

COURSE NAME : Physics for Electrical Science.

Module 1 . SEMICONDUCTOR PHYSICS

Topics : Intrinsic semiconductor, Derivation of density of electrons in conduction band and density of holes in valence band. Intrinsic carrier concentration , Variation of intrinsic carrier concentration with temperature , Extrinsic semiconductor (qualitative) - Formation of pn junction , Fermi Level in semiconductors - intrinsic and extrinsic . Energy band diagram of pn junction - Qualitative description of charge flow across a pn junction - Forward and Reverse biased pn junctions , Diode equations (Derivation) - VI characteristics of pn junction .

Introduction

An atom is the smallest distinguishable unit of different kinds of matter. Substances are formed by ^{the} bonding of atoms. When atoms are bonded, the individual energy levels of electrons of every atom merge each other to form energy bands of allowable energy states. The gap between the energy bands are called forbidden energy gap, in which no electrons can exist .

The outermost energy band of an unexcited atom is the valence band. If energy is provided to the atoms in the valence band, electrons may jump to the conduction band.

Figure 1 shows the valence band & conduction bands which are separated by forbidden energy gap.

Conduction Band

Forbidden Energy Gap

Valence Band

Fig 1: Different energy bands of a substance.

Classification of Materials

Depending on the structure of the energy band, materials can be classified into three categories.

i) Insulators ii) semi-conductors iii) conductors.

(i) Insulators

These materials are characterized by a wide energy gap. Since the forbidden energy gap is very large, the applied field will not provide sufficient energy to the e^- s to jump from the valence band to the conduction band. \therefore In an

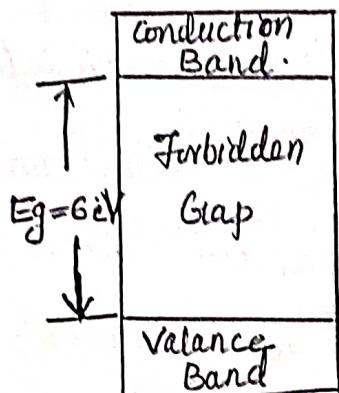
$$Eg \rightarrow Si \quad 1.21 \text{ eV}$$

$$Ge \quad 0.785 \text{ eV}$$

insulator conduction is very poor.

e.g. Diamond, wood etc.

The width of the forbidden energy gap Eg is around 6 eV.



Fig(i): Energy band diagram of insulator.

(ii) Semiconductor - A substance in which the width of the forbidden energy gap is relatively small ($\approx 1 \text{ eV}$) is called a semiconductor.

Examples are silicon & Germanium. The width of the forbidden energy gap Eg of Si and Ge are 1.21 eV and 0.785 eV respectively at 0°K.

[At 0°K, the valence band is full, and conduction band is empty and these materials behave as an insulator] As the temperature is increased,

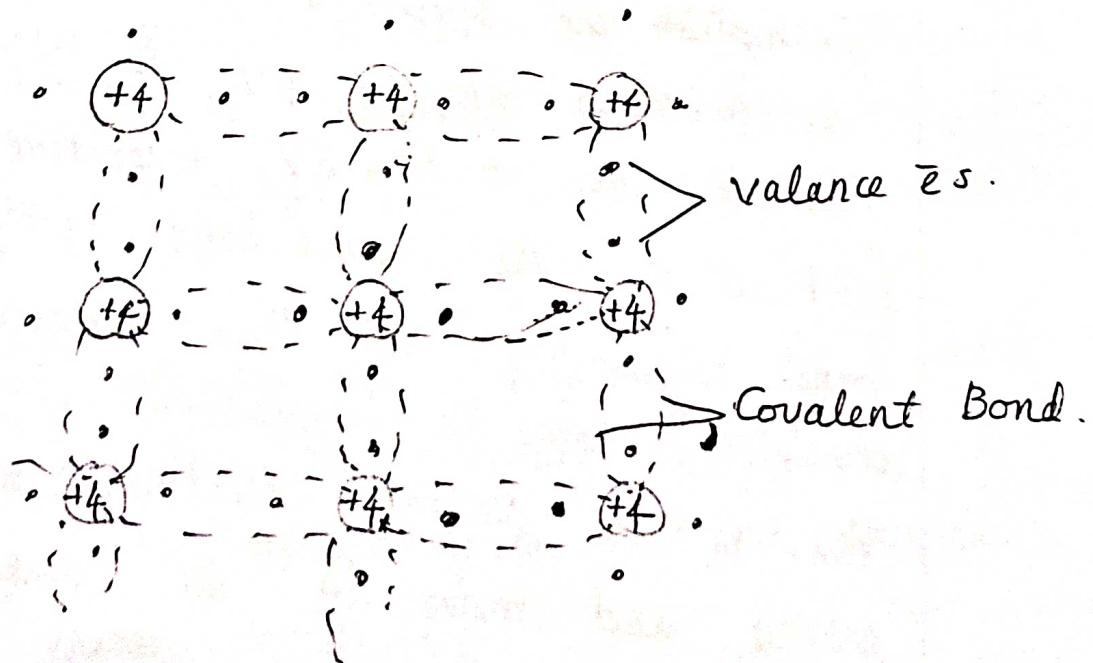
some of the valence electrons acquire sufficient energy and move to the conduction band.

The electrons in the conduction band are called free electrons. The absence of electron in the valence band is called a 'hole'.

Intrinsic Semiconductor

Semiconductor in the pure form is known as intrinsic semiconductor.

The silicon & germanium are the commonly used semiconductors and these have four valence electrons. The four valence e⁻s associated with each Si or Ge atom forms the pairs of electrons with neighbouring atoms as shown in figure.



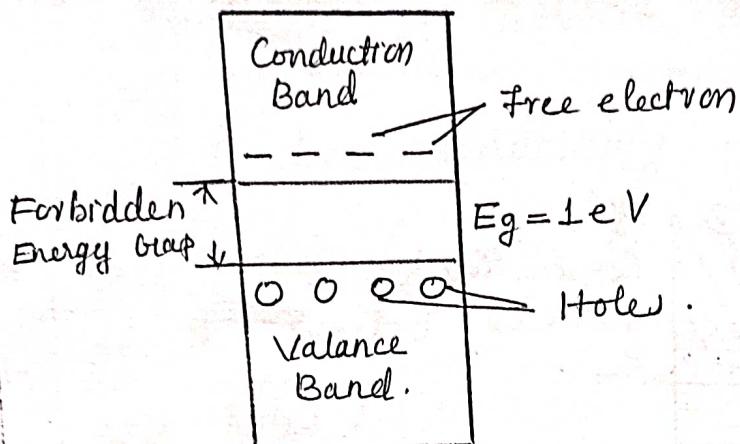


Fig (b): Energy band diagram of a semiconductor.

As the temperature is increased, more number of covalent bonds are broken, thereby resulting in more free \bar{e} s in the conduction band and holes in the valence band which increases the conductivity of the material. Thus the semiconductor has negative temperature coefficient of resistance.

(iii) Conductors — Elements in which valence

band and conduction band overlap each other are called conductors. In conductors current is due to free electrons only.

As temperature increases, the free \bar{e} s collide frequently and interfere with each other's progress under the influence of an applied electric potential. Thus conductivity of the material decreases with increase in temperature & hence the

conductors have positive temperature coefficient of Resistance.

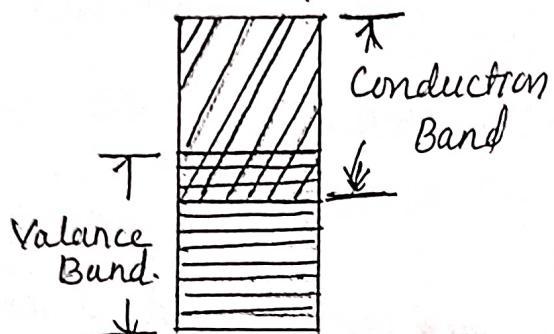


Fig (c) : Energy Band diagram of a conductor.

Intrinsic Semiconductor

An intrinsic semiconductor is a pure form of semiconductor material without any significant impurities or dopants. It possess electrical conductivity that lies between that of conductors and insulators.

eg: Silicon, Germanium.

Even at room temperature, some covalent bonds in the material may break and as a result some electron-hole pairs are produced. Hence when an electric field is applied across the intrinsic semiconductor current conduction takes place. This current conduction is due to these free electrons and holes.

Properties of Intrinsic Semiconductors.

1. Low conductivity — Intrinsic semiconductors have relatively low electrical conductivity because of the limited number of charge carriers (free electrons and holes).
2. Equal e^- and hole concentration — In an intrinsic semiconductor, the number of electrons in the conduction band = number of holes in the valence band. i.e. $n = p$.
3. Temperature dependence :-
The conductivity of an intrinsic semiconductor increases with increase in temperature.
(i.e. they have a negative temperature coefficient of resistance.)
4. Intrinsic semiconductors have a well-defined crystalline structure.
5. Intrinsic semiconductors have a characteristic energy gap (E_g) between valence band and conduction band. This energy gap determines the semiconductors optical properties, such as absorption & emission spectra.
6. The electrical properties of intrinsic semiconductors significantly alter with the addition of even a small amount of impurity.

Derivation of Density of electrons in conduction band and density of holes in valence band.

Electrons are the charge carriers in the conduction band and holes are the charge carriers in the valence band.

(i) Density of Electrons in Conduction Band.

The density of es in the conduction band n is given by the eqn: $n = \int_{E_c}^{\infty} dn$.

where dn is the number of electrons present in the energy interval E and $E+dE$, in the conduction band.

$$dn = (\text{Probability of Occupancy}) \times (\text{Density of States})$$

$$dn = F(E) z(E) dE$$

where $z(E) dE$ is the total number of available energy levels in dE space or the density of states.

and $F(E)$ is the Fermi-Dirac distribution function. The energy of conduction band varies from E_c to $+\infty$.

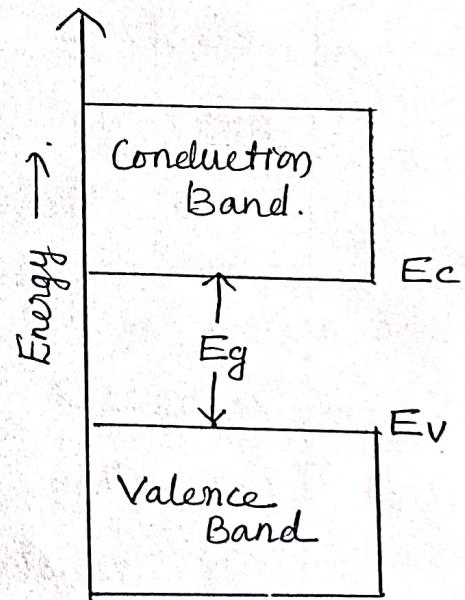


Fig (i) Energy Band Diagram.

\therefore The total number of electrons in the conduction band is given by,

$$n = \int_{E_c}^{\infty} dn = \int_{E_c}^{\infty} Z(E) dE \quad \text{--- (1)}$$

The standard expression for the density of states is

$$Z(E) dE = \frac{4\pi}{h^3} (2m_e^*)^{3/2} E^{1/2} dE,$$

where m_e^* is the effective mass of electron in the periodic potential.

To find the density of electrons in the conduction band, E can be replaced with $(E - E_c)$.

\therefore The density of states,

$$Z(E) dE = \frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_c)^{1/2} dE \quad \text{--- (2)}$$

Probability of occupancy of electron is given by the Fermi-Dirac distribution function.

$$\text{i) } F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \quad \text{--- (3)}$$

For all possible temperatures,

$$(E - E_F) \gg kT.$$

$$\text{ii) } \left(\frac{E - E_F}{kT}\right) \gg 1 \quad \therefore \exp\left(\frac{E - E_F}{kT}\right) \gg 1$$

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

Substituting eqns. ② & ④ in ① :-

$$n = \int_{E_c}^{\infty} \exp\left(\frac{E_F-E}{kT}\right) \cdot \frac{4\pi}{h^3} (2m_e^*)^{3/2} (E-E_c)^{1/2} dE \quad (5)$$

The integration can be done by substitution method.

$$\therefore \text{put } \frac{E-E_c}{kT} = x$$

$$\text{Then At } E = E_c \Rightarrow x = 0$$

$$\text{At } E = \infty \Rightarrow x = \infty$$

\therefore In terms of x limits varies from $x=0$ to ∞

$$\text{Also } E - E_c = kT x$$

$$\therefore dE = kT \cdot dx$$

$$\text{We have } \exp\left(\frac{E_F-E}{kT}\right) = \exp\left(\frac{E_F}{kT}\right) \cdot \exp\left(-\frac{E}{kT}\right)$$

where $\exp\left(\frac{E_F}{kT}\right)$ is a constant &

$$\text{from } \frac{E-E_c}{kT} = x \Rightarrow -\frac{E}{kT} = -\frac{E_c}{kT} - x$$

\therefore In terms of x eqn. ⑤ can be written as

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_0^{\infty} \exp\left(\frac{E_F}{kT}\right) \cdot \exp\left(-\frac{E_c}{kT} - x\right) (kTx)^{1/2} kT dx$$

$$\therefore n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \exp \frac{E_F}{kT} \cdot \exp \frac{-E_C}{kT} (kT)^{3/2} \int_0^\infty e^{-x} x^{1/2} dx$$

$$\text{or } n = \frac{4\pi}{h^3} (2m_e^* kT)^{3/2} \exp \left(\frac{E_F - E_C}{kT} \right) \int_0^\infty e^{-x} x^{1/2} dx. \quad (6)$$

In equation (6) $\int_0^\infty e^{-x} x^{1/2} dx$ is a standard integral.

- From Gamma function it can be written as

$$\int_0^\infty e^{-x} x^{1/2} dx = \frac{\sqrt{\pi}}{2}$$

$$\text{or } n = \frac{4\pi}{h^3} (2m_e^* kT)^{3/2} \exp \left(\frac{E_F - E_C}{kT} \right) \cdot \frac{\sqrt{\pi}}{2}$$

$$n = 2 \left(\frac{2\pi m_e^* k T}{h^2} \right)^{3/2} \exp \left(\frac{E_F - E_C}{kT} \right) \quad (7)$$

where m_e^* is the effective mass of electron.

k - Boltzmann's constant, $k = 1.38 \times 10^{-23} \text{ J/K}$

T - Temperature in Kelvin.

h - $6.625 \times 10^{-34} \text{ Js}$, Planck's constant.

E_F - Fermi Energy

Equation (7) represents the density of electrons in the conduction band of an intrinsic semiconductor

Density of Holes in the Valence Band of an Intrinsic Semiconductor.

Let $d\rho$ be the number of holes available in the energy interval between E and $E + dE$ in the valence band.

Then $d\rho = (\text{Probability of occupancy}) \cdot (\text{Density of states})$
 Since $F(E)$ is the probability of occupancy of electrons. Then $(1 - F(E))$ represents the probability of occupancy of holes.

\therefore The number of holes in the valence band,

$$\rho = \int_{-\infty}^{E_V} d\rho$$

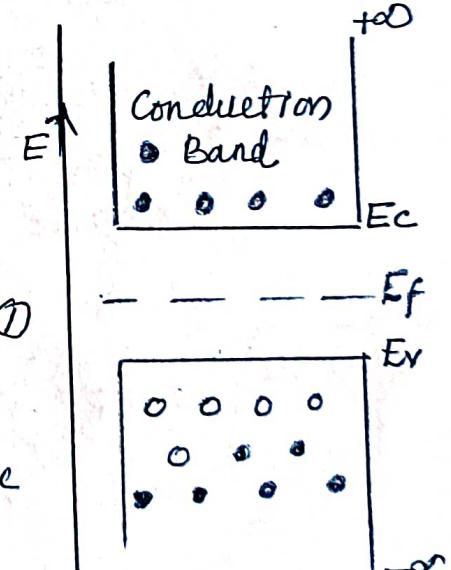
$$\text{ii} \quad \int_{-\infty}^{E_V} d\rho = \int_{-\infty}^{E_V} (1 - F(E)) Z(E) dE \quad \text{--- (1)}$$

where $F(E)$ is the Fermi-Dirac distribution function and

$$(1 - F(E)) = 1 - \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \quad \text{--- (2)}$$

By Taylor's series expansion

$$\frac{1}{1+x} = 1 - x + x^2 - x^3 + \dots$$



If α is too small,

$$\frac{1}{1+\alpha} = (1-\alpha)$$

∴ from equation ② ; the 2nd term on R.H.S becomes \Rightarrow

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

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

$$\therefore (1 - F(E)) = \exp\left(\frac{E-E_F}{kT}\right) \quad \text{--- } ③$$

Density of states of holes,

$$z(E) dE = \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_V - E)^{1/2} dE \quad \text{--- } ④$$

where m_h^* is the effective mass of holes.

and h is the Planck's constant.

$$\therefore h = 6.625 \times 10^{-34} \text{ J.s.}$$

Substituting eqn: ③ & ④ in ① :-

$$P = \int_{-\infty}^{E_V} \exp\left(\frac{E-E_F}{kT}\right) \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_V - E)^{1/2} dE.$$

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} \exp \frac{-E_F}{kT} \int_{-\infty}^{E_V} \exp\left(\frac{E}{kT}\right) (E_V - E)^{1/2} dE \quad (5)$$

Equation (5) can be solved by using substitution method. For that put $\frac{E_V - E}{kT} = x$

$$\text{i} (E_V - E) = x kT. \quad (6)$$

$$\text{and } \frac{E_V}{kT} - x = \frac{E}{kT}$$

At $E = -\infty \quad x = \infty$
At $E = E_V \quad x = 0$

Also differentiating eqn. (6) on both sides :-

$$-dE = kT \cdot dx \quad \text{or} \quad dE = -kT \cdot dx.$$

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} \exp \frac{-E_F}{kT} \int_{+\infty}^0 \exp\left(\frac{E_V}{kT} - x\right) (2kT)^{1/2} kT dx$$

$$\text{i} p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} (kT)^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right) \int_{\infty}^0 e^{-x} x^{1/2} dx$$

$$\therefore p = \frac{4\pi}{h^3} (2m_h^* kT)^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right) \int_0^\infty x^{1/2} e^{-x} dx. \quad (7)$$

In eqn. (7) the standard integral is

$$\int_0^\infty x^{1/2} e^{-x} dx = \frac{\sqrt{\pi}}{2}$$

$$p = \frac{4\pi}{h^3} (2m_h^* kT)^{3/2} \cdot \exp\left(\frac{E_v - E_F}{kT}\right) \cdot \frac{\sqrt{\pi}}{2}$$

$$p = 2 \cdot \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp\left(\frac{E_v - E_F}{kT}\right) \quad \text{--- (8)}$$

In eqn. (8) m_h^* is the effective mass of holes, and eqn. (8) represents the density of holes in the valence band of an intrinsic semiconductor.

Intrinsic Carrier Concentration (n_i)

The density of e^- s and holes in an intrinsic semiconductor is given by

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

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

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

$$n_i = n = p$$

$$n_i^2 = n \cdot p.$$

$$n_i^2 = 2 \left(\frac{2\pi m_e^* k T}{h^2} \right)^{3/2} \exp \left(\frac{E_F - E_C}{k T} \right) \cdot 2 \left(\frac{2\pi m_h^* k T}{h^2} \right)^{3/2} \exp \left(\frac{E_V - E_F}{k T} \right)$$

$$\therefore n_i^2 = 4 \left(\frac{2\pi k T}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} \exp \left(\frac{E_V - E_C}{k T} \right).$$

But $(E_C - E_V) = E_g$, is the band gap energy.

$$\Rightarrow (E_V - E_C) = -E_g.$$

$$n_i^2 = 4 \left(\frac{2\pi k T}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} e^{-\frac{E_g}{k T}}$$

\therefore The intrinsic carrier concentration,

$$n_i = 2 \left(\frac{2\pi k T}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-\frac{E_g}{2kT}}.$$

Variation of Intrinsic Carrier Concentration with Temperature.

The intrinsic carrier concentration is given

by

$$n_i = 2 \left(\frac{2\pi k T}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/4} \exp \left(\frac{-E_g}{2kT} \right) \quad \text{①}$$

where n_i - intrinsic carrier concentration.

E_g - Energy Gap.

k - Boltzmann's constant & T - absolute temperature

$$\therefore n_i(T) \propto T^{3/2} \cdot \exp\left(\frac{-E_g}{2kT}\right) \quad \text{--- (2)}$$

From eqn. (2) it is clear that $n_i(T)$ increases exponentially with temperature. As temperature increases intrinsic carrier concentration, n_i increases exponentially as more electrons jump from the valence band to the conduction band, creating more electron-hole pairs. At a given temperature, material with larger band gaps have lower intrinsic carrier concentrations due to the requirement of more energy to excite electrons from the valence band to the conduction band.

Also the increased carrier concentration leads to high leakage current in semiconductor devices. Hence performance of such device may be degraded at high temperatures.
