SAMPLE STUDY MATERIAL

Electrical Engineering

EE / EEE

Postal Correspondence Course

GATE , IES & PSUs

Semiconductor Material & Devices

Contents

CHAPTER-1

INTRODUCTION

1) Thermal Voltage (V_T)

It represents "*temperature in terms of voltage*".

$$V_T = \frac{\overline{K}T}{q}\text{Volt} \qquad \overline{K}, = \text{Boltzmann constant}$$

$$\overline{k} = kq$$

$q = 1.6 \times 10^{-19}$ K
$K = 8.62 \times 10^{-5} ev/^{o}K$

Boltzmann constant is ratio of universal gas constant to Avogadro's number

$$\therefore \qquad K = \frac{8.314}{6.022\times10^{23}} \qquad J/^{o}K \quad = 1.38\times15^{23} J/^{\circ}K$$

$$\because \qquad 1ev = 1.6\times10^{-19} J. \qquad \therefore \qquad K = 1.38\times10^{-23} J/^{\circ}K = 8.62\times10^{-5} ev/^{\circ}K$$

$$V_T = KT = \frac{T}{11600}Volt.$$

At room temperature T = 300 K

$$V_T \text{ at room temperature} \quad V_T = \frac{300}{11600} = 0.256 \quad \text{Volt.}$$

$$\boxed{V_T \;\; = 26 \text{ mV}}$$

2) Standard Temperature

(i) Absolute Temperature 0^{o} K = –273^{o} C
(ii) Room Temperature 300^{o} K = 27^{o} C
(iii) Ambient Température $T_A 290^{o}$ K = 17^{o} C

Key Points :

→ Temperature in ^{o}C = Temperature in ^{o}K – 273
→ Temperature in ^{o}K = Temperature in ^{o}C + 273

3) Electron Voltage (Ev)

Electron Volt: Unit of Energy

For energies involved in electron devices, 'joule' is too large a unit. Such small energies are Conveniently measured in electron volt, abbreviated as eV. The electron volt is the kinetic energy gained by an electron, initially at rest, in moving through a potential difference of 1 volt. Since e = 1.6×10^{-19}C

1 ev is defined as the energy gain by the electron in moving through a potential difference of 1 volt. It is the unit of 'Energy'

$1 \text{ ev} = |q| \times p_d$
$= 1.6 \times 10^{-19}\text{C} \times 1 \text{ volt} \quad = 1.6 \times 10^{-19}$ J

4) Leakage Current (I_o)

This current is generated only due to temperature variation.

$$I_{o(T_2)} = Io_{(T_1)} 2^{\left[\frac{T_2 - T_1}{10}\right]}$$

It is also called minority carrier current or Reverse saturation current or thermally generated current.

Advantages: The **Si** has small leakage current *i.e.* **Si** has small I_0

$$I_o = \overset{Si}{¦}_A \; \overset{Ge}{«}_A$$

→ I_O doubles for every 10^o rise in temperature.
Alternatively, we can say that I_0 increases by 7% for every 1ºC (or 1ºK) rise in temperature.

5) Current (I)

Rate of change of charge carriers. $i = \frac{dq}{dt}\,Ampere.$

→ In a Semiconductor current is carried by both e^- and holes.

→ In Semiconductor there are two types of current.
i) Drift Current ii) Diffusion Current

(i) **Drift Current**: The steady flow of e' in one direction caused by applied electric field constitutes an electric current, called the 'Drift Current'.

OR

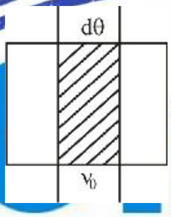
→ It is the current due to Potential Gradient.

(ii) **Diffusion Current**: It is the current due to concentration gradient.

6) Current Density (J)

Current density is a measure of the density of an electric current flowing through a solid per unit area. Current density is a vector which points in the direction of current flow.

$$\vec{J} \Rightarrow |\vec{J}| = \frac{I}{A} = \frac{Current}{Area}\left(\frac{\text{A}}{\text{m}^2}\right) = \frac{d¯}{dt \times A}$$



$$\frac{d¯}{dt} = \text{Number of change carrier flow in 1 second at a point}$$

$$d¯ = ° \times A \times V_d$$

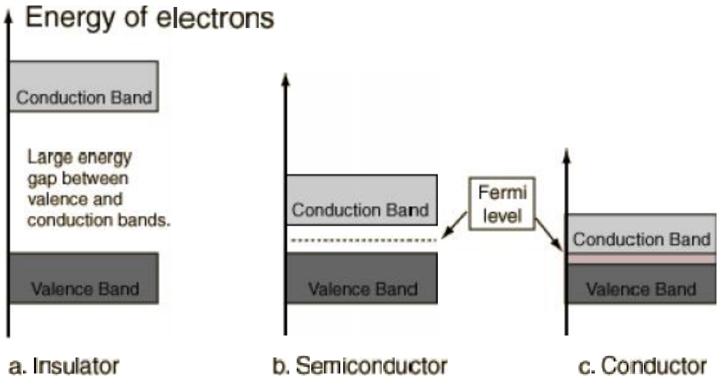
Let the energy above the Fermi energy E_F be E_1 Then $\Delta E = E_1$ ΔE_F, and the probability of occupancy f (E_1) of the level E_1 is given by the FD distribution function, i.e.

$$J = n\,q\,V_d = n\,q\,«_E$$

$$\underbrace{J = \pm E}_{\text{Ohm's law in Point form.}} \qquad \text{Where } \pm = nq«$$

Where ± = Conductivity

7) Energy Band in Solid

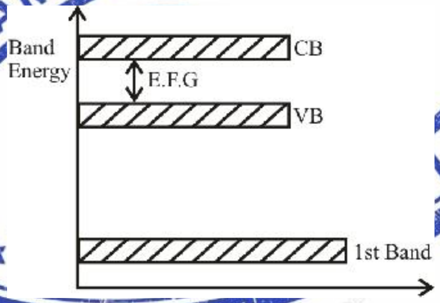


The range of energies possessed by an $\bar{e}$ in a solid is known as "Energy Band"

1) **Valence Band:** The range of energy possessed by in band e^- is known as "Valence Band". They are not free to conduct , thus, no contribution to conductions .

2) Conduction Bond: In certain material the valence e^- are loosely attached to the nucleus some valence electron may get detached to become free e^- which are responsible for the conduction of current in a conductor, they are called conduction e^-. The range of energies possessed by conduction e^- is known as conduction band. The e^- in the conduction band are free e^-.

3) Forbidden Energy Gap: The difference in energy between C.B. and V.B. in the energy band diagram is known as F.E.G.



→ No electron can stay in the forbidden energy gap.

Typical values of the energy gap:

	0K	300K
Ge	0.785 ev	0.72 ev
Si	1.21 ev	1.1 ev

Energy gap decreases linearly with temperature

$$Eg(T) \cong Eg(T) - 3.46\times10^{-4}T$$

Key Point : Free e^- exist only in conduction band and holes exist only in V.B.

Effect of Temperature : Due to thermal energy electron jumps from V.B. to C.B. and gets free.

→ When temperature increases then carrier concentration also increase and both $\bar{e}$ & holes (C.B.) decrease. Then the conductivity ↑ and Band gap ↓

8) Classification of Solids According to the BAND GAP

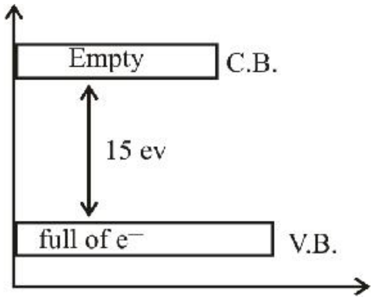
i) Insulator :

An insulator, also called a dielectric or non-conductor, is a material that resists the flow of electric current.

An electrical insulator is a material whose internal electric charges do not flow freely, and which therefore does not conduct an electric current, under the influence of an electric field. A perfect insulator does not exist, but some materials such as glass, paper and Teflon, which have high resistivity, are very good electrical insulators. Examples include rubber-like polymers and most plastics.

An insulating material used in bulk to wrap electrical cables or other equipment is called insulation.

The valance band is full of e^- while the conduction band is empty and the energy gap between V.B. and C.B is very large i.e. 15 ev.



For Insulator: Temperature (Increases) → Resistance (Decreases) : Negative temperature of resistance coefficient.

At room temperature it behaves as a perfect insulator. The resistance of the insulator decrease with increase in temperature so insulators have negative temperature Co-efficient of resistance.

Some insulating / non-conducting materials

- Plastics and solidified resins
- Rubber and Silicones
- Glass and ceramics
- Most metal oxides
- Most minerals and crystals
- cold, un-ionized gases (including Air)
- Oil
- Vacuum
- Water, if purified and de-ionized
- The depletion zone within a semiconductor
- asphalt
- fiberglass
- porcelain
- ceramic
- quartz
- (dry) cotton
- (dry) paper
- (dry) wood
- plastic
- diamond

Application :

- Insulators are commonly used as a flexible coating on electric wire and cable. Since air is a non-conductor, no other substance is needed to "keep the electricity within the wires".
- In microelectronic components such as transistors and ICs, the silicon material is normally a conductor because of doping, but it can easily be selectively transformed into a good insulator by the application of heat and oxygen. Oxidized silicon is quartz, i.e. silicon dioxide.

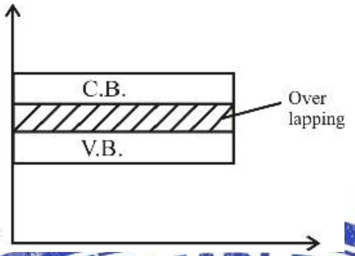
- In high voltage systems containing transformers and capacitors, liquid nonconductor oil is the typical method used for preventing sparks. The oil replaces the air in any spaces which must support significant voltage without electrical breakdown.

ii) **Conductor:** The substance which easily allow the passage of electric current through it.

In terms of energy band gap the V.B. and C.B. are overlapping, a slight potential difference across the conductor cause the free e^- to constitute a electric current.

Silver is the best known conductor, but in an oxygen rich environment it tarnishes. Silver is used in specialized equipment, such as satellites, and as a thin plating to mitigate skin effect losses at high frequencies.

As a general conductor copper is the most commonly used on Earth because it's cheap, reasonably flexible, reasonably light and the 2nd best conductor and the best per unit weight. Copper allows for ease of soldered and crimped/clamped connections.



→ Positive temperature co-efficient. Due to overlapping

$$R_{(T_1)} = R_{(t0)}[1+\sim(T_1-T_0]$$

"α" called temperature coefficient measured in "/ºC" and is positive for metals.

Example: $Al = 13 = \underbrace{2+8}+\underset{\mapsto free\ \bar{e}}{3}$

Here are a few common examples of conductors and insulators:

- Silver
- Gold
- Iron
- Brass
- Mercury
- concrete
- copper
- aluminum
- steel
- bronze
- graphite

9) DOPING :

It is the process of adding impurity to the pure semiconductors according to our requirements. Impurities change the conductivity of the material so that it can be fabricated into a device.

- Group V impurities are called ***Donors***, since they “donate” electrons into the Conduction Band.
  - *Semiconductors doped by donors are called n-type semiconductors.*
- **Acceptor energy levels**
  - Ge : 10 meV
  - Si : 45 – 160 meV
  - GaAs : 25 – 30 meV
  - ZnSe : 80 – 114 meV
  - GaN : 200 – 400 meV
- Acceptor and donor impurity levels are often called ***ionization energies*** or ***activation energies***

If both types of impurities are present :

If the total concentration of donors (N_D) is larger than the total concentration of acceptors (N_A) have an ***n-type semiconductor,*** in the opposite case we have a ***p-type semiconductor***

There are two types of Dopants.

i) **Trivalent impurities:** It is also called acceptor type impurities.

Example: Boron, Aluminum, Gallium, Indium, Telenium for P type.

ii) **Pentavalent impurities:** It is also called Donor type impurities.

Example: Bismuth, Phosphor, Arsenic, Antimony for N type.

Charge Neutrality Equation :

To calculate the charge concentration, the charge neutrality condition is used, since the net charge in a uniformly doped semiconductor is zero

Otherwise, there will be a net flow of charge from one point to another resulting in current flow.

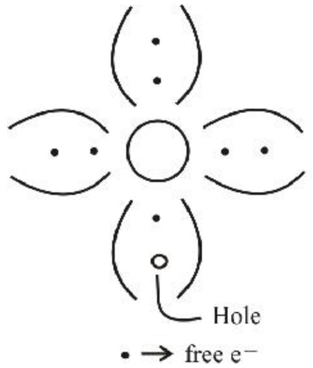
$$p + N_D^+ = n + N_A^-$$

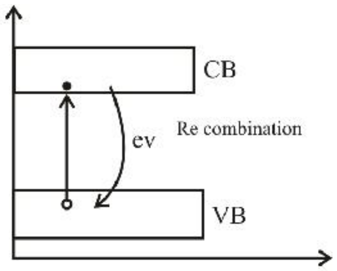
- ➢ p is the concentration of holes in the valence band.
- ➢ n is the electron concentration.
- ➢ N_D^+ is the ionized donor concentration.
- ➢ N_A^- is the ionized acceptor concentration.

10) Type of Semiconductor

i) Intrinsic Semiconductor ii) Extrinsic Semiconductor

i) **Intrinsic Semiconductor:** There are pure Semiconductor’s in which no impurity is added. At 0^oK it behaves a perfect insulator.





Always present in VB

In intrinsic Semiconductor numbers of e^{-} = no. of holes = $¦_i$

Where $¦_i$ — intrinsic concentration.

e^{-} and holes always moves in opposite direction but they contributes current in the same direction.

So the direction of current is opposite to the flow of e^{-} but in the same direction of flow of holes.

Hole is the charge carrier having q = 1.6×10^{-19} C.
Conductivity: $\pm = ¦\, q«$ ($\pm$ = conductor)

For Semiconductor: $\pm = nq«_e + pq«_h$

$$\pm_i = n_i q\left(«_e + «_n\right) mho/cm$$

n = no. of e⁻ p = no. of holes q = charge

$$«_e , «_h = mobility\, of\ e^{-}\ \&\, holes$$

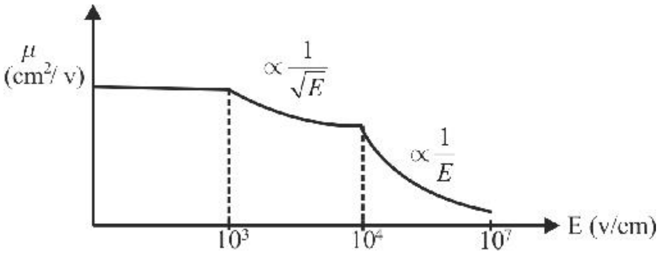
Where mobility is defined as the ratio of drift velocity to the applied electric field.
Mobility varies inversely with the temperature as $\mu \propto T^{-m}$, where "m" is an empirical constant.

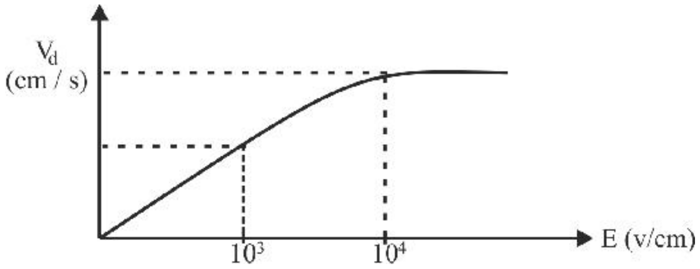
Mobility v/s applied electric field:

$\because \quad \mu = \dfrac{V_d}{E}$

$\therefore \quad V_d\ v/s$ E groups will be :

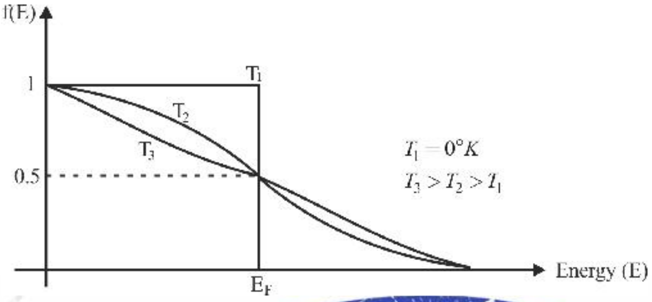
The drift velocity first increases linearly,and then sub-linearly and finally becomes saturated with respect to the applied electric field.





∴ The probability of moles = 1–probability of electrons = 1 – f(E)

Fermi-Dirac function is giving the probability of occurrence of electrons.



ii) **Extrinsic Semiconductor:** These are the Semiconductor in which impurity are added to increase the conductivity of the Semiconductor and have to control it.

→ when impurity is Trivalent then Semiconductor is called P- type.

→ When impurity is penta-valent then Semiconductor is called N- type.

Conductivity : For n- type of Semiconductor.

$$\pm_{s/C} = nq\text{«}_e + pq\text{«}_n$$

For N- type : $\pm_N = nq\text{«}_e = nq\text{«}_n = N_D\text{«}_n$ $N_D =$ Donor

→ Over all N-type Semiconductor is electrically neutral. (No net addition or removal of charges) According to the law of "electrically neutrality."

$N_D + p = N_A + n$

Total positive charge = Total negative charge

In N-type Semiconductor $N_A = 0$

$N_D + p = n$

$N_D >> p$

$$\boxed{N \cong N_D}$$

Key point: The noise due to minority carriers (holes) is called Thermal noise, Also called white noise, Johnson Noise.

→ Conductivity of P-type Semiconductor: $\pm_P$

$$\pm_P = p_q\text{«}_n + n_q\text{«}_e$$

$$\pm_P = p_q\text{«}_n$$

$$\pm_P = N_A\, q\, \text{«}_n$$

According to the law of electrically neutrality:

$p + N_D = n + N_A$

In p-type Semiconductor $N_{\vartriangle} = o$

$p = N_A + n$

$N_A >> n$ $\boxed{p \approx N_A}$

Key Point: N-type Semiconductoris superior to P-type Semiconductor

$\boxed{«_n >> «_p}$

10) General Properties of Ge and Si:

S. N.	Properties	Ge	Si.
1.	Atomic Structure	32	14
2.	Total no. of atoms or Density or Density of atoms/cm^3	4.421×10^{22}	5×10^{22}
3.	Intrinsic concentration $n_i = atoms/cm^3$	2.5×10^{13}	1.5×10^{10}
4.	Intrinsic Resistivity $°_i = \Omega - cm$	45	230000
5.	$E_g^o(oH)$ ev	0.785	1.21
6.	E_G300 ev	0.72	1.1
7.	$«_n$ cm^2/V-sec	3800	1300
8.	$«_p$ cm^2/V-sec	1800	500
9.	$D_n\}$ Diffusion constant	99	34
10.	$D_p\}$ Diffusion constant	47	13
11.	Maximum operating temperature	75° C	+175^{O}C
12.	Leakage Current (I_o)	$«_A$	n_A
13.	Power handling capacity	Low	High
14.	Knee voltage	0.3	0.7
15.	Dielectric constant	16	12

11) MASS ACTION LAW

Under the thermal equilibrium the product of free $e^-$and holes concentration is constant. That is independent of amount of donor and acceptor impurity doping.

$\boxed{PN = \text{Constant}}$ → mass action law

In case of intrinsic semiconductor

$$n = p = ¦_i \qquad \boxed{pn = ¦_i^2}$$

$¦_i$ = intrinsic concentration.

12) DIFFUSION LENGTH (L)

Distance travelled by the charge carriers before recombination takes place. It is denoted by L.

$$L_p = D_n\,²_p \qquad L_n = D_n\,²_n$$

L_p = Diffusion length for holes.

L_n = Diffusion length for e^-

² = Carrier lifetime $« / \sec$ or $m / \sec$.

$$\boxed{L = \sqrt{D²} \quad m^2 / \sec}$$

→ **Lifetime of Carriers :** It is defined as the average time taken by the carriers from generation to recombination after recombination the carrier called dead carriers as known as for the condition is possible with this carriers.

13) EINSTEIN’S RELATIONSHIP

These equation given by Einstein but named in his honour.

$$\frac{D_p}{«n} = \frac{Dn}{«e} = V_T = \frac{KT}{q} = \frac{T}{11600}$$

$$V_T = \frac{KT}{q} \quad . \quad V_T \text{ At } 0^o\text{C}$$

V_T = 26 mV at room temperature (300 k)

14) FERMI ENERGY OR FERMI LEVEL

It is the energy level at which probability of finding e^- is half.

→ **Fermi Dirac Function (F (E)):**

$$\boxed{F(E) = \frac{1}{1 + e^{(E - E_F)/KT}}}$$

Where E = Energy of e^- in eV

E_F = Energy of Fermi level.

At $E = E_F$

$$F(E) = \frac{1}{1+e^{o}} = \frac{1}{1+1} = \frac{1}{2} = 0.5 = 50\% \quad \text{Probability}$$

N_C and N_V are called as effective density of states in the conduction and valence bands respectively.

$\therefore$ Number of electrons in conduction band , $n = N_c.e^{-\frac{(E_C - E_E)}{KT}}$

$\therefore$ Number of lollp in valence band , $p = N_V.\bar{e}^{\frac{(E_F - E_V)}{KT}}$

Mathematically, $N_C = 2\left(\frac{2\pi m_e KT}{h^2}\right)\frac{3}{2}$

and , $N_V = 2\left(\frac{2\pi m_h KT}{h^2}\right)\frac{3}{2}$

where M_e and m_h are the respective effective masses of the electrons and holes.

Queation-1: Derive an expression for intrinsic concentration.

Solution:

$$\because \qquad (n_i)^2 = n.p = N_c.e^{-\frac{(E_C - E_F)}{KT}} \times N_v.e^{-(E_F - E_V)} / KT$$

$$= N_c.N_v.e^{-(E_C - E_v)/KT} = A/T^3.e^{-(E_C - E_V)KT}$$

Where “A” is a constant

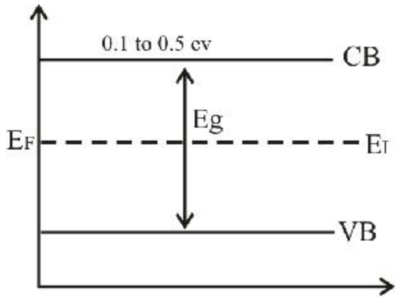
$$\therefore \qquad (n_i)^2 = A.T^3.e^{-(E_C - E_v)/KT}$$

We can also replace $E_C - E_V$ by E_C i.e. the energy gap.

Question-2: Why is $\mu_p < \mu_n$?(mobility of e^- > mobility of holes

Solution: Because holes have higher effective mass than electrons and holes have to move in the valence band , where density of states is more.

→ **Fermi Level in Intrinsic S/C:** In the intrinsic S/C the Fermi level is always at centre of the band gap and it is independent in temperature. The Fermi energy is equal to:



$$E_F = E_v + \frac{E_g}{2} \qquad = E_v + \frac{E_c - E_v}{2} \quad = \frac{E_c + E_v}{2}$$

For N-type:

The concentration of e^- in N-type semiconductor is given by $n = N_c e^{-\frac{(E_c - E_F)}{KT}}$

N_C = function of mass and temperature

$$N \approx N_D \qquad N_D = Donor$$

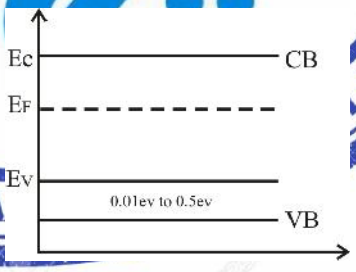
$$N_D = N_c e^{(E_C - E_F)/KT}$$

$$-E_C + E_F = KT \ \ln \frac{N_D}{N_C}$$

$$E_F = E_C + KT \ \ln \frac{N_D}{N_C}$$

$$E_F = E_C - KT \ \ln \frac{N_C}{N_D}$$

For P-type semiconductor:



$$p = Nv\, e^{-(E_F - E_v)/KT}$$

$$N_V \propto \left(m_P T\right)^{\frac{3}{2}}$$

$$p \approx N_A \qquad N_A = Acceptor$$

$$N_A = N_V e^{-(E_F - E_V)/KT}$$

$$-E_F + E_V = KT \ \ln \frac{N_A}{N_V}$$

$$E_F = E_V + KT \ \ln \frac{N_V}{N_A}$$

$$E_F = E_V + KT \ \ln \frac{N_V}{N_A}$$

Brief summary :

- The most widely used material is silicon.
- Pure crystals are intrinsic semiconductors.
- Doped crystals are extrinsic semiconductors.
- Crystals are doped to be n type or p type.
- n type semiconductors have few *minority* carriers (*holes*).
- p type semiconductors have few *minority* carriers (*electrons*).
- In metals, the conduction band and valence band partly overlap each other and there is no forbidden energy gap.
- In insulators, the conduction band is empty and valence band is completely filled and forbidden gap is quite large = 6 eV.
- The energy band above the forbidden gap is called conduction band and the energy band below the forbidden gap is called valence band.
- Hole is a of positive charge which is produced when an electron breaks away from a covalent bond in a semiconductor. Hole has a positive charge equal to that of electron. Mobility of hole is smaller than that of electron.
- In n-type semiconductor electrons are majority carriers and holes are minority carriers.
- In p-type semiconductor, holes are majority carriers and electrons are minority carriers.
- Electrical conductivity of semiconductor is the reciprocal of its resistivity.
- Depletion region is a layer created around the junction which is devoid of free charge carriers and has immobile ions.
- The electron effective mass is inversely proportional to the curvature of an electron band E (k).
- Donors are impurity atoms which increase the electron concentration, i.e. n-type dopant, whereas acceptors are impurity atoms which increase the hole concentration, i.e. p-type dopant.

PRACTICE SET

1. An electron at rest is accelerated through a potential difference of 100 V. Calculate its final kinetic energy in J and eV. What is its final velocity?

77 Final Selections in Engineering Services 2014.

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