EN671: Solar Energy Conversion Technology

Solar Photovoltaic Fundamentals

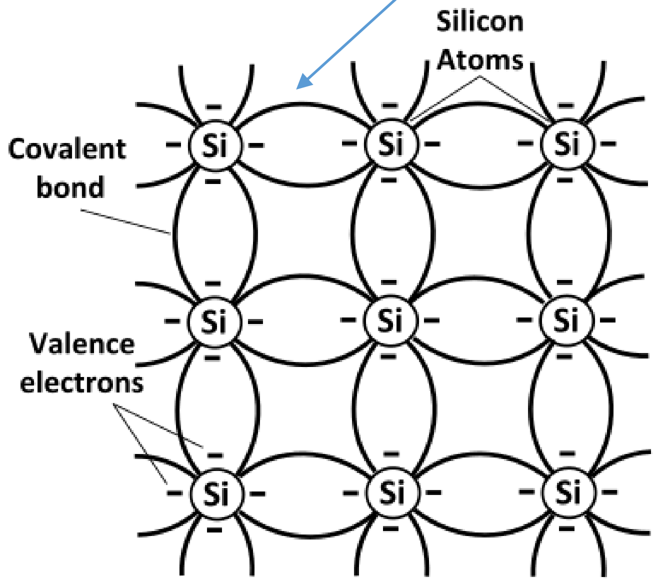
Dr. Pankaj Kalita
Associate Professor
School of Energy Science and Engineering
Indian Institute of Technology, Guwahati

Semiconductor Physics

- **Classification of semiconductors**
- **Doping**
- **Fermi energy level**
- **p-n junction**
- **Drift current and diffusion current**
- **Generations of solar cell material**

Semiconductors

Each pair of atom attracted by them with equal and opposite forces



- ✓A semiconductor is an element with electrical properties between a conductor and an insulator
- ✓Best semiconductors (Si and Ge) have 4 valance electrons
- ✓Best conductors - silver, copper and gold (one valence electron)
- ✓Best insulators have eight valance electrons.

✓Si is the most abundant element on earth after Oxygen.
✓Refining process of Si is costly.

Semiconductors

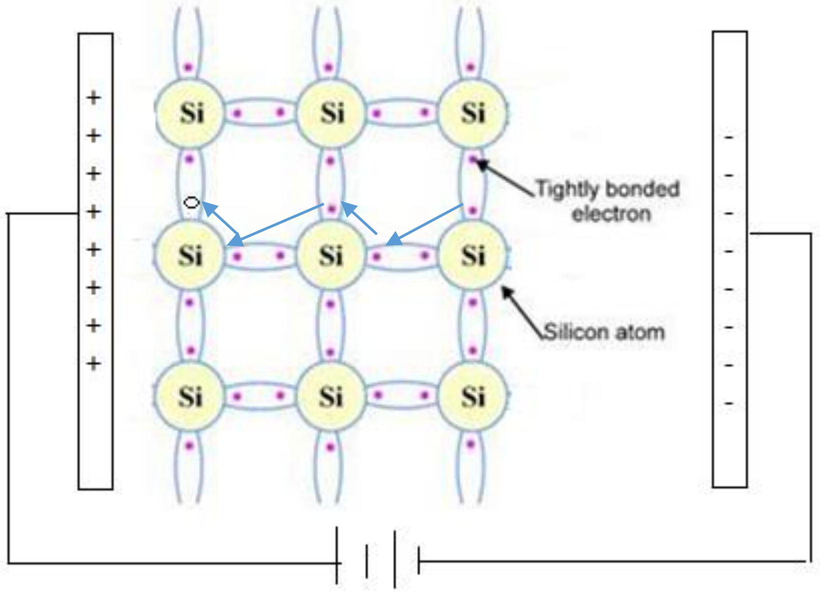
- At absolute zero temperature, a semiconductor is a perfect insulator.
- With increase in temperature vibration of atoms can occasionally dislodge an electron from the valence orbit.
- Dislodge electron is known as free electron, vacancy thus created in the valance orbit is known as a hole

✓ Breaking of covalent bond

Free electron hole pair produced

Accelerated by applying light and heat

Free electron



Free electron hole flow through a semiconductor

In pure silicon crystal, thermal energy creates equal number of free electrons and holes

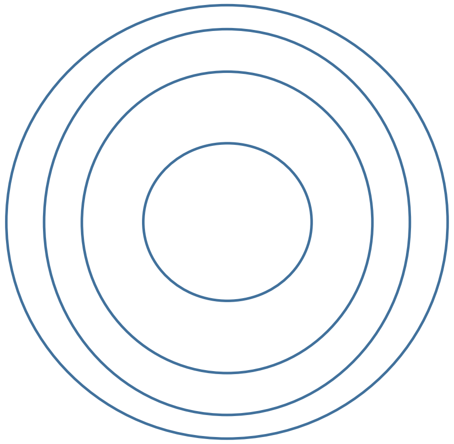
Semiconductors

- The free electrons move randomly throughout the crystal.
- Free electron will approach a hole, feel its attraction and fall into it.
- The merging of free electrons and a hole is known as recombination.
- The amount of time between creation and disappearance of an electron-hole pair is called **lifetime** (varies from a few nanoseconds to several microseconds)

In Summary, at any instant the following conditions exists within the Si crystal:

- ✓ Some free electron-holes are being created
- ✓ Some free electron-holes are being recombined
- ✓ Some free electron and holes exist temporarily, awaiting recombination.

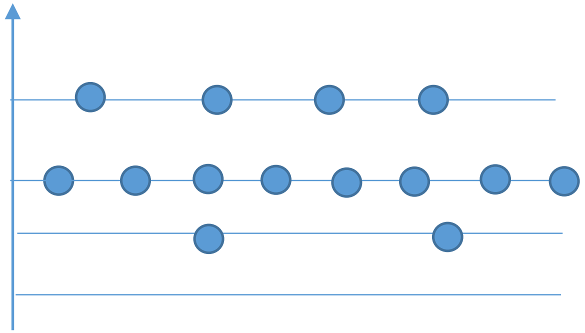
Orbits and energy levels



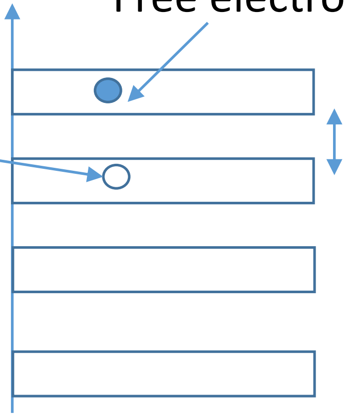
Orbits

Quantum Theory

Each radius of an orbit as equivalent to an energy level



Energy levels



Energy bands in any intrinsic Si crystal

- ✓ Atom: An electron (in an orbit) is influenced by the charges of the atom.
- ✓ Crystal: orbit of each electron is also influenced by charges of many other si atoms around it

Crystal

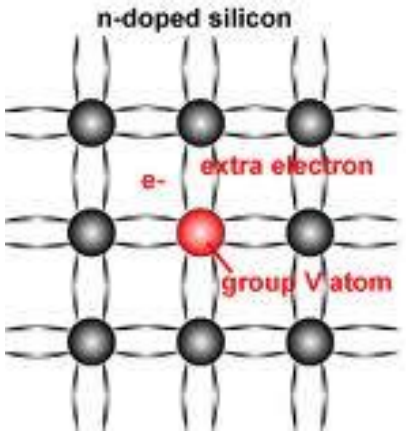
- ✓ Radius of each electron of same orbit is slightly different hence energy level of corresponding orbits are different.
- ✓ For every orbit there are billions of slightly different energy levels that forms a cluster of band of energy.

Semiconductors

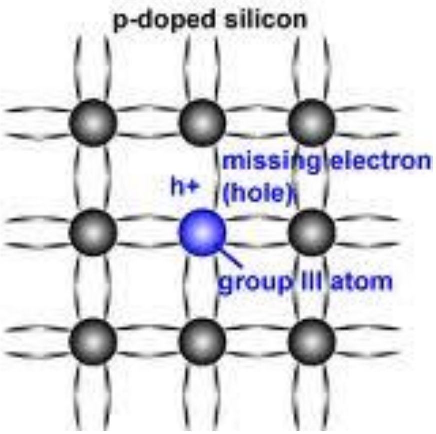
Intrinsic SC

1. chemically **very pure** and possesses **poor conductivity**
2. It has **equal** numbers of negative charge carriers (**electrons**) and positive charge carriers (**holes**)
3. Small current flow by thermal agitation

Impurity atom
Phosphorous

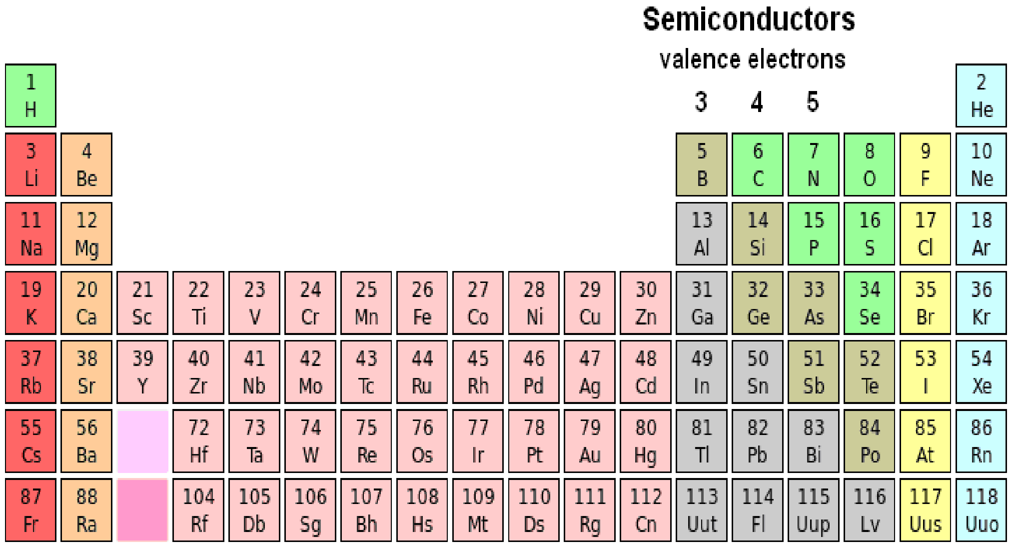


Impurity atom
Boron

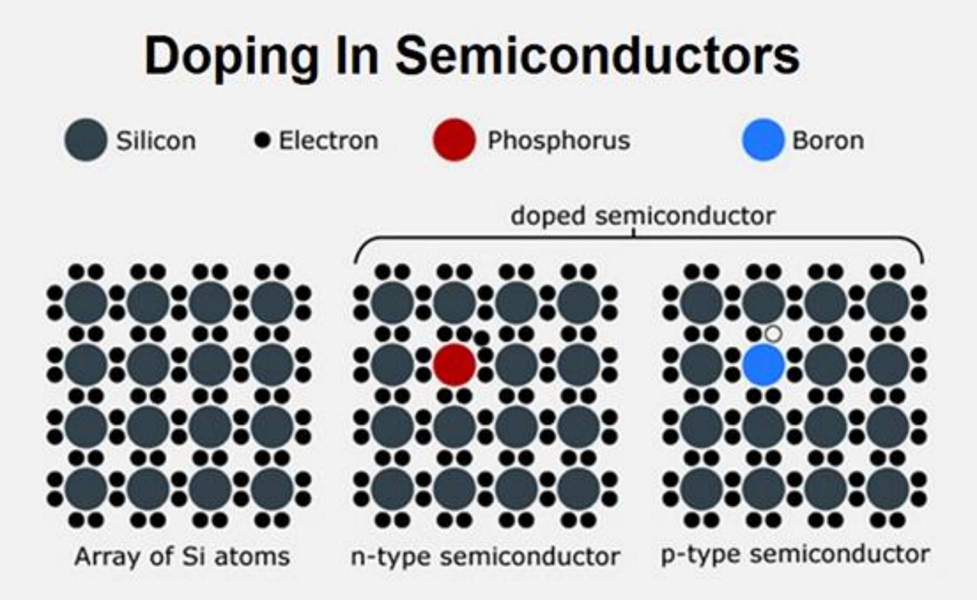


Extrinsic SC

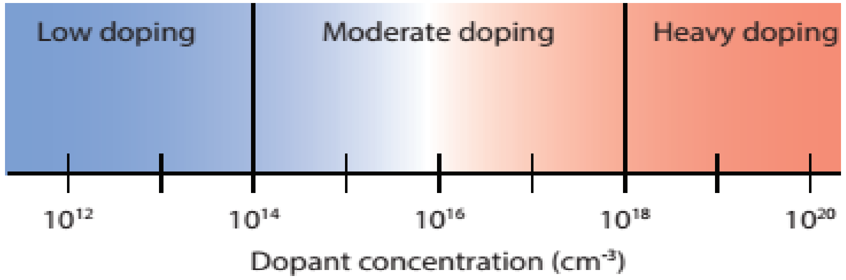
1. small amount of **impurities added** by a process, known as **doping**
2. numbers of negative carriers (**electrons**) and positive carriers (**holes**) are **not equal**
3. **Doping** gives rise to negative charge conductor(**n-type SC**). Or positive charge conductor (**P-type SC**).
4. Added 1 part in 10 million



- **Doping:** The process of addition of an impurity in an intrinsic semiconductor material in order to alter its electrical characteristics is known as doping.



The impurity ions having valency greater than that of the semiconductor produces an extra electron. In this case, electrons are the majority charge carriers, and holes are the minority charge carriers.



Fermi level (E_f): Fermi level or characteristics energy (in eV) for a crystal, represents the energy state with a 50% probability of its being filled by charge carriers.

- At thermal equilibrium, the concentration of electrons and holes is same and equal to the intrinsic carrier concentration for intrinsic semiconductors.

$$\boxed{n_e = n_h = n_i}$$

- According to Maxwell–Boltzmann statistics, the electron and hole concentration is given as follows:

$$n_e = N_C\left(T\right)\exp\left[\frac{\left(E_F - E_C\right)}{kT}\right]$$

$$n_h = N_V\left(T\right)\exp\left[\frac{\left(E_V - E_F\right)}{kT}\right]$$

where E_F is energy of the Fermi level; E_C is the energy at the bottom of the conduction band; and E_V is the energy at the top of the valance band

For intrinsic semiconductors:

$$\boxed{n_i^2 = n_e \times n_h = N_V\left(T\right) \times N_C\left(T\right)\exp\left[\frac{-\left(E_C - E_V\right)}{kT}\right]}$$

Independent of Fermi energy level

The concentration factors N_C and N_V are given by

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

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

where m_e =9.11 × 10^{-31} kg and m_h are the effective masses of electrons and holes, which are constant with temperature; and h is Plank's constant.

For intrinsic semiconductor in terms of E_F

$$n_e = n_h$$

$$\Rightarrow N_c(T)\exp\left[\frac{E_F - E_c}{kT}\right] = N_V(T)\exp\left[\frac{E_V - E_F}{kT}\right]$$

$$\Rightarrow \frac{N_V}{N_c} = \exp\left[\frac{E_F - E_c - E_V + E_F}{kT}\right]$$

Taking log

$$\ln\frac{N_V}{N_c} = \frac{E_F - E_c - E_V + E_F}{kT}$$

$$\Rightarrow 2E_F = E_c + E_V + kT\ln\frac{N_V}{N_c}$$

$$\Rightarrow E_F = \frac{E_c + E_V}{2} + \frac{kT}{2}\ln\left(\frac{m_h}{m_c}\right)^{3/2} \Rightarrow \boxed{E_F = \frac{E_c + E_V}{2} + \frac{3kT}{4}\ln\frac{m_h}{m_c}}$$

For crystalline silicon, at 300 K

$$N_c = 3.22\times10^{19}\,\mathrm{cm}^{-3}$$

$$N_V = 1.83\times10^{19}\,\mathrm{cm}^{-3}$$

For a extrinsic or doped (low doping) semiconductor, if n_0, p_0 and n_i are the electron, the hole, and the intrinsic carrier concentrations, respectively, then at thermal equilibrium:

$$\boxed{n_o p_o = n_i^2}$$

✓ **Doping in a pure semiconductor -** Affects the carrier concentration and other electrical properties of the semiconductor.

The Fermi level of a *n*-type material is,

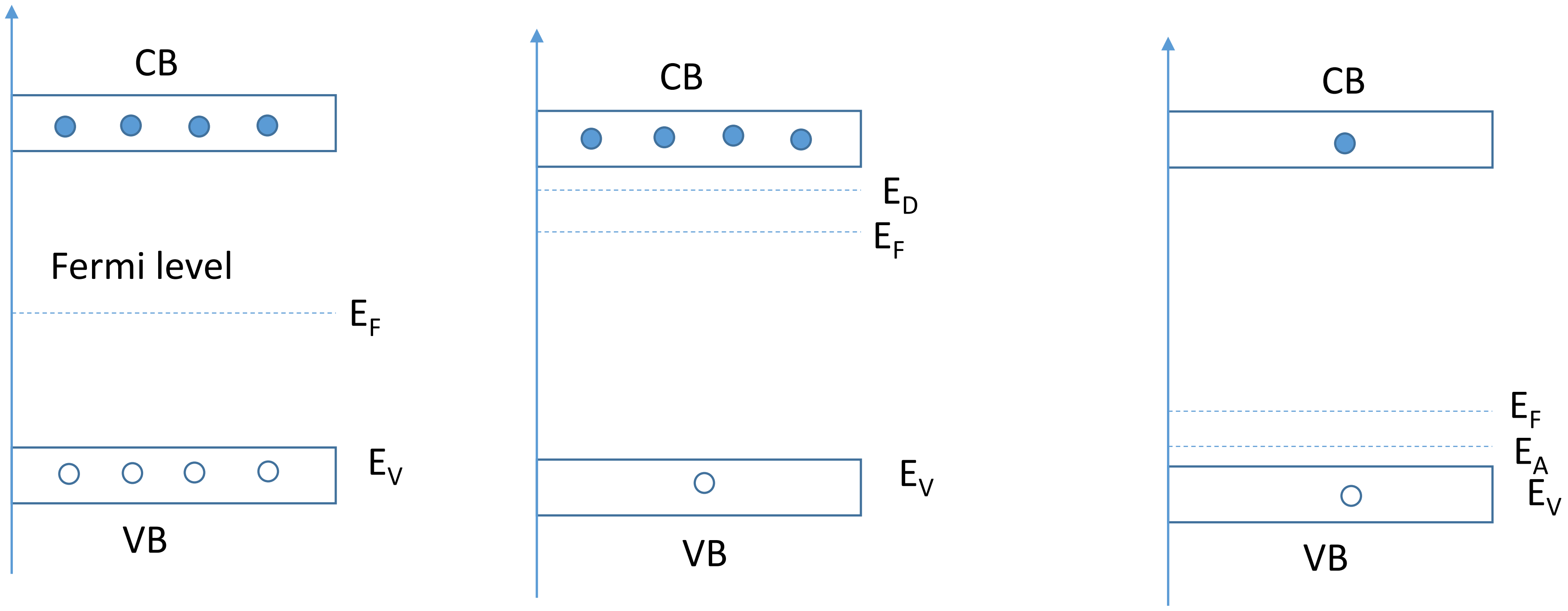
$$\boxed{E_F = E_c - kT \times ln\frac{N_C}{N_D}}$$

The Fermi level of a *p*-type material is,

$$\boxed{E_F = E_V + kT \times ln\frac{N_V}{N_A}}$$

E_c	Conduction band Energy
N_C	Effective density of states in conduction band
N_D	Donor concentration (donor density)
k	Boltzmann constant (in eV per degree Kelvin)
T	Absolute temperature in K
E_V	Valence band energy
N_V	Effective density of states in valence band
N_A	Acceptor concentration (acceptor density)

Position of Fermi level in intrinsic, *n*-type and *p*-type Si



Intrinsic Si

n – type Si

p – type Si

A shift of the position of the Fermi energy in the band diagram and the introduction of the allowed energy level into the bandgap due to the doping

Q1: A *p*-type silicon has effective density of states in the valance band as 1 x 10^{22} per cm^3 . An impurity from the 3rd group with concentration of 1 x 10^{19} per cm^3 is added . If the band gap for silicon is 1.1 eV, find the closeness of the fermi level with valence band at the temperature of 27 ^oC.

$$k = 8.629112 \times 10^{-5} \text{eV/K}$$

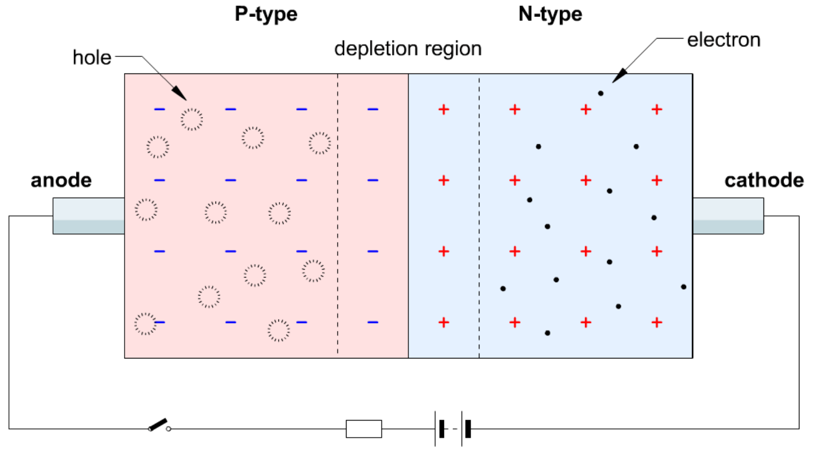
$$\boxed{\begin{aligned} & E_F = E_V + kT \times ln\frac{N_V}{N_A} \\ & \Rightarrow E_F - E_V = kT \times ln\frac{N_V}{N_A} = 0.1788\text{eV} \end{aligned}}$$

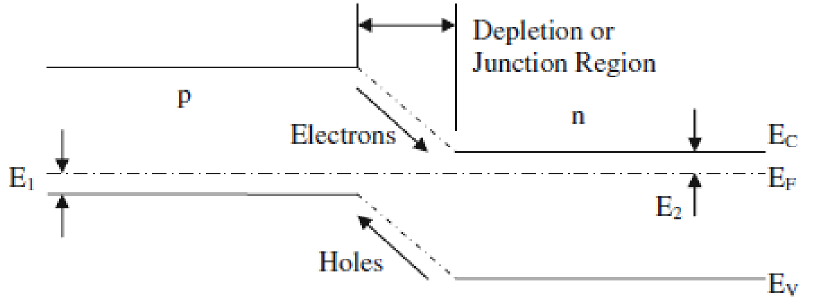
$1.38064852 \times 10^{-23}$ J/K

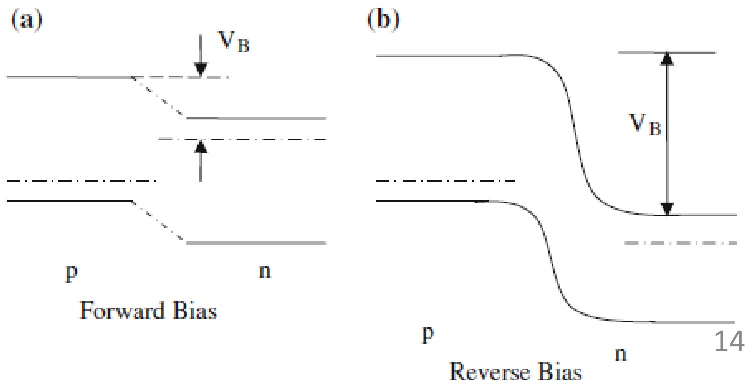
1 ev = 1.602 x 10^{-19} J

p–n Junction

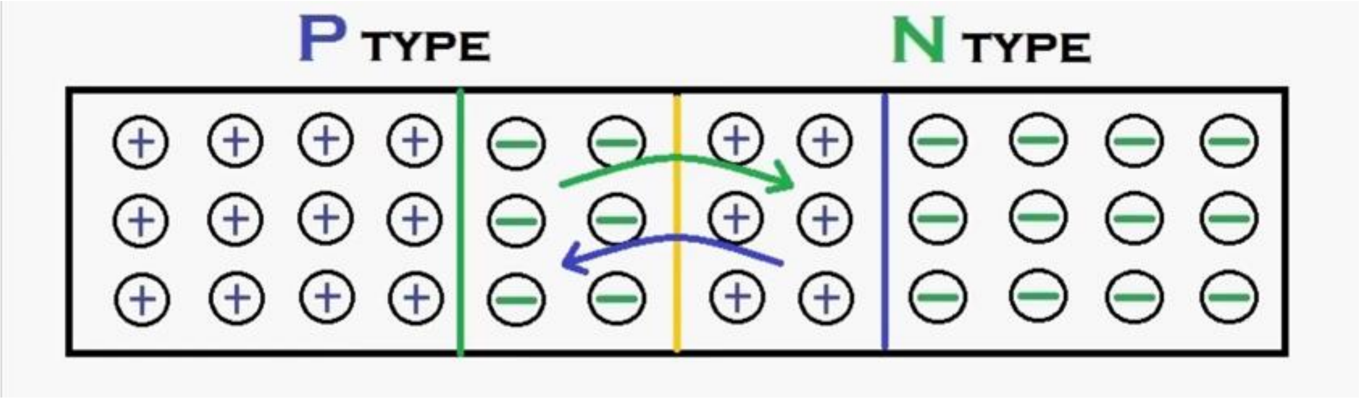
- The electronic inhomogeneity is the essential need for the conversion of solar energy into electricity.
- The electronic asymmetry is created by putting the p-type and n-type semiconductors in contact.
- At the junction between the p-type and n-type semiconductors, the majority charge carriers flow in the opposite direction, thus creating a positive charge in the n-region and a negative charge in the p-region. During the flow of charge carriers, the recombination process results in a region having no mobile charges; this region is known as the "**depletion region**."
- The steady state is achieved when the built-in potential across the junction opposes the flow of charge from either side.





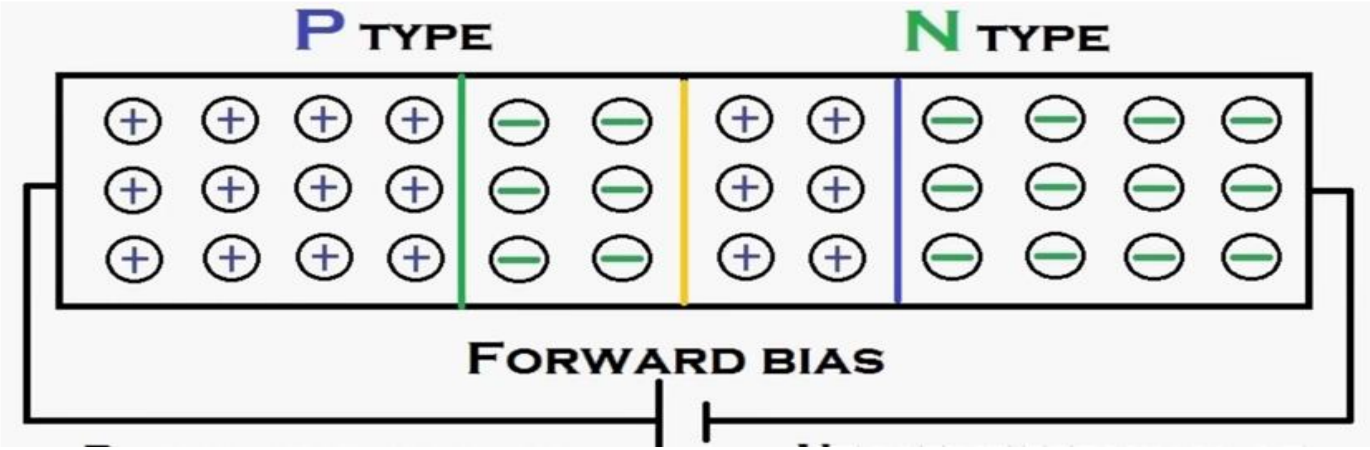


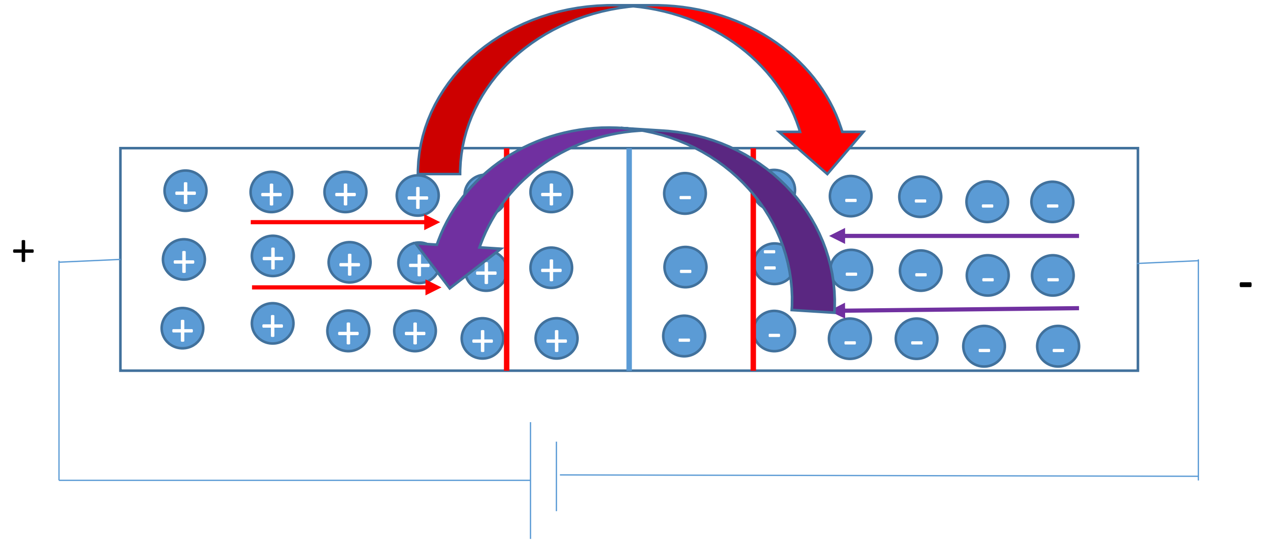
Diffusion current



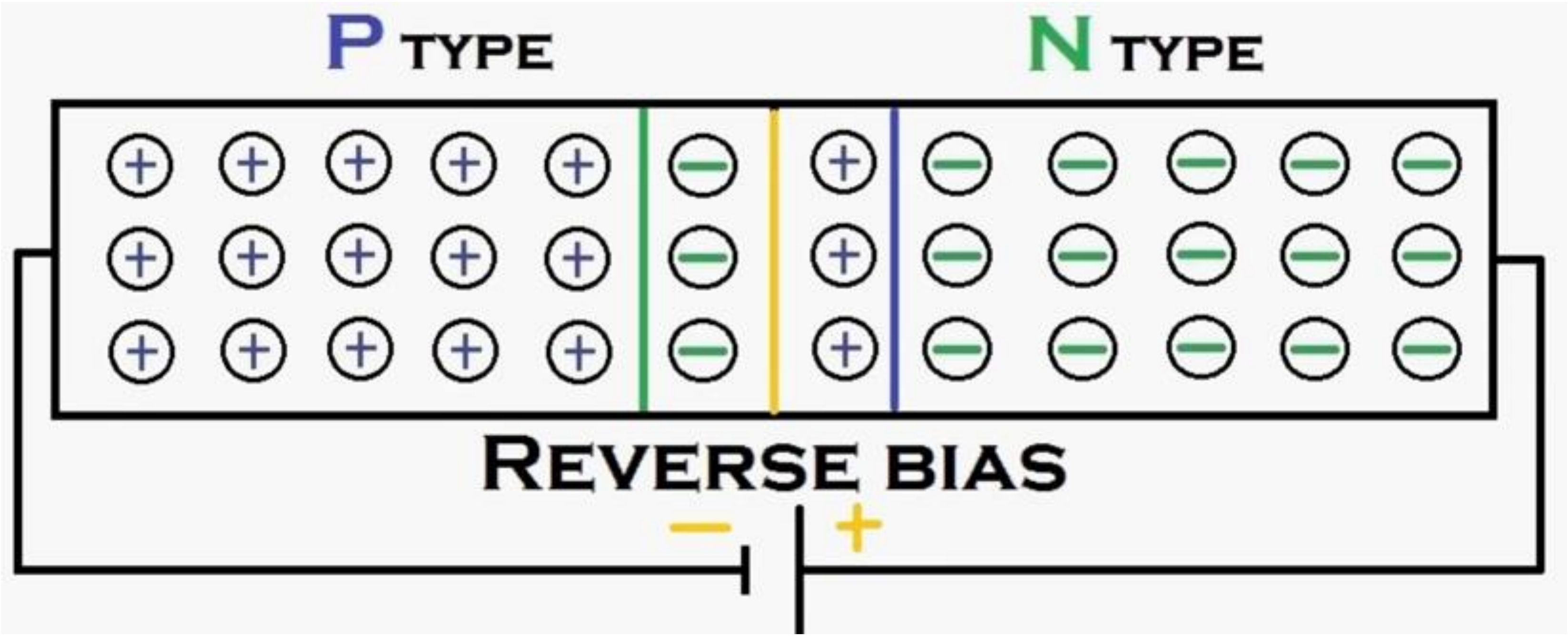
✓ **The movement of electrons and holes in then space charge region gives rise to diffusion current**

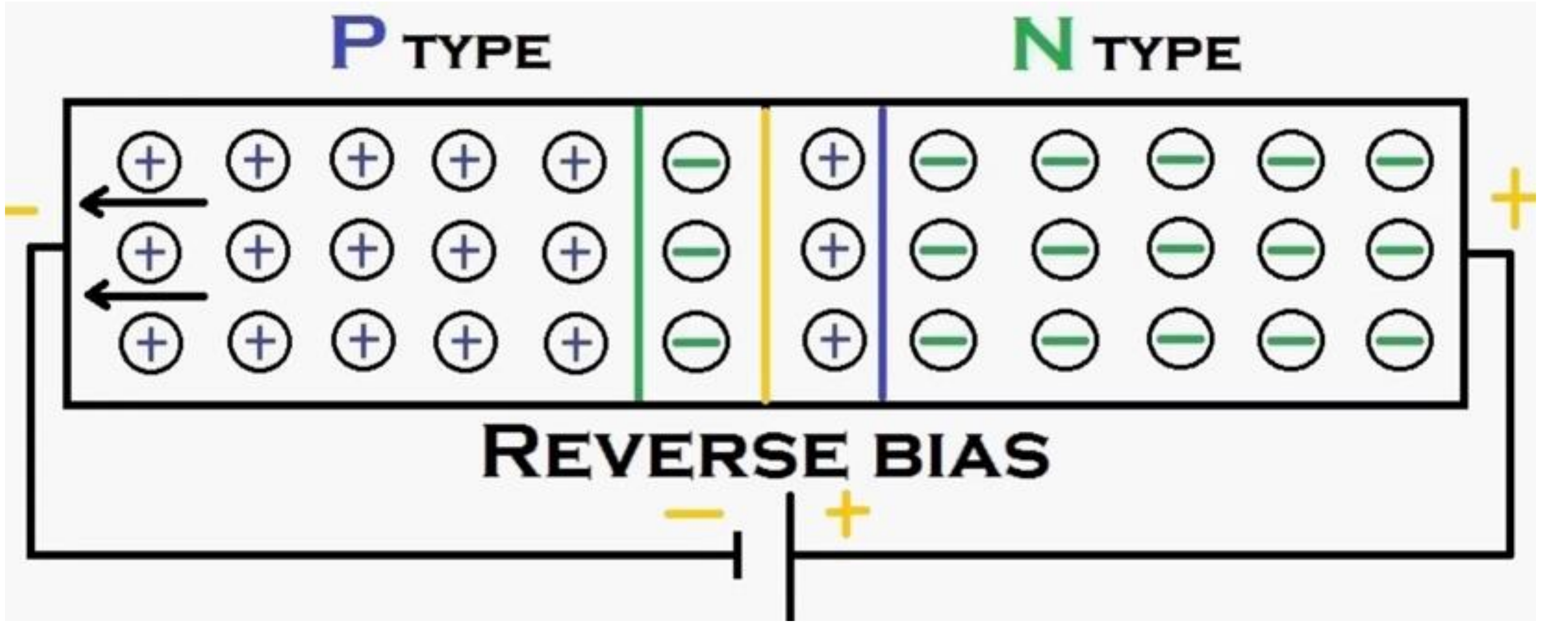
Drift Current





✓ If the voltage in the forward bias is above a specified range, the electrons in the n region drifts through the junction and migrate to the p region and the holes in the p region migrated through the junction to the n region which gives rise to flow of current called Drift current.


P TYPE
N TYPE
REVERSE BIAS
−
+



- ✓ Electrons get attracted to the positive terminal of the battery
- ✓ Results in the increase of the depletion layer
- ✓ If the battery voltage is above a particular voltage electrons and holes breakdown (avalanche breakdown) through the PN junction and cross resulting in the current to flow through the circuit

Generation of Solar Cell materials

- First Generation
  - Solar cells are based on Si wafer technology
  - Solar cells are Single junction with 33 % theoretical efficiency
  - Requires high energy and labour
  - Energy conversion efficiency : 15-20%
  - Widely used solar cells
- Second Generation
  - Solar cells includes amorphous solar cells (CdTe, CIGS, a-Si and micromorphous silicon)
  - Efficiency is low compared to 1st generation solar cells, **Cost of production is low**
  - Not require high energy and labour
  - Manufactured by depositing the thin film of the materials on substrate (Si, glass or ceramics) using chemical vapor deposition, molecular beam epitaxy or spin-coating technique.

Generation of Solar Cell materials

- Third Generation
  - Focus on the improvement of the energy conversion efficiency and light-absorption coefficient of second-generation solar cells while keeping the production cost close to that of second generation cells.
  - The enhancement in efficiency can be achieved by manufacturing multi junction solar cells, improving the light-absorption coefficients (concentrating solar cells) and using techniques to increase the carrier collection.

Summary

- Classification of semiconductors
- Doping
- Fermi energy level
- *p*-*n* junction
- Drift current and diffusion current
- Generations of solar cell material

Thank you