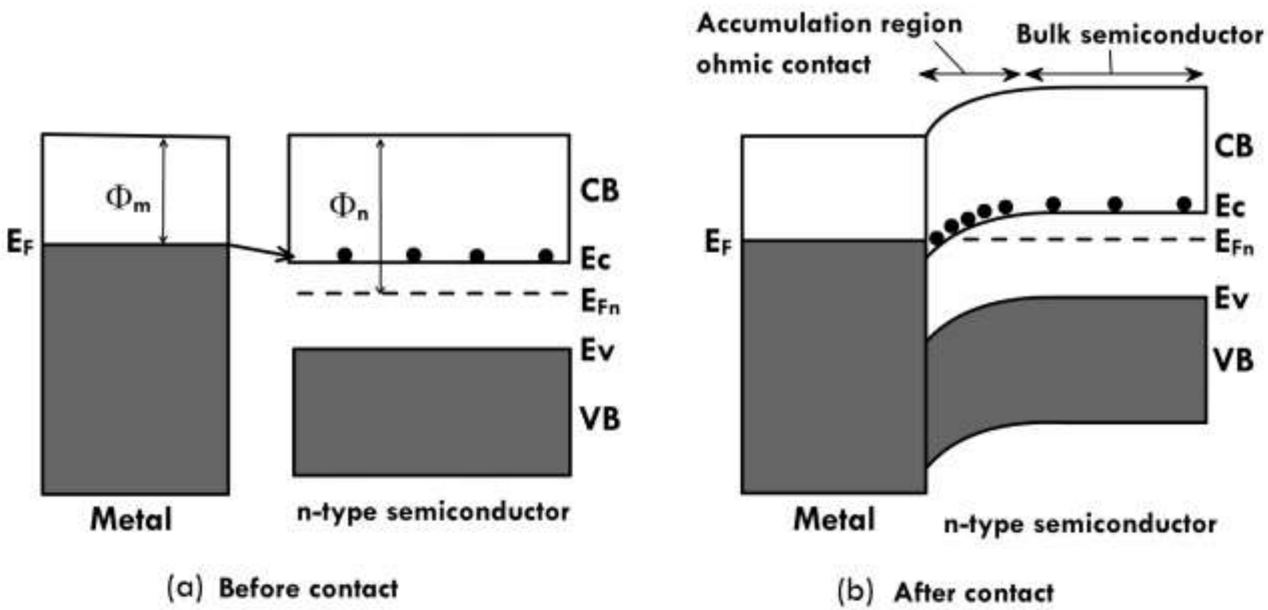


Figure 13: Ohmic junction (a) before and (b) after contact. Before contacts the Fermi levels are at different positions and they line up on contact to give an accumulation region in the semiconductor. Adapted from *Principles of Electronic Materials - S.O. Kasap*.

Rectifying Junction or Schottky Junction

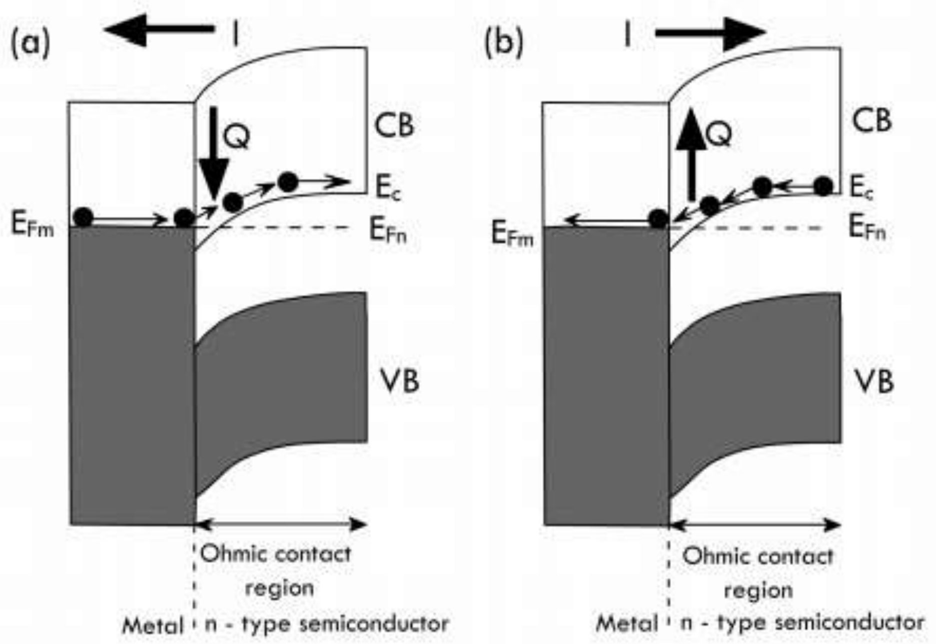


Figure 14: Current flow through an Ohmic junction can lead to heat (a) absorption or (b) release. This depends on the external bias, that determines the direction of heat flow. When electrons move from metal to higher energy levels in the semiconductor heat is absorbed and the reverse happens when electrons flow from semiconductor to metal. Adapted from *Principles of Electronic Materials - S.O. Kasap.*

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18PYB103J –Semiconductor Physics

Module 2 Lecture 13

1. ***Semiconductor material for optoelectronic applications – Introduction***
2. ***Photocurrent in a P-N junction diode***

Semiconductor material for optoelectronic applications – Introduction

Major semiconducting materials used for optoelectronics are III – V and II – VI groups.

Among the two groups of semiconductors, III – V is more suitable as they are direct band gap materials which is necessary condition needed for opto electronic devices to convert electrical energy into light energy conversion.

III – V materials – Column III and V in the periodic table

III column – Al, Ga, In

V column - N, P, As, Sb

Semiconductor material for optoelectronic applications – Introduction

Important applications for some III – V semiconducting materials

AlGaAs – Light emitter and modulator

GaInAsP – Optoelectronic device

AlGaInP – Red Emitter LED

GaAsP – Visible LED

AlGaAsSb – Light emitter and detector

Semiconductor material for optoelectronic applications – Introduction

The suitable choice of above materials depends on their quantum dimensions (1D, 2D or 3D) for optoelectronic applications.

II – VI semiconducting materials – column II and VI in periodic table. They are having wide range of optoelectronic properties ranging from far IR to UV region. This can be easily tuned to different band gap (Eg) by incorporating magnetic ions. They have stronger polarity due to ionic bonding character.

Semiconductor material for optoelectronic applications – Introduction

Important applications of some II – VI semiconductors

ZnSe – Blue-Green LEDs

ZnS – UV emitters, Display

ZnO – UV emitters

CdS – Visible light LEDs

CdSe – Colour LEDs (Short wave)

Semiconductor material for optoelectronic applications – Introduction

Color Name	Wavelength (Nanometers)	Semiconductor Composition
Infrared	880	GaAlAs/GaAs
Ultra Red	660	GaAlAs/GaAlAs
Super Red	633	AlGaInP
Super Orange	612	AlGaInP
Orange	605	GaAsP/GaP
Yellow	585	GaAsP/GaP
Incandescent White	4500K (CT)	InGaN/SiC
Pale White	6500K (CT)	InGaN/SiC
Cool White	8000K (CT)	InGaN/SiC
Pure Green	555	GaP/GaP
Super Blue	470	GaN/SiC
Blue Violet	430	GaN/SiC
Ultraviolet	395	InGaN/SiC

WHAT IS PHOTO DIODE?

- It is a form of light-weight sensor that converts light energy into electrical voltage or current. Photodiode is a type of semi conducting device with PN junction. Between the p (positive) and n (negative) layers, an intrinsic layer is present. The photo diode accepts light energy as input to generate electric current.
- It is also called as Photodetector, photo sensor or light detector. Photo diode operates in reverse bias condition i.e. the p – side of the photodiode is connected with negative terminal of battery (or the power supply) and n – side to the positive terminal of battery.

WHAT IS PHOTO DIODE?

- Typical photodiode materials are Silicon, Germanium, Indium Gallium Arsenide Phosphide and Indium gallium arsenide.
- Internally, a photodiode has optical filters, built in lens and a surface area. When surface area of photodiode increases, it results in more response time. Few photo diodes will look like Light Emitting Diode (LED). It has two terminals as shown below. The smaller terminal acts as cathode and longer terminal acts as anode.

PHOTO CURRENT IN PN JUNCTION DIODE (PHOTO DIODE)

- In a photodiode, the incident optical signal generates electron-hole pairs that gives rise to a photo current across PN junction.
- When a PN junction is illuminated with light of photon energy (E) greater than E_g, photons are absorbed in semiconductor and electron-hole pairs are generated both in n-region and p-region of the junction.

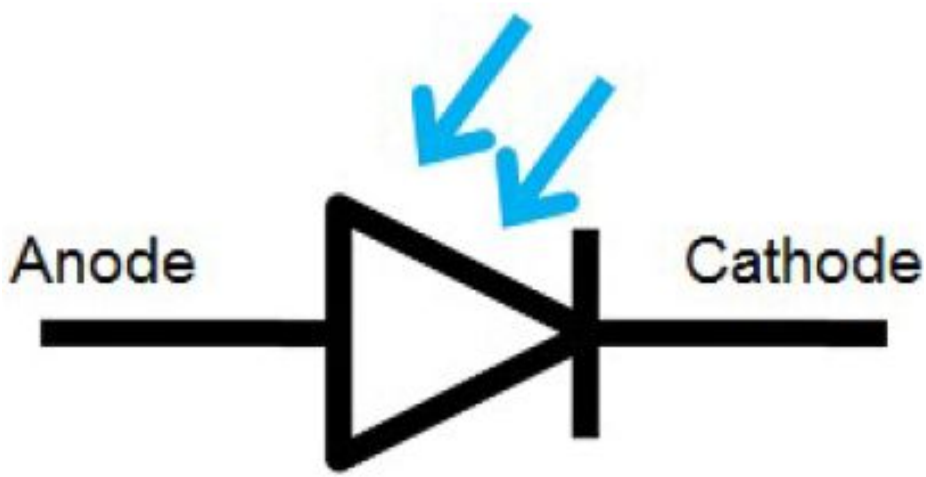


PHOTO CURRENT IN PN JUNCTION DIODE (PHOTO DIODE)

- For the electron-hole pair to contribute towards current in external circuit, the generated electron and holes must be separated before they recombine.
- Once electron-hole pairs are generated in the depletion layer, the electric field in the built-in-potential or contact potential sweeps away the electron and holes in opposite directions.
- The photo generated minority carriers which are generated within one diffusion length from the depletion layer edge, can also diffuse to the depletion region without recombining.

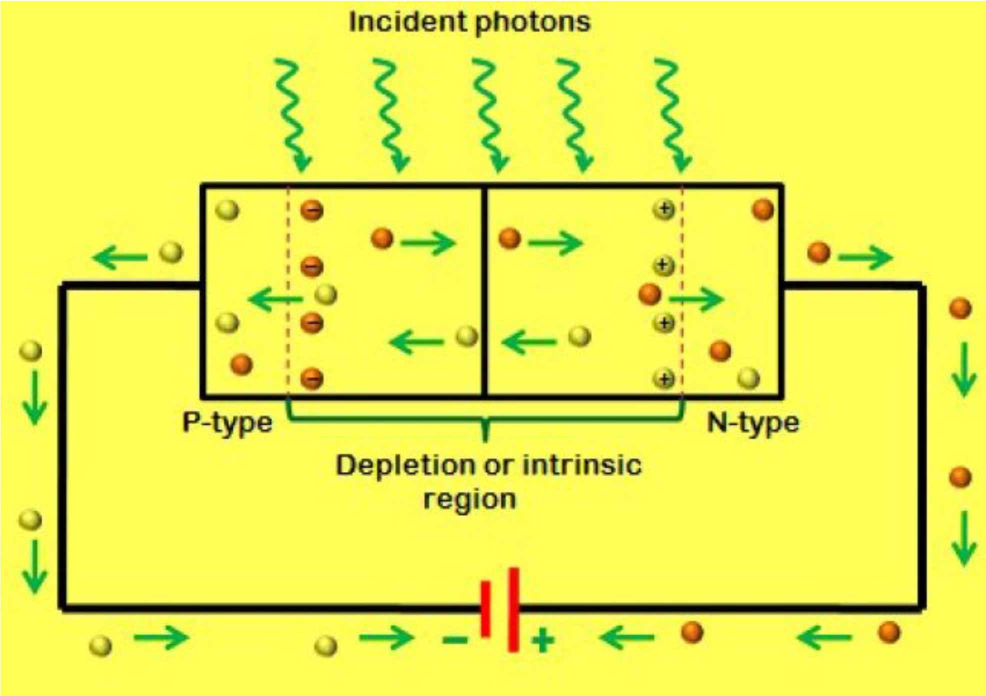
PHOTO CURRENT IN PHOTO DIODE

- They are then swept across the junction due to the electric field present in the depletion region. Due to the direction of electric field being from the n-region to p-region, the holes flow towards the p-region and electrons to the n-region.
- Since the direction of this photo generated current I_L is opposite to that in a forward- biased diode, the total current in the illuminated PN junction diode is

$$I_L = I_n L + I_p L + I_d$$

WORKING OF A PHOTODIODE

- Generally, when a light is made to illuminate the PN junction, covalent bonds are ionized. This generates hole and electron pairs. Photocurrents are produced due to generation of electron-hole pairs. Electron hole pairs are formed when photons of energy more than 1.1eV hits the diode.
- When the photon enters the depletion region of diode, it hits the atom with high energy.
- This results in release of electron from atom structure. After the electron release, free electrons and hole are produced.



WORKING OF A PHOTODIODE

- In general, an electron will have negative charge and holes will have a positive charge. The depletion energy will have built in electric filed. Due to that electric filed, electron hole pairs moves away from the junction.
- Hence, holes move to anode and electrons move to cathode to produce photo current. The photon absorption intensity and photon energy are directly proportional to each other. When energy of photons is less, the absorption will be more. This entire process is known as Inner Photoelectric Effect.

ENERGY BAND DIAGRAM OF A PHOTODIODE

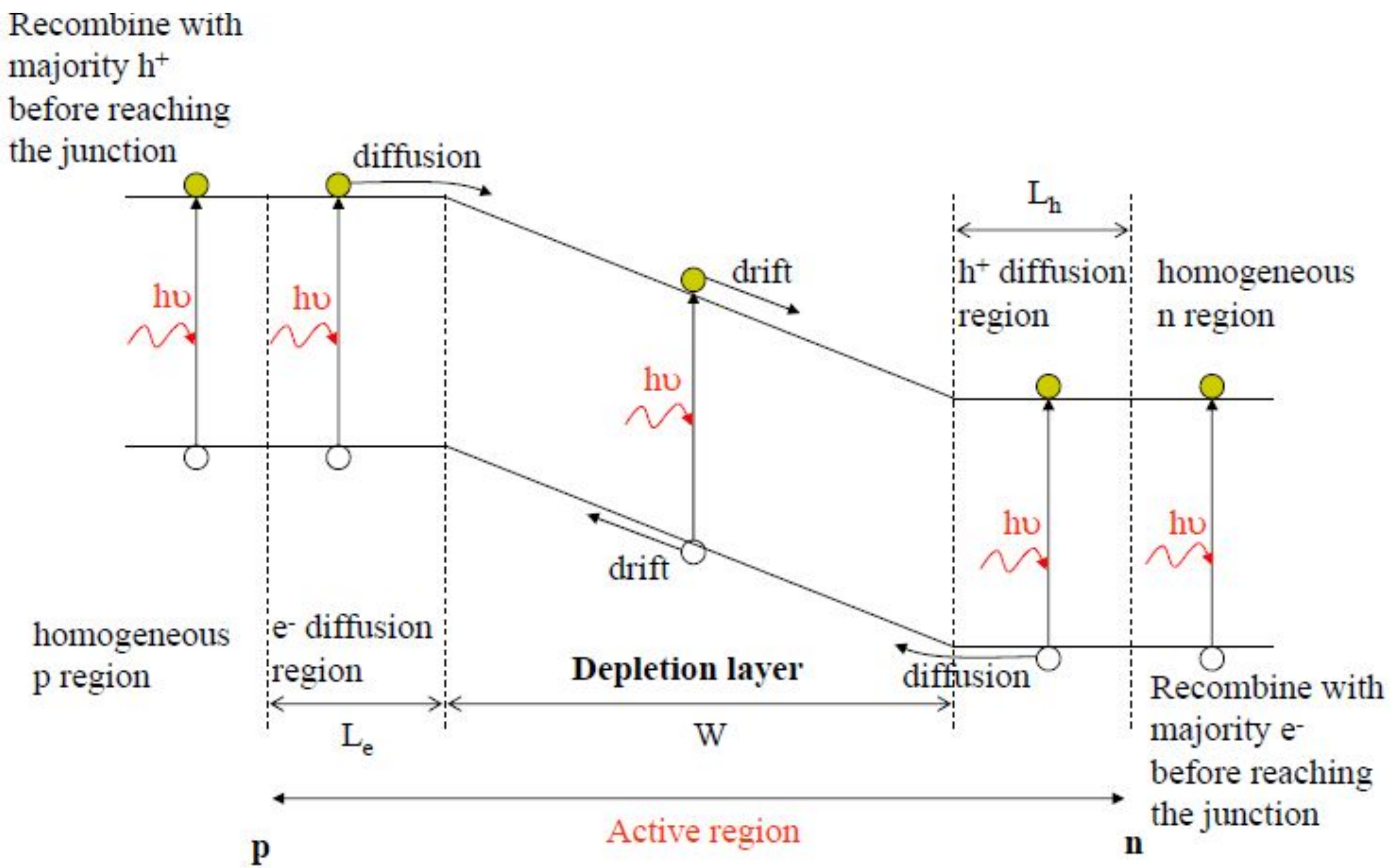
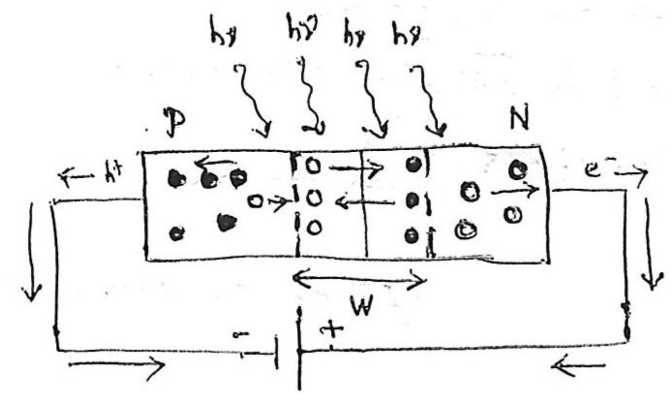


PHOTO CURRENT IN PHOTO DIODE

The photocurrent generated in photodiode has three component

1. Photo generated current in space-charge region
2. Photo generated current in n-region
3. Photo generated current in p-region



If G is the generation rate of excess carrier and A is diode area then photo current, the excess carrier in depletion region quickly moved by electric field (electron to n-region and holes to p-region).

PHOTO CURRENT IN PHOTO DIODE

- The photo generated current in the depletion region is

$$I_1 = Ae\int G dx = eGWA$$

where W is the depletion width and this current is very fast (prompt photocurrent).

- In addition to the carriers generated in the depletion region, electron-hole pairs are generated in the neutral n-region and p-region of the diode.

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PHOTO CURRENT IN PHOTO DIODE

- We may expect that holes generated within a distance L_p (the diffusion length) of the depletion region edge will be able to enter the depletion region from where the electric field will sweep them into p-side.

$$I_p = eG_L L_p A$$

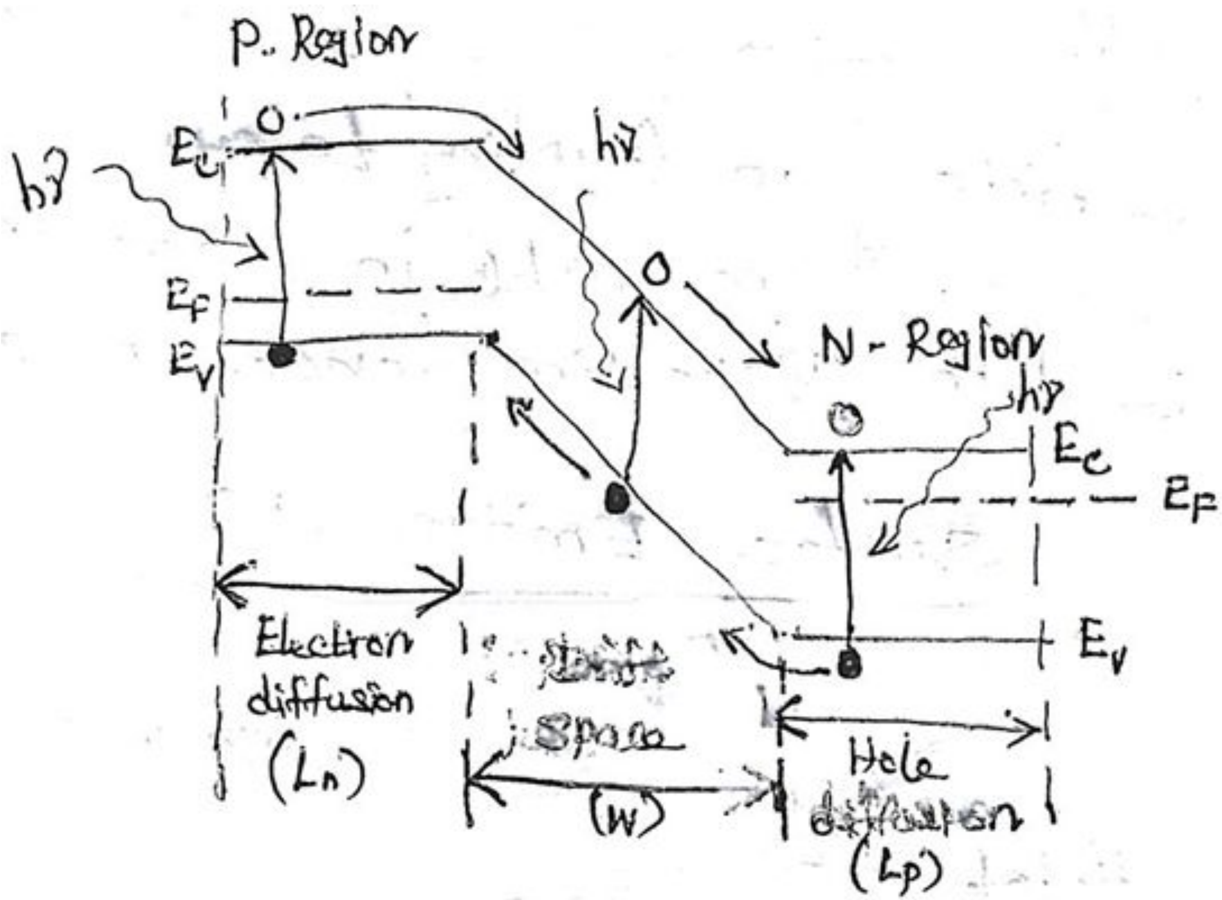
- Similarly, excess electrons produced in p region will give photo current.

$$I_n = eG_L L_n A$$

PHOTO CURRENT IN PHOTO DIODE

- So total current due to carriers in the neutral region and the depletion region is given by

$$I_L = eG_L(L_p + L_n + W)A$$



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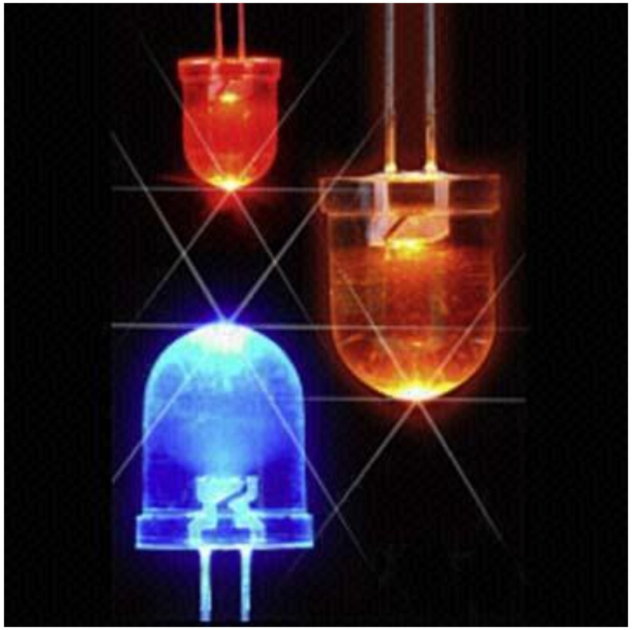
18PYB103J –Semiconductor Physics

Module 2 Lecture 14

1. ***Light emitting diode – Construction & Working***
2. ***Classification of Light emitting diode (edge and surface)***

What is LED?



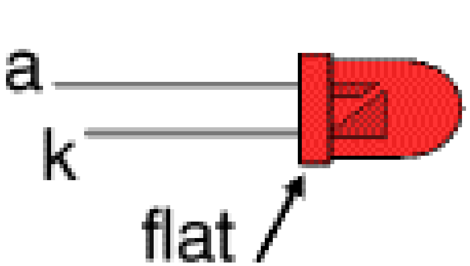
- Semiconductors bring quality to light!

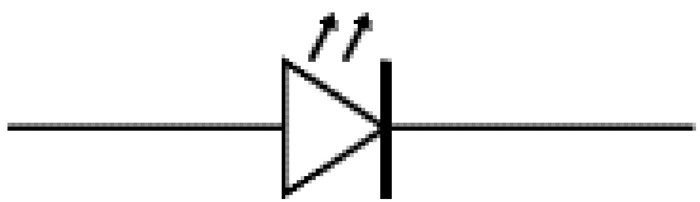
LED are semiconductor p-n junctions that under forward bias conditions can emit radiation by electroluminescence in the UV, visible or infrared regions of the electromagnetic spectrum. The quanta of light energy released is approximately proportional to the band gap of the semiconductor..

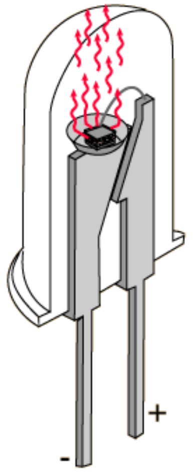

12:16
Inside a Light Emitting Diode
Emitted Light Beams
Diode
Transparent Plastic Case
Terminal Pins
0.9999
LED SIGN
9:58

•A light emitting diode (LED) is essentially a PN junction opto-semiconductor that emits a monochromatic (single color) light when operated in a forward biased direction.

•LEDs convert electrical energy into light energy. They are frequently used as "pilot" lights in electronic appliances to indicate whether the circuit is closed or not.





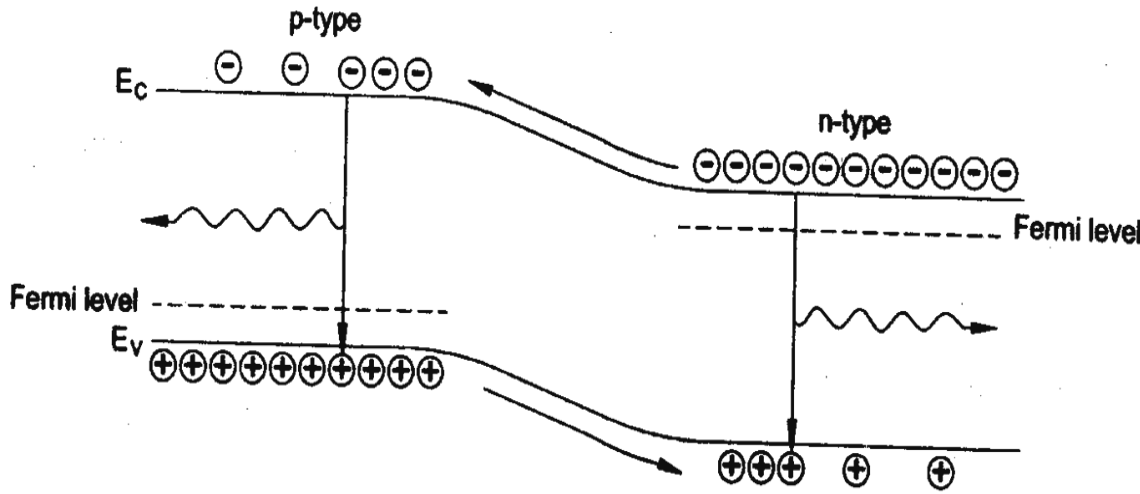


Light Emitting Diodes

Principle

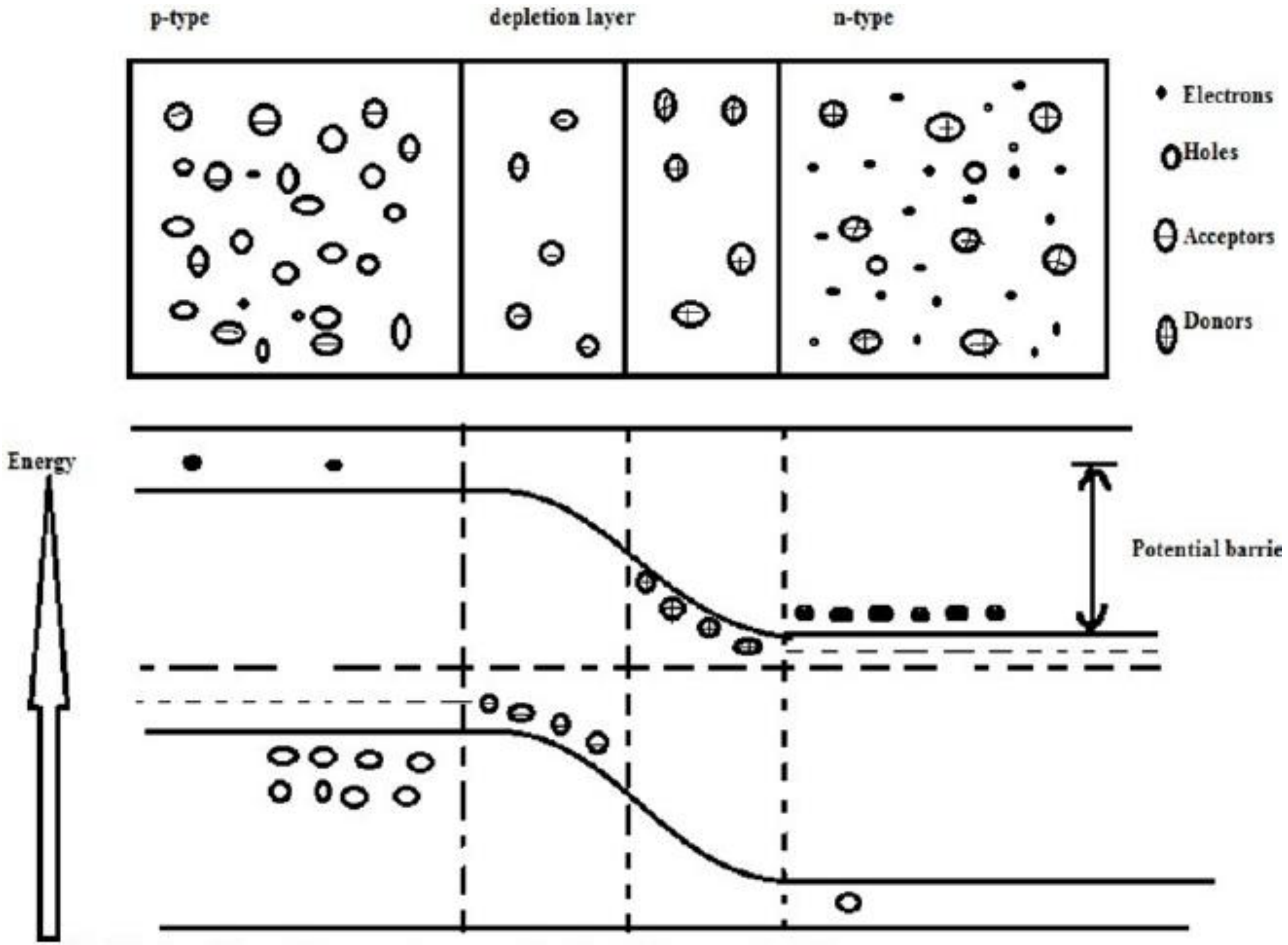
- The p-n junction diode is forward biased. Due to forward bias, the majority carriers from ‘n’ and ‘p’ regions cross the junction and become minority carriers in the other junction (i.e.) Electrons, which are majority carriers in ‘n’ region cross the junction and go to ‘p’ region and become minority carriers in p-region.
- Similarly, holes which are majority carries in ‘p’ region cross the junction and go to ‘n’ region and become minority carriers in ‘n’ region and this phenomenon is called ***minority carrier injection.***

Radiative Recombination



Now if the biasing voltage is further increased, these excess minority carriers diffuse away from the junction and they directly recombine with the majority carriers. (i.e.) the electrons, which are excess minority carriers in p-region recombine with the holes which are the majority carriers in 'p' region and emit light. Similarly, the holes which are excess minority carriers in 'n' region recombine with the electrons which are majority carriers in 'n' region and emit light.

Radiative Recombination



Radiative Recombination

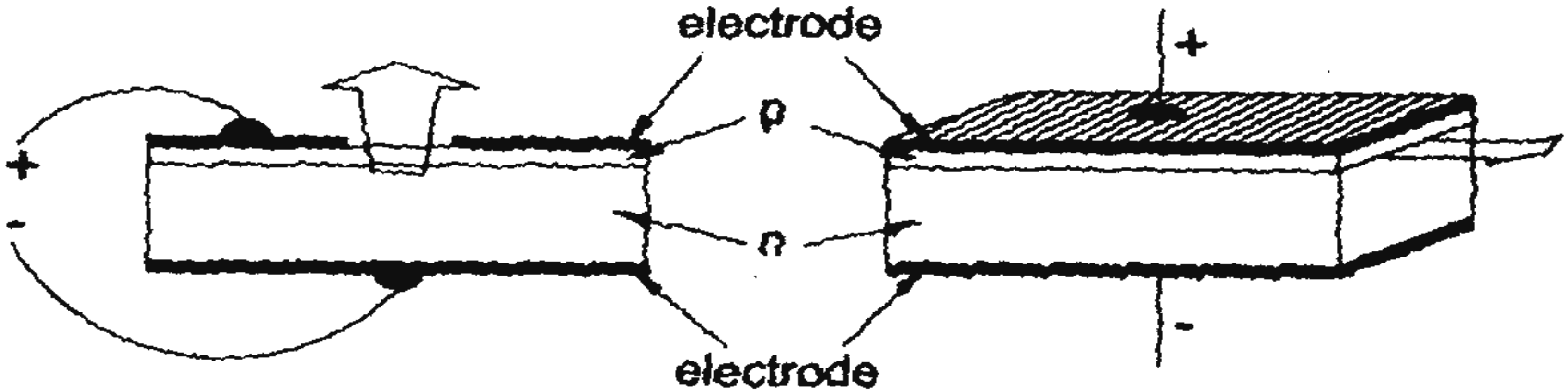
Thus radiative recombination events lead to photon emission. The number of radiative recombination is proportional to the carrier injection rate and hence to the total current flowing through the device as given by $\boldsymbol{I} = \boldsymbol{I}_0\left[\exp\left(\frac{\boldsymbol{eV}}{\beta \boldsymbol{kT}}\right) - 1\right]$

where I_0 - the saturation current ; V- the forward bias voltage; k - the Boltzmann constant ; β -varies from 1 and 2 depending on the semiconductor and temperature.

The optical photon emitted due to radiative recombination has the energy very close to the bandgap energy E_g and frequency of the emitted photon is given by $\frac{hc}{\lambda} = E_g$ where λ - the photon wavelength; h – Planck's constant; c - the velocity of light in vacuum.

LED Construction

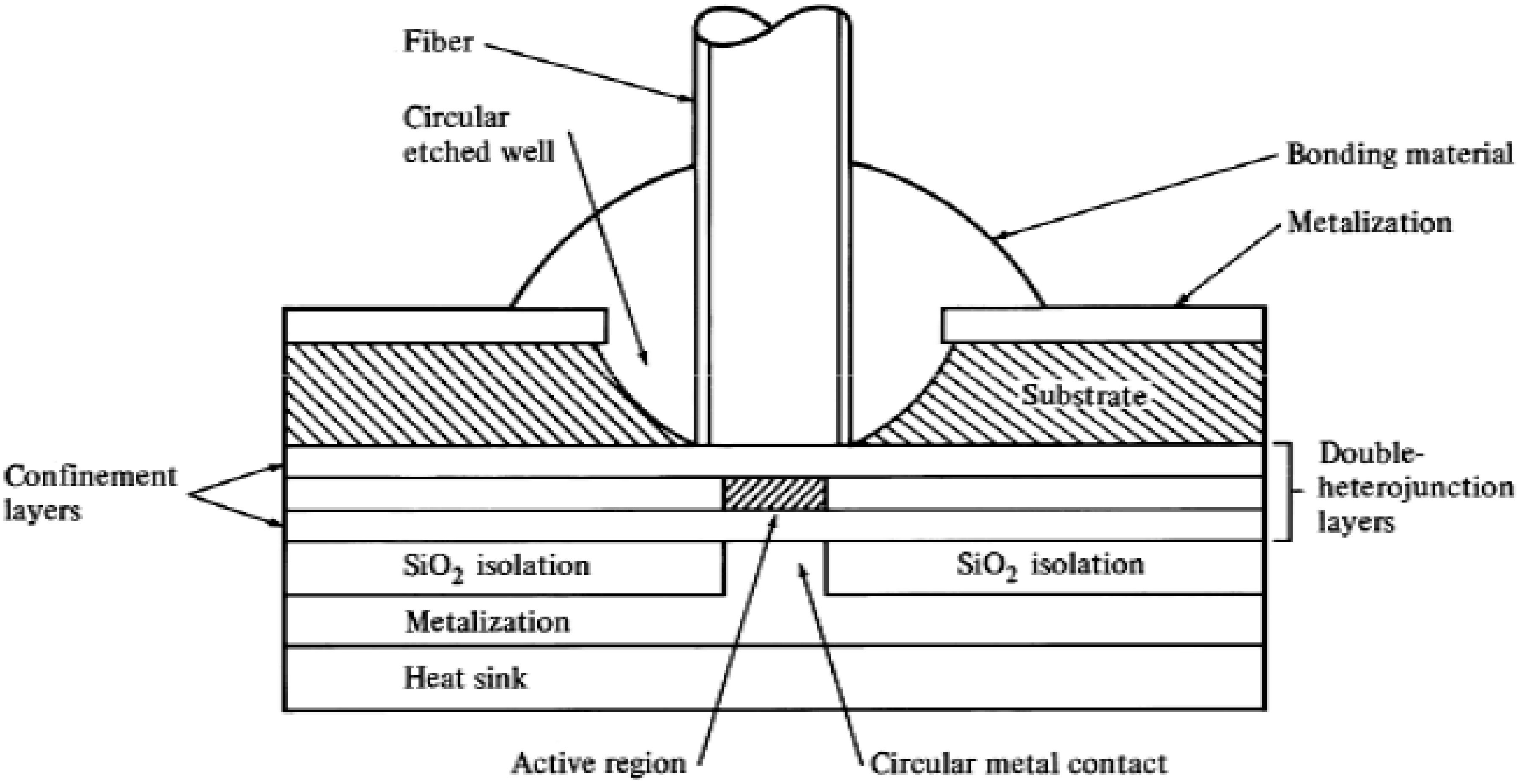
An LED must be constructed such that the light emitted by the radiative recombination events can escape the structure.



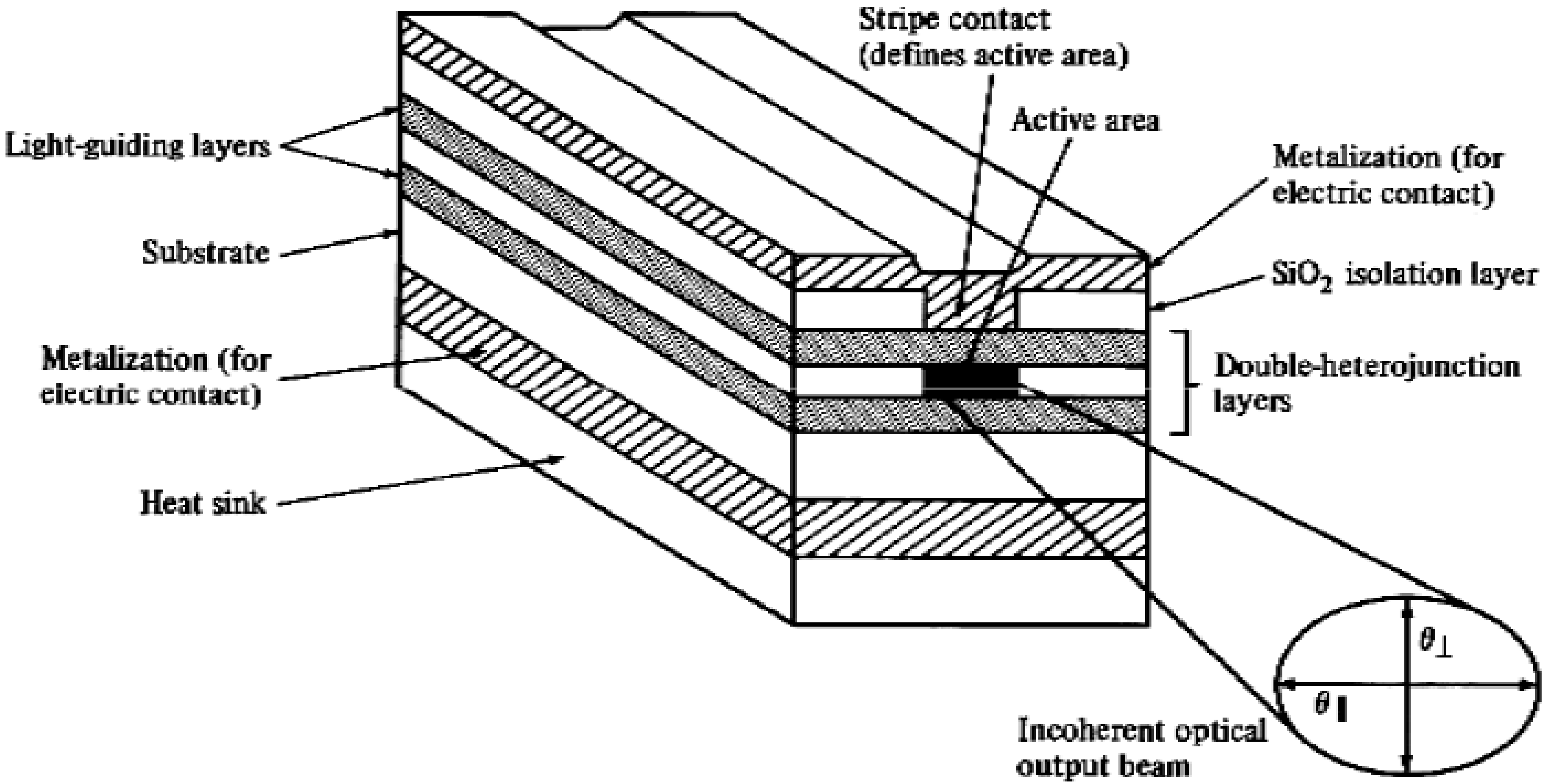
(a) Surface emitting LED

(b) Edge emitting LED

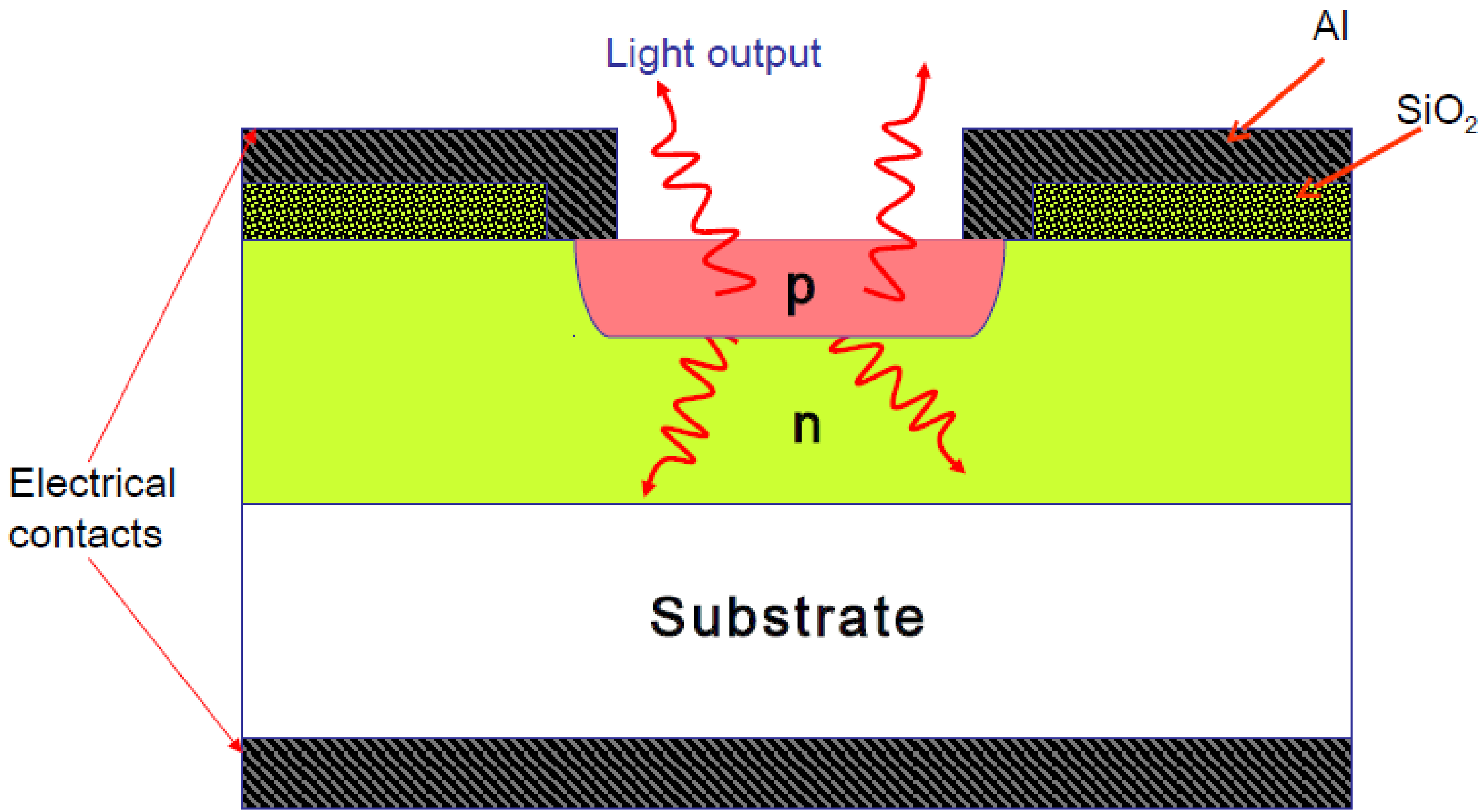
Surface Emitting LED



Edge Emitting LED



Construction of Typical LED



LED Construction

- LEDs can be designed as either surface or edge emitters. Surface emitting LEDs can be made such that the bottom edge reflects light back towards the top surface to enhance the output intensity. The main advantage of edge emitter LEDs is the emitted radiation is relatively direct. Hence edge emitter LEDs $\sin\theta_c = \frac{n_2}{n_1}$ higher efficiency in coupling to an optical fibre.
- Although the internal quantum efficiency of LEDs is 100%, the external efficiencies are much lower. The main reason is that most of the emitted light radiation strikes the material interface at greater than critical angle and hence trapped with in the device. The internal critical angle at the semiconductor – air boundary is given by

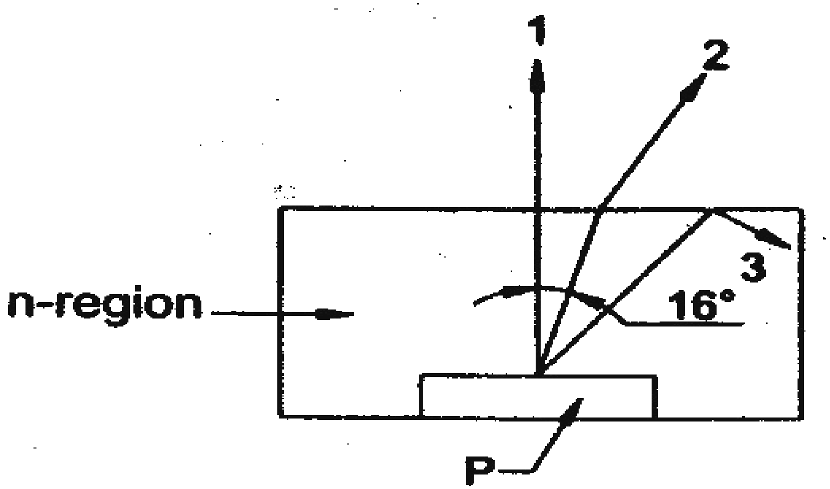
Critical angle

Where n_1 is the refractive index of air = 1.0

n_2 is the refractive index of the semiconductor

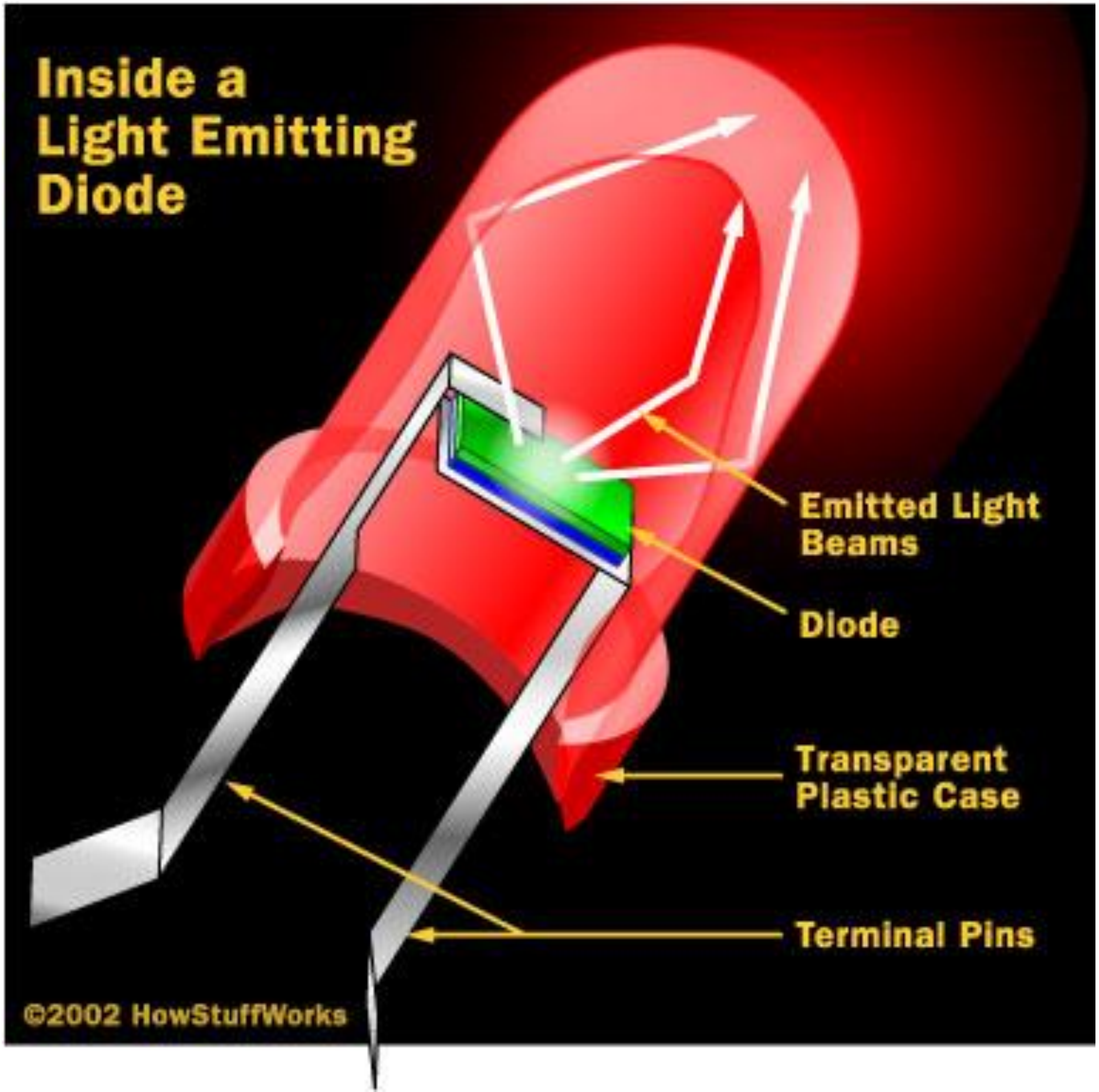
For group III semiconductor $n_2 = 3.5$

Therefore $\theta c = 16°$



Therefore all rays of light striking the surface at an angle exceeding 16° suffer total internal reflection and as a result most of the emitted light is reflected back inside the semiconductor crystal.

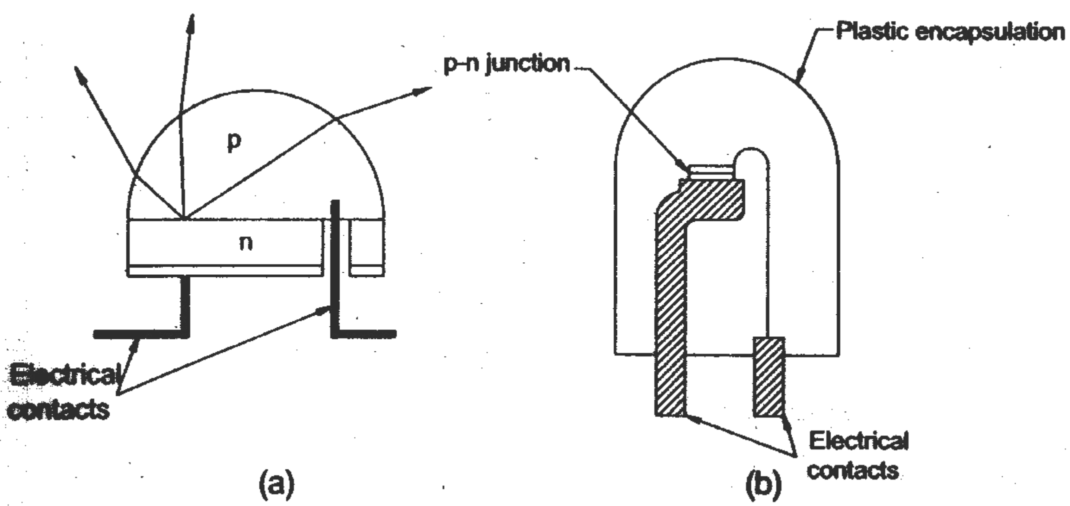
Inside a Light Emitting Diode



1. Transparent Plastic Case
2. Terminal Pins
3. Diode

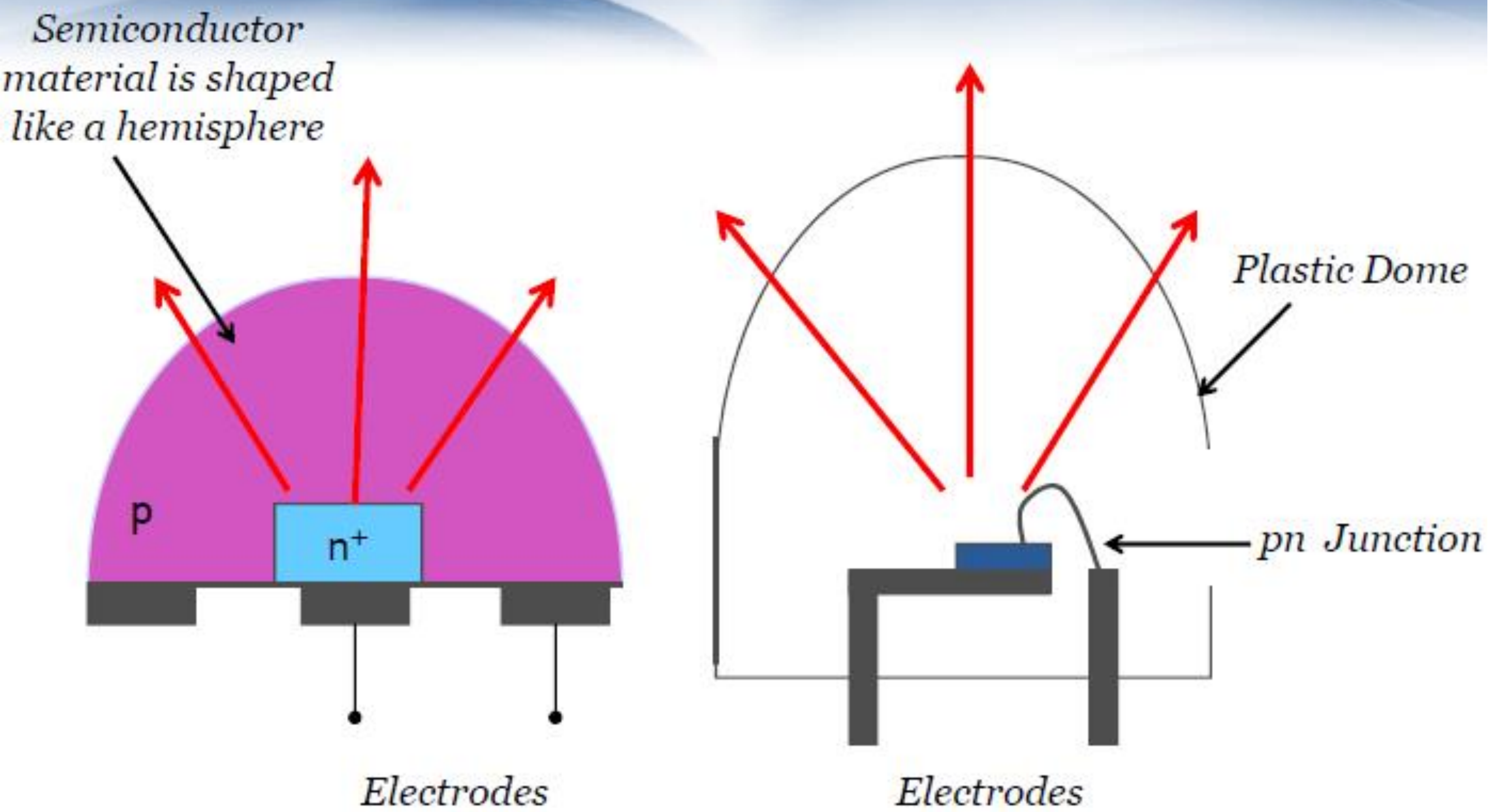
Hemispherical Dome shape

- Hence to improve the external efficiency losses caused bulk absorption has to be minimized and the surface transmission has to be increased. One method to achieve this is to give the semiconductor a dome structure.
- Hemi spherical domes made from plastics are effective in increasing the external efficiency by a factor 2 or 3. There will be some losses at the plastic/ air interface but these are easily minimized by molding the plastic into an approximately hemispherical shape.



Hemispherical Dome shape

Why do we need the DOME ?



To reduce TIR ...

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LED Materials

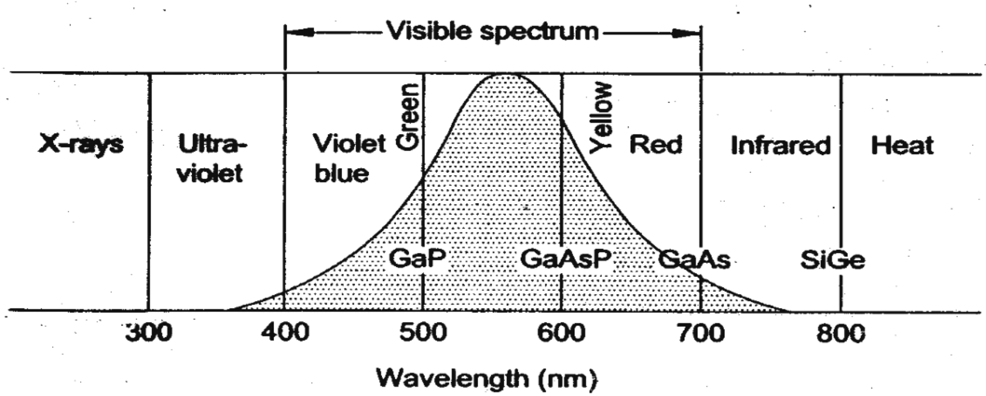
- The choice of the materials for an LED is decided by the spectral requirements for a particular application. The most commonly used materials for LEDs are GaP, GaAs and their related ternary compound Ga Asx P1-x
- The bandgap radiation of GaP, GaAs and GaAsP. GaP which gives a peak at 560 nm is very close to the wavelength of maximum eye response.

LED Materials

•This makes GaP one of the most useful of all visible semiconductor light sources since in addition to green light both red and other colours can be produced by appropriate dopants.

Wavelength response of LED materials

Materia l	Dopant	Band gap (eV)	Wavelength (Nm)	Quantum efficiency (%)
GaP	N	2.88	430	0.6
GaP	Zn0	1.80	690	0.2
GaP	N	2.25	550	0.1
GaAs	P	1.88	660	0.2
AlGa	As	1.84	675	0.2



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18PYB103J –Semiconductor Physics

Module 2 Lecture 15

1. ***Introduction to Optoelectronic integrated circuits***
2. ***Organic light emitting diodes – basic concepts***

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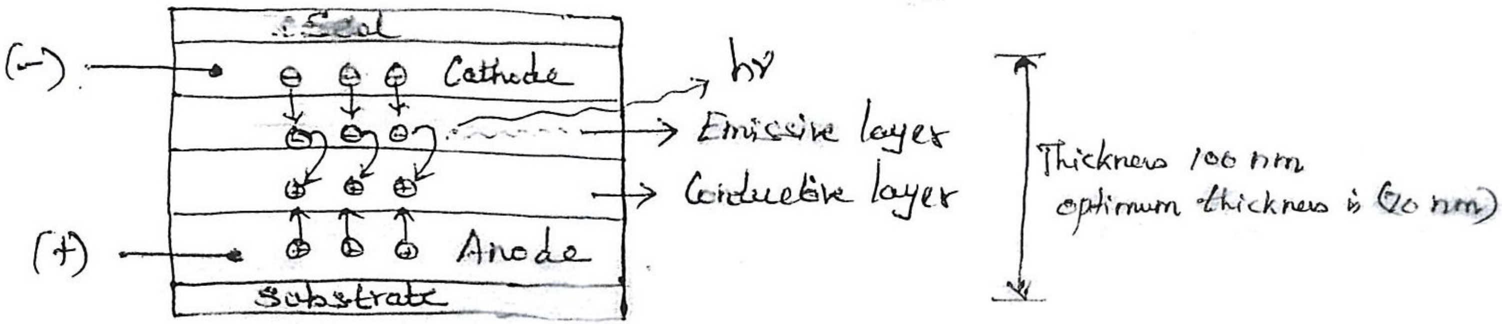
ORGANIC LIGHT EMITTING DIODE (OLED)

A type of LED where emissive electroluminescent layer is a film of organic compound which emit light in response to an electric current.

Structure of OLED:

A simple OLED is made of six different layers. On the top and bottom layers of protective glass or plastic. The top layer is called seal and the bottom layer is substrate. In between seal and substrate, a negative terminal (cathode) and positive terminal (anode), and finally between cathode and anode there are two layers made of organic molecules called emissive layer which produces light and the conductive layer.

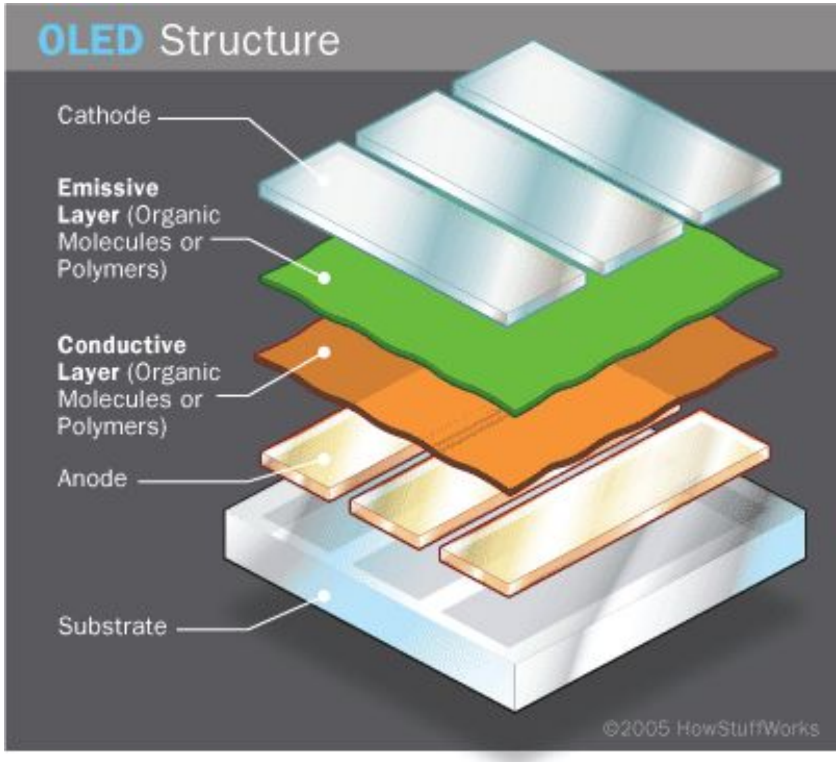
ORGANIC LIGHT EMITTING DIODE (OLED)



1. Substrate – Clean glass / plastic
2. Anode – Positively charged (Indium Tin Oxide) which ejects holes
3. Organic layer –Emissive and Conductive layers –Polyaniline and Polyfluorene
4. Cathode – Negatively charged which injects electrons

Conjugated polymers are having characteristics of LED and having energy gap (Eg) same like semiconductors by doping with p-type/ n-type materials used for light emission

OLED COMPONENTS



Like an LED, an OLED is a solid-state semiconductor device that is 100 to 500 nanometers thick or about 200 times smaller than a human hair. OLEDs can have either two layers or three layers of organic material; in the latter design, the third layer helps transport electrons from the cathode to the emissive layer.

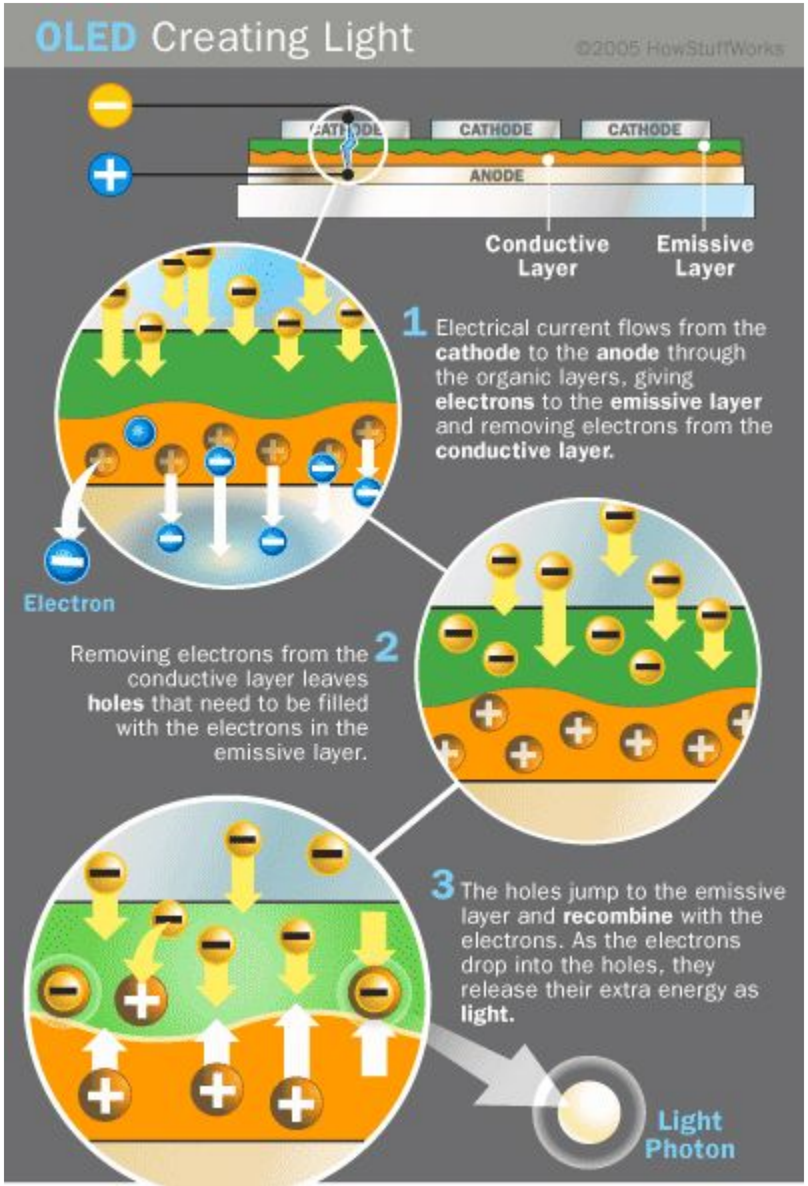
HOW DO OLEDS EMIT LIGHT?

OLEDs emit light in a similar manner to LEDs, through a process called **electro phosphorescence**.

The process is as follows:

1. The battery or power supply of the device containing the OLED applies a voltage across the OLED.
2. An electrical current flows from the cathode to the anode through the organic layers (an electrical current is a flow of electrons). The cathode gives electrons to the emissive layer of organic molecules. The anode removes electrons from the conductive layer of organic molecules. (This is the equivalent to giving electron holes to the conductive layer.)

HOW DO OLEDS EMIT LIGHT?



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HOW DO OLEDS EMIT LIGHT?

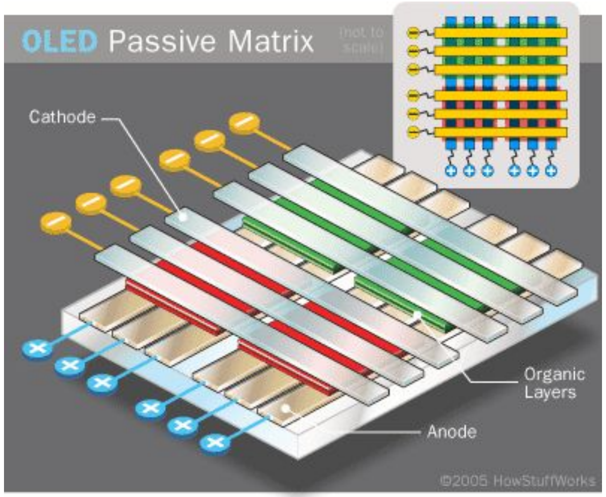
3. At the boundary between the emissive and the conductive layers, electrons find electron holes. When an electron finds an electron hole, the electron fills the hole (it falls into an energy level of the atom that's missing an electron). When this happens, the electron gives up energy in the form of a photon of light.
4. The OLED emits light.
5. The color of the light depends on the type of organic molecule in the emissive layer. Manufacturers place several types of organic films on the same OLED to make color displays.
6. The intensity or brightness of the light depends on the amount of electrical current applied: the more current, the brighter the light.

TYPES OF OLED

1. **Passive-matrix OLED (PMOLED)** – PMOLEDs have strips of cathode, organic layers and strips of anode. The anode strips are arranged perpendicular to the cathode strips. The intersections of the cathode and anode make up the pixels where light is emitted. External circuitry applies current to selected strips of anode and cathode, determining which pixels get turned on and which pixels remain off. Again, the brightness of each pixel is proportional to the amount of applied current.

TYPES OF OLEDS

PMOLEDs are easy to make, but they consume more power than other types of OLED, mainly due to the power needed for the external circuitry. PMOLEDs are most efficient for text and icons and are best suited for small screens (2- to 3-inch diagonal) such as those you find in cell phones, Personal Digital Assistants (PDAs) and MP3 players. Even with the external circuitry, passive-matrix OLEDs consume less battery power than the LCDs that currently power these devices.



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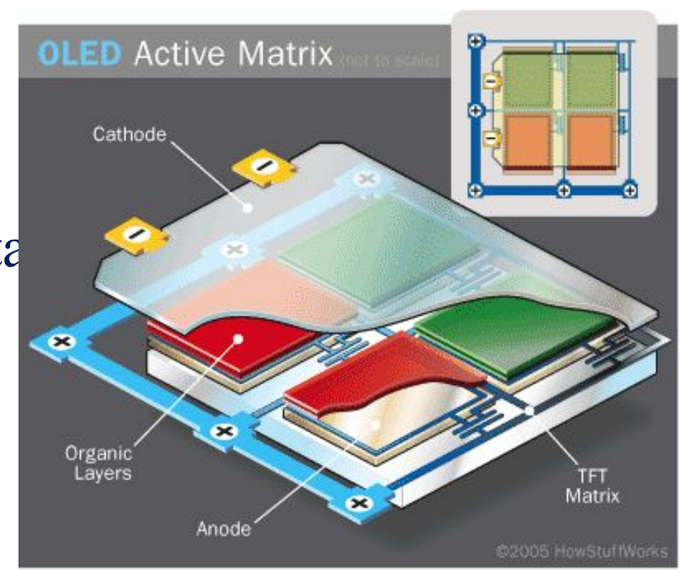
TYPES OF OLEDS

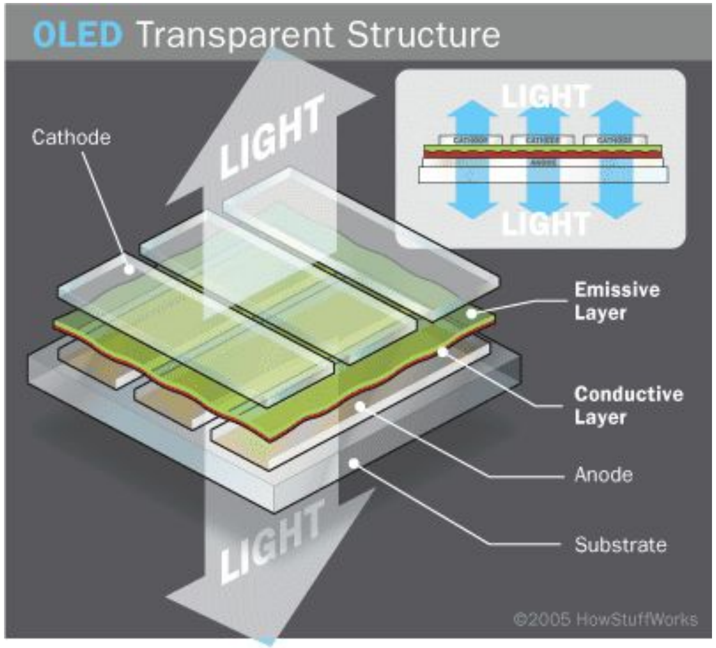
2. Active-matrix OLED (AMOLED) – AMOLEDs have full layers of cathode, organic molecules and anode, but the anode layer overlays a thin film transistor (TFT) array that forms a matrix. The TFT array itself is the circuitry that determines which pixels get turned on to form an image.

AMOLEDs consume less power than PMOLEDs because the TFT array requires less power than external circuitry, so they are efficient for large displays. AMOLEDs also have faster refresh rates suita for video. The best uses for AMOLEDs are computer monitors, large-screen TVs and electronic signs or billboards.



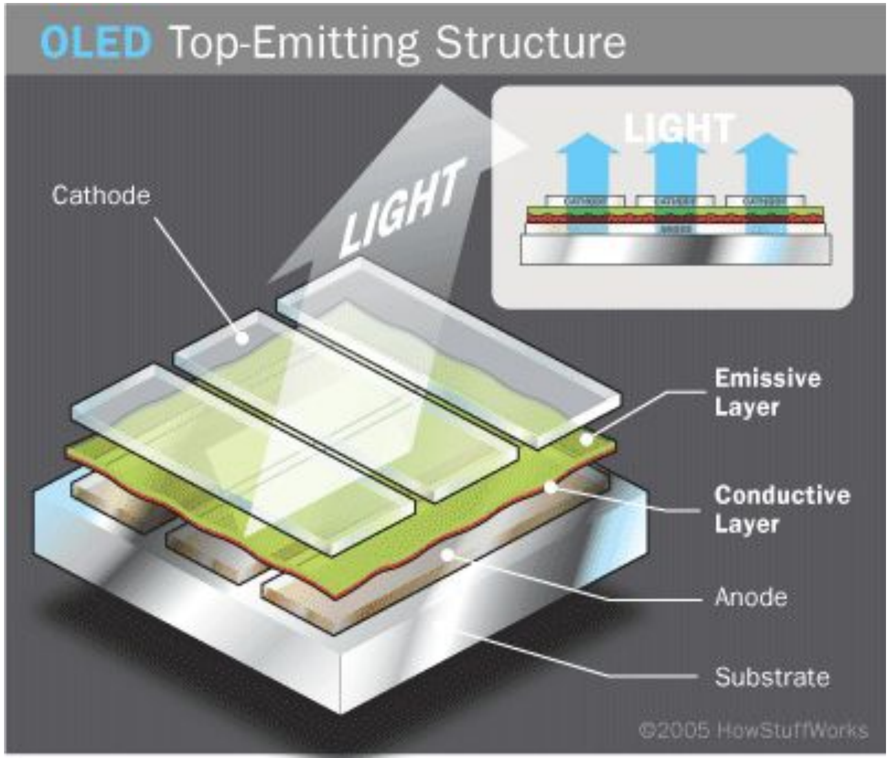
TYPES OF OLEDS

3. Transparent OLED (TOLED) - Transparent OLEDs have only transparent components (substrate, cathode and anode) and, when turned off, are up to 85 percent as transparent as their substrate. When a transparent OLED display is turned on, it allows light to pass in both directions. A transparent OLED display can be either active- or passive-matrix. This technology can be used for heads-up displays.



TYPES OF OLEDS

4. Top-emitting OLED (TEOLED) - Top-emitting OLEDs have a substrate that is either opaque or reflective. They are best suited to active-matrix design. Manufacturers may use top-emitting OLED displays in smart cards.



TYPES OF OLEDS

5. Foldable OLED (FOLED) - Foldable OLEDs have substrates made of very flexible metallic foils or plastics. Foldable OLEDs are very lightweight and durable. Their use in devices such as cell phones and PDAs can reduce breakage, a major cause for return or repair. Potentially, foldable OLED displays can be attached to fabrics to create "smart" clothing, such as outdoor survival clothing with an integrated computer chip, cell phone, GPS receiver and OLED display sewn into it.

TYPES OF OLEDS

6. White OLED (WOLED) - White OLEDs emit white light that is brighter, more uniform and more energy efficient than that emitted by fluorescent lights. White OLEDs also have the true-color qualities of incandescent lighting. Because OLEDs can be made in large sheets, they can replace fluorescent lights that are currently used in homes and buildings. Their use could potentially reduce energy costs for lighting.

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OLED ADVANTAGES

The LCD is currently the display of choice in small devices and is also popular in large-screen TVs. Regular LEDs often form the digits on digital clocks and other electronic devices. OLEDs offer many advantages over both LCDs and LEDs:

1. The plastic, organic layers of an OLED are thinner, lighter and more flexible than the crystalline layers in an LED or LCD.
2. OLEDs are brighter than LEDs. Because the organic layers of an OLED are much thinner than the corresponding inorganic crystal layers of an LED, the conductive and emissive layers of an OLED can be multi-layered. Also, LEDs and LCDs require glass for support, and glass absorbs some light. OLEDs do not require glass.

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OLED ADVANTAGES

3. OLEDs do not require backlighting like LCDs and hence they consume much less power than LCDs. This is especially important for battery-operated devices such as cell phones.
4. OLEDs are easier to produce and can be made to larger sizes. Because OLEDs are essentially plastics, they can be made into large, thin sheets.
5. OLEDs have large fields of view, about 170 degrees. OLEDs produce their own light, so they have a much wider viewing range.

OLED DISADVANTAGES

OLED seems to be the perfect technology for all types of displays, but it also has some problems:

1. Lifetime - While red and green OLED films have longer lifetimes (46,000 to 230,000 hours), blue organics currently have much shorter lifetimes.
2. Manufacturing - Manufacturing processes are expensive right now.
3. Water - Water can easily damage OLEDs

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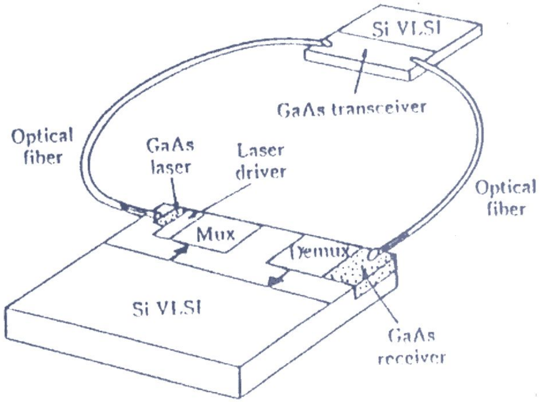
OLED APPLICATIONS

1. OLEDs are used in small-screen devices such as cell phones, PDAs and digital cameras.
2. Because OLEDs refresh faster than LCDs -- almost 1,000 times faster -- a device with an OLED display could change information almost in real time.
3. Several companies have already built prototype computer monitors and large-screen TVs that use OLED technology.

OPTOELECTRONIC INTEGRATED CIRCUITS

- Optoelectronic Integrated Circuits (OEICs) which involves monolithic integration of optical devices (lasers, waveguides) and electronics (transistors, modulators) devices.
- Integrated optoelectronic circuits (OEICs) have numerous applications in the different fields of applied science and engineering due to their advantages such as high data transmission speed, improved reliability, small size, light weight and potential low cost.
- Due to these advantages, it is now widely recognized that monolithic OEICs will play an important role in the field of data processing and transmission.

OPTOELECTRONIC INTEGRATED CIRCUITS



- An OEIC consists of active and passive components, monolithically integrated on the same substrate.
- The active components are those components which require the application of voltage or the passage for current (i.e. they are the components which have to be integrated with electronic circuits).
- The passive components are those components which do not require electric signals for their operation.
- Therefore, the active components are lasers, photo detectors, switches, modulators etc and the passive components are spectral filters, couplers, multiplexers, de-multiplexers, lenses etc.

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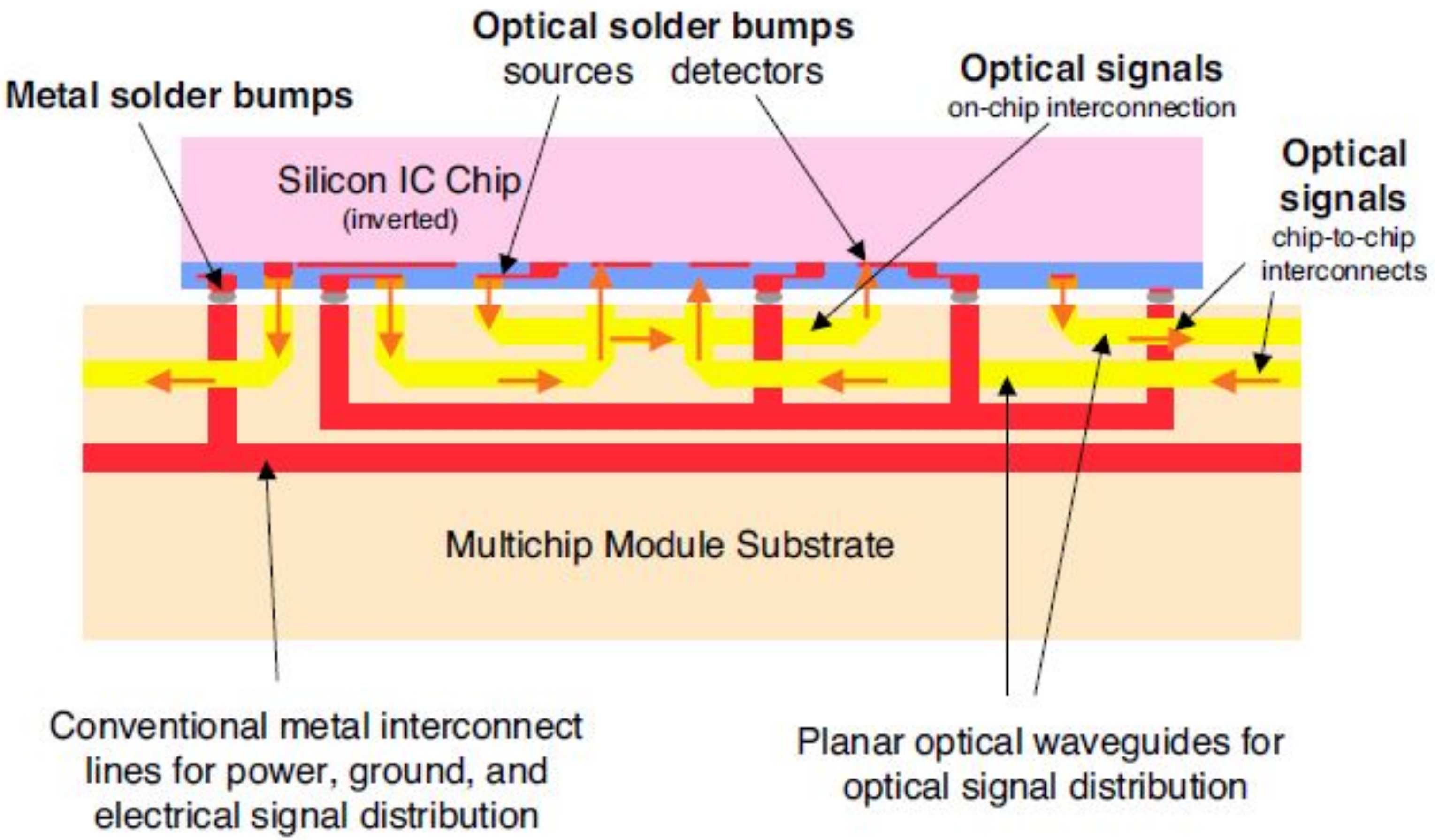
OPTOELECTRONIC INTEGRATED CIRCUITS

- Most optical elements should be connected with electronic circuitry in an OEIC. It is reasonable to expect that the progress in optoelectronic device technology will follow that of silicon based VLSI technology.
- However, the integration of several optical components on a single substrate is still a technological challenges.
- Since the technology of monolithic integration of electronic components is mature, now the task is to select a suitable material, structure and technology, which can address the challenges, faced by this new technology and can meet the demands of communication and computing systems.

Optical Solder Bumps: IC chip mounted multi-chip module substrate



DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY
SRM INSTITUTE OF SCIENCE AND TECHNOLOGY

18PYB103J –Semiconductor Physics

Module 2 Lecture 16

Solving Problems

1. Determine the wavelength of radiation given out by an LED with an energy of 3 eV, given that h = 6.626×10^{-34} m^2 kg / s and C= 3×10^{8} m/s

We know that

$$E = h\nu = \frac{hc}{\lambda}$$

$$\lambda = \frac{hc}{E} = \frac{6.626 \times 10^{-34} \times 3 \times 10^{8}}{3 \times 1.6 \times 10^{-19}}$$

= 414×10^{-9} m or 414 nm

2. Calculate the wavelength of light emission from GaAs whose band gap is 1.44 eV.

We know that

$$E = h\nu = \frac{hc}{\lambda}$$

$$\lambda = \frac{hc}{E_g} = \frac{6.626\times10^{-34}\times3\times10^{8}}{1.44\times1.6\times10^{-19}}$$

= 8628 x 10^{-10} m or 8628 Å

3. Calculate the long wavelength limit of an extrinsic semiconductor if the ionization energy is 0.02 eV.

We know that

$$E = h\nu = \frac{hc}{\lambda}$$

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

= 6.2119 x 10^{-5} m

4. An LED has a peak emission wavelength of 1.55 x 10^{-6} m. Find its band gap in eV.

We know that

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

5. A cadmium Sulphide (E_g=2.4 eV) photo detector is illuminated with light of wavelength 3000 Å. Find the total energy falling on it and comment whether electron-hole pairs are generated or not?

We know that, total energy falling on it

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